EUROPEAN JOURNAL OF STEM EDUCATION

Volume 6, Issue 1
2021

Editor-in-Chief
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Windesheim University of Applied Sciences (The Netherlands)

e-ISSN: 2468-4368

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VOLUME 6 ISSUE 1, 2021

TABLE OF CONTENTS

Research Articles

EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 01
ISSN: 2468-4368

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Pre-service Teachers' Readiness for Emergency Remote Learning in the Wake of COVID-19

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Citation: Dorsah, P. (2021). Pre-service Teachers' Readiness for Emergency Remote Learning in the Wake of COVID-19. *European Journal of STEM Education*, 6(1), 01. https://doi.org/10.20897/ejsteme/9557

Published: January 15, 2021

ABSTRACT

The purpose of the study was to determine pre-service student teachers' readiness for emergency remote learning. The study participants consisted of 115 (66 males and 49 females) pre-service teachers of Gambaga College of Education, Ghana. Online learning readiness scale (OLRS) questionnaire was used to collect the data. Pre-service teachers were ready for online learning with overall readiness mean score of 3.65. The dimension with the highest mean score was motivation for learning (M = 3.97, SD = .90) followed by self-directed learning (M = 3.82, SD = .93). However, the dimensions of learner control (M = 3.30, SD = 1.00), computer/internet self-efficacy (M = 3.43, SD = 1.16) and online communication self-efficacy (M = 3.47, SD = 1.11) recorded low means. There was no significant difference in online learning readiness between males (M =3.71, SD =.82) and females (M = 3.57, SD = .76), t (.94), p = .349. Also, there was no significant difference in readiness between level 100 pre-service teachers (M = 3.65, SD = .79) and level 200 pre-service teachers (M = 3.68, SD = .85) t (-.122), p = .903.

Keywords: pre-service teachers, COVID-19, online learning readiness, emergency remote teaching

INTRODUCTION

Rapid migration of schools to online learning due to COVID-19 pandemic has raised concerns at local and international levels about the quality of education and students' readiness to cope with the new emerging situation. The demand for high level of science and technological literacy makes Science, Technology, Engineering and Mathematics (STEM) education of high concern especially in these times. According to Lee and Campbell (2020), now is the time to create "a new normal" for science education specifically and STEM education broadly.

Students' preparedness to execute within an online educational context is very vital (Budzar, Ali & Tariq, 2016). The need to understand students' readiness for online learning is more significant than ever because online learning is becoming popular in educational environments across the world due to lockdown of schools and universities because of COVID-19 pandemic. This situation forced all levels of educational institutions to operate remotely and to put emergency remote teaching into practice (Bozkurt & Sharma, 2020). According to Dhawan (2020), betwixt the lockdown challenges, online teaching and online learning can be termed as the panacea for the crisis. Many academic institutions have shifted entirely to online teaching and learning (Dhawan, 2020).

Online learning can be defined as acquiring knowledge and skills through synchronous and asynchronous learning applications (Morrison, 2003). Distance education is characterized by the distance in time and/or space between learners and learning resources (Bozkurt & Sharma, 2020). According to Chuck et al. (as cited in Bozkurt & Sharma, 2020), what is currently being done is emergency remote teaching, which is considered a temporary solution to an immediate problem.

According to Hung et al. (2010) students should be more active in online learning environments and should be more responsible in their learning, time-management, keeping up with the class, completing work on time and they should be active contributors to instruction. Aydin and Tasci posited that understanding students' readiness for online learning is the first step for developing and implementing an effective online learning system (as cited in Cigdem, & Yildirim, 2014).

According to Conley (2007), readiness for university education can be defined as the level of preparation a student needs in order to enroll and succeed, without remediation in a credit-bearing program at higher education institution. E-learning readiness is defined as the degree to which learners are ready to take courses in online learning environment (Alem, Plaisent, Zuccaro & Bernard, 2016). Research has shown that students who succeed in an online learning environment seem to have some academic preparation characteristics such as self-directed learning, self-competence, motivation, self-discipline and learning style (Morris, Wu & Finnegan, 2005). Researchers also point out that students who are successful in the online environment are those who are well prepared and ready to follow their study online, skilled in the use of technology and browsing the Internet, and able to learn autonomously (Alem et al. 2016). Teachers can create a more suitable autonomous learning environment only if students' readiness and learner autonomy is known (Kartal & Balcikanlh, 2019).

STEM has made it possible for online platforms to be created. The internet is the main driving force for remote learning, without STEM, there would be no internet and no possibilities for online learning. Again, without a basic understanding of STEM, a readiness for remote learning is impossible.

PROBLEM

Online learning can be challenging for students because of the self-regulated nature of learning online and the distance between instructors and students. Online courses provide learners with a variety of benefits such as convenience, flexibility, and opportunities to work collaboratively and closely with teachers and other students from different schools or even across the world (Hung *et al.* 2010). But are college students ready for online learning? The transition from traditional face-to-face environment to a fully virtual one can be challenging, and students need to be aware of what the differences and expectations are for their new learning platforms (Potts & Potts, 2017). Harrell stated that previous research has identified five broad categories of factors that affect student success in online learning. These are student readiness, orientation, instructor effect through preparation and support and course content (as cited in Basol, Cigdem, & Unver, 2018). Student online learning readiness has been identified as being closely associated with the success of learning in online environments (Liu, 2019). According to Liu and Roberts-Kaye (2016), online learning readiness is defined as "cognitive awareness and maturity that a student develops for successful learning in a Web-based environment. It manifests in the attributes of recognizing the self-directed nature, formulating learning strategies, obtaining technology competencies, adjusting to digital etiquettes, and being open for help-seeking" p. 242 (as cited in Liu, 2019). Several studies such as Mosa, Mahrin, & Ibrrahim (2016) and Yilmaz (2017) have found that students' online learning readiness affects their academic achievement (as cited in Liu, 2019).

Bearing in mind that pre-service teachers' readiness for online learning might influence their cognitions and actions regarding the emergency remote online learning, it is essential to understand their online learning readiness. Researchers believe that supporting student success in learning has been the core value of education, regardless of formats (Liu, 2019).

Knowledge of student's readiness is very important since it will give teachers knowledge of learners and help them to guide students toward successful and fruitful online learning experiences. Teachers may need to help students develop self-directed learning and learner-control skills and attitudes, especially for online learning contexts (Hung et al., 2010). Again, teachers may need to improve the clarity of their syllabus and course structure before students can direct themselves toward taking full control of their own learning. Thus, teachers can help students to establish their own time- and information-management skills. Therefore, in this research, learners' online learning readiness was investigated within the dimensions proposed by Hung et al (2010). These are computer/Internet self-efficacy, learner control, motivation for learning, online communication self-efficacy and self-directed learning.

Research Questions

1. What is pre-service teachers' online learning readiness?
2. Is there any significant difference in online learning readiness between males and females?
3. Is there any significant difference in online learning readiness by course level?

LITERATURE REVIEW

Learner readiness is often used to define the ability of a learner to acquire knowledge and initiate in behavior change which lead to effective and successful learning outcomes. It suggests that for learners to benefit from educational interventions at school, they must be constantly and always ready and at their fullest potential to learn (Chorrojprasert, 2020).

Readiness for online learning means the preparedness of students to perform learning activities in an online environment. It indicates multiple dimensions, including but not limited to comfort in learning with computers, self-regulated learning strategies, and perception of learning community (Liu, 2019). Students' readiness for e-learning is viewed as connected with their capabilities to use technology for academic purposes.

Warner, Christie, and Choy (1998) defined readiness for online learning as a combination of students' preferences for online delivery, their competence and confidence in using electronic communication, and their ability to engage in autonomous learning. Lynch (2001) and Smith, Murphy, and Mahoney (2003) equate readiness for online learning with "comfort with e-learning" and "self-management of learning."

It has been reported that dominant constructs relating to learner readiness include: a desire to learn; a positive attitude toward the learning situation; a willingness to make the investment of time and effort that is necessary for learning, the ability to persevere, and an understanding of the importance and value of learning (Chorrojprasert, 2020).

Deyo, Huynh, Rochester, Sturpe and Kiser (2011) stated that learning readiness is essential for better educational performance of the students in learning process (as cited in Dangol & Shrestha, 2019). Every effort to provide quality education in school becomes meaningless due to the absence of student readiness in learning. If the student is prepared to learn, he/she can learn rapidly and if the student is not geared up to learn, he/she cannot learn successfully (Prakash, 2012). Absence of learning readiness leads to decrease the educational achievement of students. It also decreases the efficiency and effectiveness of classroom teaching and also wastes huge government investment in the school education (Dangol & Shrestha, 2019). According to Gandhi, learning readiness is the prerequisite for getting success to achieve the goals and objectives of education within students (as cited in Dangol & Shrestha, 2019). Online learning readiness is related to student motivation and academic achievement. Cigdem and Ozturk (2016) stated that self-direction in online learning could strongly predict student achievement (as cited in Liu, 2019). Also Horzum, Kaymak, and Gungoren (2015) concluded that student online learning readiness could predict motivation and perception of academic achievement.

According to Chorrojprasert (2020), there are four characteristics that a learner should possess in order to learn effectively, particularly in classroom setting. These are a disposition for learning, adequate cognitive functioning, adequate knowledge base for the content being presented and adequate study skills and strategies.

A number of concepts have been used for learner readiness among which are learner autonomy, self-efficacy, self-regulation or self-directed learning, responsible learning, learner's attitudes and beliefs, learner's intellectual character and learning strategies (Chorrojprasert, 2020). Learner readiness is the process in which learners are able to actively and effectively control and monitor their motivation, cognition and behaviors and successfully complete the target academic tasks (Blidi, 2017).

Students who own their learning can go beyond simply following teacher directions. They are more likely to complete complex assignments, solve problems that require persistence, and create original or novel work of high quality (Conley & French, 2013).

Hung, Chou, Chen, and Own (2010) presented a concept that claims that besides the computer/internet and online communication self-efficacies; students' readiness for e-learning is depicted in their potential for self-directed learning, learner control, and motivation for learning.

Motivation for learning encompasses learners' all kinds of movements towards and engagements with learning activities. According to Wolters (2010), the primary factor that facilitates students' persistence in their academic tasks is their motivational beliefs. Motivated learners are attributed to have low latency and high perseverance about task engagement (Artino & Stephens, 2009), and therefore, their motivational orientation towards a task has significant influences on their performances (Hung et al. 2010).

Motivation and engagement are closely related. Motivation is an internal state, while engagement is the manifestation of motivation behaviorally. Research proved that student engagement leads to higher achievement in the classroom (Conley & French, 2013). Motivation and engagement factors involve students' ability to see the value in coursework, motivate to excel, see the value of learning, and enjoy a challenge. These skills are particularly important in a college setting where students are required to manage their own time and take responsibility for their own learning. Engagement is thought of as comprising three components: behavioral engagement (compliance with norms and expectations), emotional engagement (interest, enjoyment), and cognitive engagement (investment in learning, challenge-seeking) (Conley & French, 2013). Motivation must manifest itself in the potential for self-guided action, and students must be both emotionally and cognitively engaged to succeed (Conley, 2007).

THEORETICAL FRAMEWORK

The study is based on Bandura's self-efficacy theory (Bandura, 1977). Bandura (1997) defines self-efficacy as "beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments" (p. 3). Self-efficacy is a key contributing factor to learners' success because self-efficacy "influences the choices learners make and the courses of action they pursue" (Pajares, 2002, p. 116). Self-efficacy is not only a good predictor of learners' academic outcomes, but efficacious learners also tend to adapt, persist, and cope well, even when they have little prior online experience (Swan, 2004).

Readiness for online learning means the preparedness of students to perform learning activities in an online environment. It indicates multiple dimensions, including but not limited to comfort in learning with computers, self-regulated learning strategies, and perception of learning community (Liu, 2019). Borotis and Poulymenakou (2004) defined online readiness as "being mentally and physically ready for certain online learning experience and actions". Warner, Christie and Choy (1998) describe online learning readiness of students in three major aspects: preferences for online learning as opposed to face-to-face learning instructions, capability and confidence in using the technological tools and ability to learn independently. Hung et al. (2010) included sub-dimensions of "self-directed learning, learner control, motivation, computer/internet self-efficacy towards learning and online communications self-efficacy" to measure online learning readiness. According to Engin (2017), a consideration of the sub-dimensions of online readiness revealed aspects such as self-confidence, self-knowledge, self-control, to communicate and self-expression.

Knowles (1975), defined self-directed learning as a process in which individuals take the initiative in understanding their learning needs, establishing learning goals, identifying human and material resources for learning, choosing and implementing appropriate learning strategies, and evaluating learning outcomes. Students' motivational orientation (intrinsic or extrinsic) has significant effects on their learning performance (Hung et al., 2010). According to Ryan and Deci (2000), intrinsic motivation is a critical element in cognitive, social, and physical development because it is through acting on one's inherent interests that one grows in knowledge and skills. Internet self-efficacy is defined as the trust Internet users have in them while using Internet. Internet self-efficacy could be different from computer self-efficacy in setting up, maintaining, and using the Internet behavior series (Hung et al., 2010). Tsai and Tsai (2003) showed that students with high Internet self-efficacy learned better than those with low Internet self-efficacy in a Web-based learning task. Online learning may also involve computer-mediated communication.

The concept of learner control was previously employed in the classroom to enhance the learning process by allowing learners to choose the way they learnt, or how they expressed what they had learnt. This concept was later implemented with technology-assisted instruction (Taipjutorus, Hansen, & Brown, 2012). According to Milheim and Martin (1991), the nature of online learning makes it possible to provide learners with the opportunity to make their own choices and put them in charge of their learning pace, sequence, and content.

METHODOLOGY

Design

A cross-sectional survey design was adopted for the study using a quantitative approach. A cross-sectional survey collects data to make inferences about a population of interest at one point in time. Cross-sectional surveys have been described as snapshots of the populations about which they gather data (Hall, 2008). Quantitative research methods primarily rely on the collection and analyses of numerical data in the study of social phenomena (Leung & Shek, 2018). Sharing the characteristics of positivism, quantitative research design has several unique features. These include: the quality assurance that bias and subjectivity are minimized in data collection and analyses, Value neutrality in the research, the research is guided by evidence obtained from systematic research rather than by authorities, and accuracy and precision of measurements determined by ensuring reliability and validity of research (Leung & Shek, 2018).

Participants and sampling

The study participants consisted of 115 (66 males and 49 females) pre-service teachers of which 106 are in level 100 and 9 are in level 200. All the participants were on remote learning as a result of lockdown due to COVID-19.

Convenience sampling was used to identify participants. All participants participated in synchronous and asynchronous online learning on Google classroom platform.

Data collection

The data were collected through an online questionnaire. The online learning readiness scale (OLRS) questionnaire was used to collect the data. The questionnaire was in two sections; the first section required participants to indicate their age, sex, and course level and the second section required them to indicate their level of agreement or disagreements to the 18 items of the OLRS. The 18 items measure online learning readiness on a five-point Likert type scale (1= strongly disagree, 2= Disagree, 3= Undecided, 4= Agree, 5= strongly agree).

Instrument

The Online Learning Readiness Scale (OLRS) is a multidimensional instrument developed by Hung, Chou, Chen, and Own (2010) to measure college students' readiness for online learning in Taiwan. The Online Learning Readiness Scale (OLRS) was validated in five dimensions: self-directed learning (SDL), motivation for learning (ML), computer/Internet self-efficacy (CIS), learner control (LC), and online communication self-efficacy (OCS) [Hung et al., 2010].

Self-directed learning dimension is about learners taking responsibility for their learning to reach their learning objectives. Learner control is how online learners take control over their learning such as repeating or skipping some content and on efforts by online learners to direct their own learning with maximum freedom. Motivation for learning centers on online learners' learning attitudes. Computer/Internet self-efficacy is about online learners' ability to demonstrate proper computer and Internet skills. Online communication self-efficacy describes learners' adaptability to the online setting through questioning, responding, commenting, and discussing (Hung et al, 2010). Hung et al (2010) subjected the scale through confirmatory factor analysis to determine the validity of the OLRS. Each item of the OLRS had a substantial loading between 0.55 and 0.85 on the five factors, and each loading was statistically significant. Thus, the scale constitutes a valid instrument for measuring learner readiness in online learning settings (Hung et al., 2010). In this present study, the reliability of the OLRS was determined to be .900. The reliabilities of the various dimensions were also determined as follows; CIS = .749, SDL = .778, LC = .618, ML = .772 and OCS = .743.

ONLINE LEARNING READINESS (OLR) SURVEYS

From the literature, existing surveys on students' online readiness focused on learner characteristics such as self-directed learning, interpersonal communication skills, and academic locus of control, and basic technology skills such as email, word processing, and basic software (Dray, Lowenthal, Miszkiewicz, Ruiz-Primo, & Marczynski 2011). According to Dray et al., readiness as expressed by these instruments encompasses; self-concept/self-efficacy with academics, information, technology, and locus of control and equipment owned (e.g., computers). Most instruments that measure online learning readiness focus on technology preparation and independent study strategies for students (Liu, 2019).

According to Guglielmino and Guglielmino (2003), online learning readiness can be determined by evaluating a user's competency in using technological tools. McVay (2001) developed a 13-item instrument for measuring readiness for online learning which focused on student behavior and attitudes. Smith et al. (2003) conducted an exploratory study to test McVay's Readiness for Online Learning questionnaire. The instrument yielded a two-factor structure, "Comfort with e-learning" and "Self-management of learning."

Hung et al. (2010) added new dimensions to the readiness concept which include computer/Internet self-efficacy, learner control, motivation for learning, online communication self-efficacy and self-directed learning. Computer/Internet self-efficacy is related to technical skills involving computers and the Internet (Keramati, Afshari-Mofrad, Kamrani, 2011; Peng, Tsai, & Wu, 2006). Learner control is related to flexibility and freedom in web-based study materials. Learner control is the degree to which a learner can direct his or her own learning experience and process (Shyu & Brown, 1992). Online communication self-efficacy is related to computer-mediated communication. Self-directed learning is related to students' ability to direct his or her own learning through the appropriate knowledge, skills, attitudes and habits. According to Tang & Lim (2013), online learning readiness can be described in three major features: choices for online learning as opposed to face-to-face learning instructions, competence and confidence in using the technological tools and ability to learn separately.

Warner, Christie, and Choy (1998) defined readiness for online learning in terms of three aspects: (1) students' preferences for the form of delivery as opposed to face-to-face classroom instruction; (2) student confidence in using electronic communication for learning and, in particular, competence and confidence in the use of Internet and computer-mediated communication; and (3) ability to engage in autonomous learning.

Based on previous conceptualization, Dray et al. (2011) developed a survey that consisted of two subscales: learner characteristics and technology capabilities. The learner characteristics subscale asks about individual beliefs in their ability to complete a college degree, beliefs about responsibility in problem solving (academic and technical), self-efficacy in writing and expression, orientation to time and time management, and behavior regulation for goal attainment. The second subscale measures technology capabilities which include; basic technology skills such as the ability to use email and the internet, material access to technology such as devices and bandwidth, and the nature and frequency of technology use.

ONLINE LEARNING

According to Moore, Dickson-Deane, and Galyen (2011), the concept of online learning is difficult to define; however, there are numerous concepts that are considered synonymous with to the concept such as online course, web-based learning, distance learning, and web-based training (Edwards, 2018). One common definition of online learning is an educational training program via internet and computer-based media technologies (Sangrà, Vlachopoulos, Cabrera, & Bravo, 2011). Another definition of online learning states it as distance education, involving students making use of web-based communication systems for interaction (via telecommunication and social media-based technologies). Through these technologies, individuals exchange information and communicate with their educators and fellow classmates (Sangrà, Vlachopoulos, Cabrera, & Bravo, 2011). Various terms are used for online learning such as e-learning, distance learning, distance education, computer-assisted instruction, computer-based instruction, technology based-instruction, technology-delivered instruction, computer-based simulation and simulation games (Bell & Federman, 2013).

Online learning or more commonly noted as e-learning or distance learning, is defined as learning facilitated virtually through an online interface system via computer, database, social media, network, and web technologies (Garrison, 2011). Another definition of online learning states it as distance education, involving students making use of web-based communication systems for interaction (via telecommunication and social media-based technologies). Through these technologies, individuals exchange information and communicate with their educators and fellow classmates (Sangrà, Vlachopoulos, Cabrera, & Bravo, 2011). Another description of online learning refers to it as a system of learning and teaching, involving the use of internet technologies and multimedia in order to facilitate quality learning and enable access to various educational services and resources (Sangrà, Vlachopoulos, Cabrera, & Bravo, 2011).

RESULTS

Demographic characteristics of participants

Table 1. Sex and Age distribution of participants

Sex	n	%
Male	66	57
Female	49	43
Total	**115**	**100**
Age		
18--20	16	13.9
21--24	58	50.4
25--28	37	32.2
29--31	4	3.5
Total	**115**	**100**

Table 1 shows the sex and age of participants of the study. The sex of participants comprised 66 males representing 57% and 49 females representing 43%. The ages of participants ranged from 18 to 31. Sixteen of them (13.9%) aged between 18 to 20 years, fifty eight of them (50.4%) aged between 21 to 24 years, thirty seven of them (32.2%) aged between 25 to 28 years and four of them (3.5%) aged between 29 to 31 years.

PRE-SERVICE TEACHERS' ONLINE LEARNING READINESS

Table 2. Means and standard deviations of scores OLRS and its dimensions

Dimensions	Mean	SD
Online Learning Readiness score (OLRS)	3.65	0.79
Computer/Internet Self-efficacy (CIS)	3.43	1.16
Self-Directed Learning (SDL)	3.82	0.93
Learner Control (LC)	3.30	1.00
Motivation for Learning (ML)	3.97	0.90
Online communication self-efficacy (OCS)	3.49	1.11

N = 115

Table 2 shows the means and standard deviations of online learning readiness scores of the overall scale and the five dimensions. The overall mean score of the OLRS was 3.65 suggesting that on the average pre-service teachers are ready for online learning. The mean scores for the dimensions are as follows; computer/internet self-efficacy (M = 3.43, SD = 1.16), self-directed learning (M = 3.82, SD = .93), learner control (M = 3.30, SD = 1.00), motivation for learning (M = 3.97, SD = .90). The dimension with the highest mean score is motivation for learning (M = 3.97, SD = .90) followed by self-directed learning (M = 3.82, SD = .93). This suggests that pre-service teachers are motivated for online learning. Also, pre-service teachers are self-directed for online learning. However, the dimensions of learner control (M = 3.30, SD = 1.00), computer/internet self-efficacy (M = 3.43, SD = 1.16) and online communication self-efficacy (M = 3.47, SD = 1.11) recorded low means. This suggests that pre-service teachers are not in control of their learning and their computer/internet and online communication self-efficacies are low.

Table 3. Descriptive statistics of items of the OLRS

Item	Statement	Mean	SD	Rank
1	I feel confident in performing the basic functions of Microsoft Office programs (MS Word, MS Excel, and MS PowerPoint)	3.34	1.40	17
2	I feel confident in my knowledge and skills of how to manage software for online learning.	3.38	1.39	14
3	I feel confident in using the Internet (Google, Yahoo) to find or gather information for online learning	3.58	1.48	11
4	I carry out my own study plan.	3.73	1.28	9
5	I seek assistance when facing learning problems.	3.94	1.31	4
6	I manage time well.	3.41	1.34	13
7	I set up my learning goals	3.91	1.26	6
8	I have higher expectations for my learning performance.	4.10	1.22	2
9	I can direct my own learning progress.	3.73	1.29	8
10	I am not distracted by other online activities when learning online (instant messages, Internet surfing).	2.80	1.48	18
11	I repeated the online instructional materials on the basis of my needs.	3.36	1.22	15
12	I am open to new ideas.	3.90	1.30	7
13	I have motivation to learn.	3.92	1.21	5
14	I improve from my mistakes.	4.11	1.07	1
15	I like to share my ideas with others.	3.97	1.10	3
16	I feel confident in using online tools (email, discussion) to effectively communicate with others.	3.34	1.43	16
17	I feel confident in expressing myself (emotions and humor) through text.	3.63	1.29	10
18	I feel confident in posting questions in online discussions	3.50	1.35	12

N = 115

Table 3 shows the descriptive statistics of items of the OLRS and **Figure 1** gives a graphical presentation of the mean scores of items of the OLRS. The items with the highest means are item14 (I improve from my mistakes), item 8 (I have higher expectations for my learning performance), item 15 (I like to share my ideas with others), item 5 (I seek assistance when facing learning problems) and item 13 (I have motivation to learn). The items with the lowest means are: item 10 [I am not distracted by other online activities when learning online (instant messages, Internet surfing)], item 1 (I feel confident in performing the basic functions of Microsoft), item 16 (I feel confident in using online tools (email, discussion) to effectively communicate with others), item 11 (I repeated the online instructional materials on the basis of my needs) and item 2 (I feel confident in my knowledge and skills of how to manage software for online learning).

Figure 1. Mean scores of items of the OLRS

DIFFERENCES IN READINESS BY GENDER

Table 4. Independent samples t-test of online learning readiness scores by gender

Dimensions	Sex	N	M	SD	*t*	*p*
Online Learning Readiness score (OLRS)	Male	66	3.71	0.82	0.94	0.349*
	Female	49	3.57	0.76		
Computer/Internet Self-efficacy (CIS)	Male	66	3.57	1.14	1.41	0.162*
	Female	49	3.26	1.18		
Self-Directed Learning (SDL)	Male	66	3.88	0.96	0.75	0.453*
	Female	49	3.74	0.90		
Learner Control (LC)	Male	66	3.47	0.94	2.19	0.03**
	Female	49	3.06	1.05		
Motivation for Learning (ML)	Male	66	3.97	0.92	-0.11	0.913*
	Female	49	3.98	0.89		
Online communication self-efficacy (OCS)	Male	66	3.46	1.17	-0.32	0.753*
	Female	49	3.53	1.02		

*** Significant ($p < .05$)   *Not significant ($p > .05$)*

Independent samples t-test was performed to determine if any significant differences exist between readiness of males and females. Table 4 shows the results of the independent samples t-test. There was no significant difference in online learning readiness between males (M =3.71, SD =.82) and females (M = 3.57, SD = .76), t (.94) $p = .349$. There was no significant difference between males and females in all dimensions except for learner control. The results revealed a significant difference in learner control (LC) between males (M = 3.47, SD = .94) and females (M = 3.06, SD = 1.05), t (2.19) $p = .03$.

DIFFERENCES IN READINESS BY COURSE LEVEL

Table 5. Independent samples t-test of online learning readiness scores by course level

Dimensions	Course level	N	M	SD	*t*	*p*
Online Learning Readiness score (OLRS)	Level 100	106	3.65	0.79	-0.122	0.903*
	Level 200	9	3.68	0.85		
Computer/Internet Self-efficacy (CIS)	Level 100	106	3.43	1.15	-0.224	0.823*
	Level 200	9	3.52	1.31		
Self-Directed Learning (SDL)	Level 100	106	3.83	0.94	0.509	0.612*
	Level 200	9	3.67	0.93		
Learner Control (LC)	Level 100	106	3.28	1.00	-0.577	0.565*
	Level 200	9	3.48	1.09		
Motivation for Learning (ML)	Level 100	106	3.96	0.92	-0.473	0.637*
	Level 200	9	4.11	0.77		
Online communication self-efficacy (OCS)	Level 100	106	3.49	1.08	0.032	0.975*
	Level 200	9	3.48	1.43		

**Not significant ($p > .05$)*

Independent samples t-test was performed to determine if any significant difference exits in readiness by course level. **Table 5** shows the results of the independent samples t-test. It was found that there was no significant difference in readiness between level 100 students (M = 3.65, SD = .79) and level 200 students (M = 3.68, SD = .85) t (-.122) p = .903. For all the dimensions of the scale, there was no significant difference in readiness between level 100 and level 200 students.

DISCUSSION

Pre-service teachers' readiness for online learning

The first research question sought to determine pre-service teachers' online learning readiness. The study found that pre-service teachers' overall readiness for online learning was higher than average (M = 3.65, SD = .79). The readiness scores for the five dimensions ranged from 3.30 to 3.97. The dimension with the highest mean scores was motivation for learning (ML) [M = 3.97, SD = .90] followed by self-directed learning (SDL) [M = 3.82, SD = .93]. However, the dimensions of learner control (M = 3.30, SD = 1.00), computer/internet self-efficacy (M = 3.43, SD = 1.16) and online communication self-efficacy (M = 3.49, SD = 1.11) recorded low means.

The findings agrees with others for example, Cigdem and Yildirim (2014) used Hung et al.'s Online Learning Readiness Scale (OLRS) in their study reported that readiness mean scores were between 3.564 and 4.455 over the mid-point indicating that the participants were in generally ready for online learning. They found that participants had the highest readiness in the dimension of ML, followed by SDL and LC, and the lowest readiness in the dimensions of OCS and CIS. Cigdem and Ozturk (2016) reported that students' motivation for learning (M = 4.15) is higher than both their computer self-efficacy (M = 3.55) and their self-directed learning inclinations (M = 3.82). Hung et al (2010) found that students' levels of readiness were high in computer/Internet self-efficacy, motivation for learning, and online communication self-efficacy and were low in learner control and self-directed learning. Kayaoğlu and Akbaş (2016), reported that, except for the computer and internet self-efficacy issue, the other factors referring to the online learning motivation, online communication self-efficacy, self-directed learning and learner control in an online context appear to be higher than 3.50. The overall results reveal that the participants seem to be ready for an online learning adoption. They added that students need to improve their computer and internet self-efficacy. Kırmızı (2015), in a study to investigate the relation between learning readiness and student satisfaction at higher education, found that participants have a high level of learner readiness and satisfaction. The dimensions of readiness were computer self-efficacy, self-directed learning, learner control, motivation, and online self-efficacy.

Rasouli, Rahbania and Attaran (2016) in their study to investigate students' readiness for e-learning application in higher education, found that the readiness mean score of students studied in 5 factors was 3.54 out of 5. This indicated that the average readiness of art students to participate in e-learning was high. Yağcı, Sırakaya and Özüdoğru (2015) also reported that readiness of pre-service teachers toward web-based teaching was found in the range between median and high levels. However, Stokes, Cannavina, and Cannavina (2004) in a study of readiness levels of medical school students for web-based learning environments found no sufficient readiness level.

Online learning readiness of males and females

The study found no significant difference in online learning readiness between males and females. Hung et al (2010) also found that gender made no statistical differences in the five OLRS dimensions, but that higher grade (junior and senior) students exhibited significantly greater readiness in the dimensions of self-directed learning, online communication self-efficacy, motivation for learning, and learner control than did lower grade (freshman and sophomore) students. Yağcı, Sırakaya and Özüdoğru (2015) also found no significant difference in the readiness levels of female and male pre-service teachers toward web-based teaching.

Online learning readiness by course level

The study found no significant difference in readiness between level 100 and level 200 students. Yağcı, Sırakaya and Özüdoğru (2015) also found no significant difference in readiness at the grade level. However, Hung and et al (2010) reported that there was significant difference in online learning readiness levels of students according to their grade level. Hung et al. added that students' maturity may play an important role in their monitoring, managing, control, and motivation relative to online learning.

CONCLUSION

The findings of the study revealed that pre-service teachers' readiness for online learning is high. However, they recorded low readiness in dimensions of learner control, computer/internet self-efficacy, and online communication self-efficacy. Students need to be encouraged to take control of their learning. Studies have shown that the sense of control learners' gain while interacting with instructional media and content can result in increased satisfaction, enjoyment, and confidence. The nature of online learning makes it possible to provide learners with the opportunity to take charge of their learning pace, sequence, and content.

Also, students need to improve on their computer and internet self-efficacies. Teachers need to encourage students, especially those with lower self-efficacy in online communication, to participate in the discussions, ask questions, post ideas and their thoughts, and to seek assistance when facing problems online. Teachers could also stimulate peer assistance among students. Hung et al (2010) suggested that teachers can provide students with an appropriate induction into the world of online learning by having students get to know their teacher or peers through online tools and by responding promptly and positively to students' inquiries through online tools. Computer self-efficacy is mainly related to learners' confidence in their ability to use computers and other type of technology. Studies have found that computer self-efficacy has a positive relationship with students' cognitive and emotional engagement factors and suggested that computer self-efficacy is a very important and critical factor to student satisfaction with e-learning. Teachers can persuade and encourage students to increase their computer and internet self-efficacies.

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European Journal of STEM Education,
2021, 6(1), 02
ISSN: 2468-4368

Theory-driven Determinants of School Students' STEM Career Goals: A Preliminary Investigation

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Citation: Hatisaru, V. (2021). Theory-driven Determinants of School Students' STEM Career Goals: A Preliminary Investigation. *European Journal of STEM Education*, 6(1), 02. https://doi.org/10.20897/ejsteme/9558

Published: January 15, 2021

ABSTRACT

This study investigated Turkish school students' attitudes towards STEM disciplines and careers and explored determinants of students' STEM career goals. In total, 117 lower secondary school students (aged 11 to 14) completed the *STEM Semantic Survey* including an open-ended question about their career intention after high school and the reasons for their goals. Using the conceptualisation of the influences of behavioural, personal, and contextual variables in career choice decisions, the students' descriptions of career goal reasons were presented to elaborate on the variables that influence their STEM career goals. Attitudes towards individual STEM disciplines were from moderate to high and towards STEM careers were high. The gender difference was negligible. One of the key determinants of students' career intentions was interests, involving interest in a particular career (e.g., architect) and career-relevant activities (e.g., planning, drawing, and designing) or subjects (e.g., mathematics). Larger, societal influences (altruism and patriotism) were among the motives of students' career goals. Implications for research, practice, and policy-making were presented.

Keywords: draw a mathematics classroom, social cognitive career theory, STEM career goals, school students

INTRODUCTION

STEM (science, technology, engineering, and mathematics) capability is one of the key competences necessary for functioning effectively in the modern world and contributing to technological and economical high productivity (Jolly, Campbell, & Perlman, 2004; Office of the Chief Scientist, 2012). STEM capability can also be a mean of self-fulfilment and personal enrichment. Enhancing school students' STEM competences, thus, meets not only societal, but also individual needs (Sjaastad, 2012). Many countries consider the issue of competence in STEM as important and incorporate strategies for its development during schooling, at the highest policy level. Despite these influences, there remains a lack of interest in students towards STEM subjects. Both policy documents and research studies indicate international declines in degrees awarded from STEM programs (Prieto & Dugar, 2017). Reports conclude that admission in and graduation from STEM-related areas have fallen in Australia (Australian Academy of Science, 2016; Barrington & Evans, 2014), the USA (Christensen, Knezek, & Tyler-Wood, 2014), Europe (Kearney, 2016), and in Turkey (Kivanc, Sener, Mumcuogullari, & Sunacoglu, 2017). Exploring what motivates school students to learn STEM subjects, continues to be a concern for researchers, educators, and policymakers. There is a need to better understand why students would choose to study STEM-related areas, and what opportunities and resources in schools encourage them to enrol and remain in STEM fields.

PURPOSE AND RESEARCH QUESTIONS

The aims of this paper are: (1) to investigate school students' attitudes towards STEM disciplines and careers; (2) to describe behavioural (self-efficacy, outcome expectations, interests, and goals), personal (gender), and environmental (larger, societal context) influences on students' career intents; and (3) to assess the suitability of a theoretical framework for studying the factors that influence school students' STEM career goals. The overall objective is to increase understanding of theory-driven determinants of school students' career intentions concerning STEM. The *STEM Semantic Survey* (Christensen et al., 2014) provided data from a sample of Turkish lower secondary school students (aged 11 to 14), in the *Draw a Mathematics Classroom* study which is reported elsewhere (Hatisaru, 2020a; in press). Students' responses to the Survey items are analysed in light of the above aims. As a theoretical base, the conceptualisation of their career choice is based on the behavioural, personal, and environmental determinants, as suggested by Lent, Brown, and Hackett (1994, 2000). This framework is utilised to discuss what factors influence students' intentions in relation to pursuing a STEM career. The research questions that guide the study are:

1. What are students' attitudes towards individual STEM disciplines and STEM careers? How do their attitudes vary by gender?
2. What are students' intended career choice (STEM or non-STEM)? How do their choice vary by gender?
3. What are the determinants of their career goals?

BACKGROUND

Dispositions towards STEM have been explored in different ways during the last decades. Much has been written about what factors contributing to students' orientations to STEM subjects and careers. There has been consistent evidence that students' perceptions of psychosocial aspects of the classroom environment (e.g., teacher support, student cohesiveness, and competitiveness) are associated with students' STEM learning outcomes (Fraser, 2014) such as attitudes, interest, or motivation for learning (e.g., Afari, Aldridge, Fraser, & Khine, 2013). The perceived teaching and learning practices in STEM classrooms have been received attention as well. Lyons (2006) examined experiences of school science reported by high school students in Sweden, Australia, and England in three interpretive studies. Three characteristics of school science emerged from students' narrative reflections: the transmissive pedagogy; decontextualized content; and unnecessary difficulty of school science. These perceived classroom experiences were found to have negative influences on students' interest and enrolments in both in high school and tertiary level science courses.

Various other disparate explanations have been offered. Informal learning experiences and afterschool programmes in STEM (e.g., robotics summer camps and media design projects) were found positively influence high school students' attitudes towards science and technology and interest in an engineering career (Ayar, 2015; Karahan, Bilici, & Unal, 2015; Prieto & Dugar, 2017). Primary and lower secondary students evaluated science fairs positively and expressed a wish that science affairs became more regular (Gülgün et al., 2020). For high school graduates, choosing a STEM major was influenced by intentions to major in STEM and high school mathematics achievement. Intent to major in STEM was impacted by grade 12 mathematics achievement, having mathematics and science courses, and mathematics self-efficacy. All these three variables were influenced by early achievement in and attitudes towards mathematics (Wang, 2013). Thus, all self-efficacy, outcomes expectations, and significant persons have been of importance. Among a group of American and Turkish high-ability high school students, self-motivation (inclination) was the most influential factor in American students' interest to STEM careers, while it was mother's education level for Turkish students. The American students' interests to STEM careers were owing to their self-motivation to undertake STEM careers and school-related factors (e.g., STEM clubs, fairs). The Turkish students' interests were predominantly influenced by potential professional income and social expectations (influence of others involving parents, teachers, peers, and relatives) (Bahar & Adiguzel, 2016). Teachers and parents were the main source of inspiration for Norwegian university students' STEM-related educational choice. Parents who engaged in STEM themselves were models for their children making the STEM-related choices familiar to them. Teachers were also model for students who displayed how STEM might bring fulfilment in individuals' lives and who gave students positive STEM learning experiences (Sjaastad, 2012). Parents or family members were similarly influential on middle school students' future career plans from a diverse and disadvantaged rural community (Kier & Blanchard, 2021).

STEM dispositions have often been investigated with respect to gender (Tripney et al., 2010). There have been some inconsistencies in gender-related findings. While some studies have revealed that females were less positive than males in pursuing careers in STEM (Sadler, Sonnert, Hazari, & Tai, 2012), other studies showed that females' semantic perceptions of pursuing STEM careers were significantly more positive than males (Christensen et al., 2014). K-12 educators and pre-college STEM outreach programs played a role in influencing and motivating undergraduate female students – as well as male students – to enrol and persist in college level STEM degree programmes (Edzie, 2014). There have been calls that school students need to be motivated towards STEM subjects as those students were more likely to pursue STEM-related careers (Eurydice, 2011; Maltese & Tai, 2010; Prieto & Dugar, 2017). Teachers of STEM have been encouraged to move away from teacher-directed pedagogies and "make learning active" (Maltese & Tai, 2010, p. 900) to improve student motivation to and interest in STEM subjects (Hasni & Potvin, 2015). Effective pedagogies have included: engaging students in the learning processes and promoting authentic scientific inquiry (Sirinterlikci, Zane, & Sirinterlikci, 2009); embedding learning in concrete and meaningful problems or tasks and ensuring students collaborate with others to solve problems (Hatisaru & Kucukturan, 2011; Hmelo-Silver, 2004); enabling students to link the knowledge they learn at school with their lives outside the school (Potvin & Hasni, 2014); and teaching STEM in an integrated way (Knipprath et al., 2018). Students in different educational and national contexts, nevertheless, have responded to what their context provides to them in different ways (Lent et al., 2000; Thomas & Watters, 2015).

In Turkey, lower secondary education lasts for four years (grades 5 to 8, aged 10 to 15) and is provided by secondary schools. Mathematics and science are taught as a mandatory and major subject at all levels of schooling and is tested by national examinations at the end of lower and upper secondary education. Mathematical and science questions make up a good deal of the questions for both high school and university entrance exams (European Schoolnet, 2018). Teaching practices have been largely influenced by these nation-wide standardised exams. It is common for teachers to rely on lecture-style teaching and emphasising the procedural knowledge and correct use of procedures for preparing students for examinations. (Ayar, 2015; Kearney, 2016). Despite the broad agreement that teacher-directed teaching practices negatively impact students' attitudes (e.g., Hasni & Potvin, 2015), Turkish school students' attitudes towards science and mathematics yet are generally positive (Hatisaru, 2020b; Mullis, Martin, Foy & Hooper, 2016; Sjøberg & Schreiner, 2010). Students are interested in studying STEM subjects at university (Kearney, 2016). STEM-related careers, especially engineering, are appealing to many students (Ayar, 2015). Nevertheless, the number of graduates and new admissions in technical and quantitative fields have been disproportionately low. In 2012, for example, 80 037 high school graduates entered various types of engineering degree programs (e.g., mechanical, chemical, civil, petroleum, and computer) of which less than a half graduated (36 786) (Ayar, 2015). Across the country, between 2013 and 2016, the percentage of STEM graduates was only about 17%. The employment market projections for STEM occupations has been expected to be about one million between 2016 and 2023, resulting in a shortfall of around 31% of this requirement (300 000) (Kivanc et al., 2017).

While previous research has suggested that positive orientations towards STEM are fundamental to students' entrance and persistence in, and completion of STEM-related fields (success), this study suggests that success is based on various interrelated factors. The current paper offers additional empirical evidence exploring school students' STEM career intents by applying a theory which considers various aspect of career choice behaviours. The paper contributes to understanding why students' positive orientations to science, mathematics, and related quantitative disciplines have not necessarily been translating into success. Theoretical underpinning follows this section.

THEORETICAL PERSPECTIVE

One contemporary theoretical approach to individuals' career interest is Lent et al.'s (1994) Social Cognitive Career Theory (SCCT). SCCT represents a long-lasting effort to understand the mechanisms through which individuals develop interests, make choices, succeed in educational and career pursuits (Lent et al., 1994). SCCT has its root predominantly in Bandura's (1986) general social cognitive theory, which suggests the ways in which individuals, their behaviour, and environments affect one another. SCCT is a testable theory that attempts to explain the behavioural (social cognitive) and other personal and environmental variables behind career interest, choice, and performance. Several studies have utilised SSCT to explore how individuals develop occupational pursuits, make and/or remake vocational choices, and achieve career success (Lent, 2005). It has been used in STEM education for measuring, for example, high school (e.g., Bahar & Adiguzel, 2016) and college level (e.g., Lent, Sheu, Gloster, & Wilkins, 2010; Wang, 2013) students' (involving adults, Sasson, 2020) dispositions and career aspirations related to STEM. In this paper, SCCT conceptualisation was applied to describe the determinants of lower secondary students' STEM career intentions.

SCCT has two complementary aspects of theoretical analysis. The first aspect presents behavioural variables that give individuals personal control in their career choice and development: self-efficacy, outcome expectations, interests, and goals. The second aspect involves several other variables that affect individuals' career-related interests and choice behaviours such as personal history (e.g., gender, race, and pre-dispositions) and environmental or contextual features (e.g., culture, educational climate, and particular learning experiences). SCCT posits that behavioural, environmental, and personal variables influence one another through complex, reciprocal relations (Lent et al., 1994).

Self-efficacy appraisals are related to individuals' response capabilities, i.e. "Can I do this?" (Lent et al., 1994, p. 83), that serving as an influential determinant of occupational behaviours. Among others, self-efficacy beliefs are the most focal or pervading in the mechanism of human agency. Individuals do act or show perseverance in the face of career-related difficulties, only if they believe they can produce desired outcomes by their actions. Thus, efficacy beliefs play a central role in career choice and development not only in their own right, but also their impact on other variables (Bandura et al., 2001). Outcome expectations are potent motivators and involve the assumed results of performing certain prospective actions, i.e. "If I do this, what will happen?" (Lent et al., 1994, p. 83). Lent et al. (1994) cited Bandura's (1986) three types of outcomes expectations: physical (e.g., monetary); social (e.g., approval of significant others); and self-evaluative (self-satisfaction). Lent et al. (2000) expanded the theory in later years to include ultimate, distal outcome expectations that incline individuals toward a certain goal. For example, one may want to become a doctor by being attracted to its prestige and opportunity to help people that being a doctor is perceived as offering. According to Lent et al. (2000), these types of ultimate expectations correspond Bandura's self-evaluative or self-fulfilment expectations and help to sustain individuals along challenging career paths towards their long-term career intents. Anticipated working conditions and reinforces related to a particular career (e.g., favourable conditions) are additional distal outcome expectations that can be bases for career interests or choices. These types of expectations sometimes can be long-term wishes such as intending to major in a mathematics or science-related area believing that having in a degree in these fields allows someone to earn relatively more (Lent et al., 2000).

Goals are expressed choices, aspirations, career plans, and decisions, i.e. "I intend to major in an engineering field" (Lent et al., 2010, p. 390). By setting goals, individuals organise and guide their actions (e.g., attending trainings related to their goal) to sustain their goals in the long run, sometimes even with little external support, and to increase the chance of achieving the desired outcomes (Lent et al., 1994). Interests are patterns of likes and dislikes with respect to career-relevant activities and jobs. They can be influenced by individuals' career-relevant abilities, and thus individuals' career goals are likely to be prompted by their interests. For instance, one's social interests may lead to them to pursue a social-type vocation (Lent et al., 2000). According to SCCT, self-efficacy and outcome expectations give rise to interests and that each of these variables, along with environmental factors, help to shape educationally and vocationally relevant choices (Lent et al., 2010).

Environmental factors are both objective and subjective contextual influences. Objective aspects of the environment include the quality of educational experiences, parental behaviours, peer influences, and economic conditions (e.g., the financial support available to individuals for having career-related training) and can affect peoples' career choice or development (Lent et al., 2000). In their conceptualisation of the way of analysing student success in the sciences and quantitative subjects – the Engagement, Capacity, and Continuity Trilogy (the ECC Trilogy) – Jolly et al., (2004) underline the importance of objective contextual factors in career or academic success. The authors suggest that continuation in career-related subjects towards careers in those fields (success) could only be achieved within systems where individuals' goals complement with their career-related capacity and necessary resources are offered by the system.

The subjective environment refers to individual perceptions regarding opportunities, resources, or barriers that are provided in a certain environment. For example, some individuals succeed in environments where very limited resources available, while some fail in rich conditions. This relates to how they make sense of and respond to their environments (Lent et al., 2000). SCCT categorises environmental variables according to their relative proximity to the educational or career choice processes as: distal, background contextual influences; and proximal factors or affordances. Distal, background contextual factors involve role model presence and opportunities for engaging in particular academic or extracurricular activities. These factors can affect individuals' learning experiences through which their career-relevant self-efficacy and outcome expectations develop. Proximal contextual affordances (e.g., career network contacts) are important especially throughout active phases of career decision-making (Lent et al., 2000). Parenthetically, this study of lower secondary school students' career goals concentrates on distal, contextual factors. SCCT hypothesises that environmental variables can directly influence or moderate individuals' career-relevant choices and associated actions. For example, an individual who perceives supportive environmental factors (e.g., adequate support systems) is more likely to translate their career aspiration into a goal, and their goal into related actions. Or an individual within a collectivist culture may prioritise the needs or preferences of others rather than their own personal career wishes (Lent et al., 2000).

Although STEM dispositions have stimulated much research in Turkey, as in other parts of the world, the critical theoretical ingredients of school students' STEM career choice intentions have not necessarily been incorporated into investigations. These efforts may fail to identify and mediate "the central variables that nurture and sustain occupational interests and choices" (Lent et al., 2010, p. 387). The present study builds upon earlier research by including a more complete picture of Turkish school students' interests and attitudes related to STEM disciplines and careers, applying SCCT (Lent et al., 1994).

METHOD

Draw a Mathematics Classroom Study

The *Draw a Mathematics Classroom* study (Hatisaru, in press) was designed to identify lower secondary school students' (grades 6 to 8, aged 11 to 14) perceptions of instructional practices in the mathematics classroom by using a drawing technique. The research questions sought to determine, through the students' eyes, what teaching and learning practices, and teaching resources, including mathematical tasks and their representational forms (e.g., visual, symbolic), were used in mathematics classrooms. The *Draw a Mathematics Classroom Test* adapted from relevant research studies was used to collect the data. The test combined drawings with written responses. Participant students were asked to draw a picture of their mathematics classroom in where students learning and the teacher teaching. Next, they described their drawing: what the teacher was doing; what the students were doing; and what materials and tools they were using. On the back page of the Test, the *STEM Semantic Survey* (Christensen et al., 2014) was utilised (with permission). Only the responses to *STEM Semantic Survey* were analysed in this paper.

Three lower secondary schools (two public, one private) located in Ankara, the capital city, voluntarily participated in the study. The schools were co-educational metropolitan schools with a relatively middle socioeconomic population based on family income. The instrument was implemented in Turkish at the beginning of the 2018-2019 school year under the auspices of school principals. The counselling teachers at each school conducted the survey at a time convenient for the schools. It took approximately thirty minutes to complete the task.

In data analysis, a priori thematic saturation was employed to gauge the degree to which pre-determined codes or categories were sufficiently represented in the data (Saunders et al., 2017). Among the 400 drawings, similar student depictions and descriptions were seen repeatedly, so after the 120th occurrence, the relevant categories was considered to be saturated and the coding of the remaining drawings was terminated. Of the 120 student responses, three were excluded from the analysis because they contained minimal information (Hatisaru 2020a; in press). The sample was further reduced to a final size of 95 students in this paper, because 22 students were missing data in ten or more of the Survey items used in the analysis. The 95 students were comprised of male (n=47) and female (n=48) students across grade 6 (n=12), grade 7 (n=36), and grade 8 (n=47). Participants were coded as S1, S2, S3, and so on.

STEM Semantic Survey

The *STEM Semantic Survey* includes five consistent adjective pairs for a target statement reflecting individuals' attitudes towards each individual STEM discipline: science; technology; engineering; and mathematics (e.g., see **Table 1**). The fifth scale in the Survey is STEM career scale with the target statement: *"To me, a career in science, technology, engineering, or mathematics is:"* The same adjective pairs are used for all five scales. On top of the Survey, an instruction is given: *"Choose one circle between each adjective pair to indicate how you feel about the object"*. All items in the Survey were rated on a 7-Strongly Agree to 1-Strongly Disagree scales. Christensen et al. (2014) reported internal consistency reliabilities for the five scales as follows: Alpha=.90 for Science; Alpha=.89 for Mathematics; Alpha=.93 for Engineering; Alpha=.89 for Technology; and Alpha=.92 for STEM career. According to the authors, these reliability estimates fell into the range of "very good" to "excellent" based on the Devellis' (1991) guideline (p. 175).

The *STEM Semantic Survey* was translated into Turkish by the author who is fluent in Turkish and English languages. An additional open-ended item was added to the Survey to gather the influence of SCCT variables on students' interest to STEM careers: *"What career would you want to pursue after high school? Why?"*

Table 1. Science scale in the STEM Semantic Survey

To me, SCIENCE is:

1.	fascinating	1	2	3	4	5	6	7	ordinary
2.	appealing	1	2	3	4	5	6	7	unappealing
3.	exciting	1	2	3	4	5	6	7	unexciting
*4.	means nothing	1	2	3	4	5	6	7	means a lot
*5.	boring	1	2	3	4	5	6	7	interesting

Data Analysis

Analysis of Likert items

To analyse students' attitudes towards STEM disciplines and careers, mean and standard deviations were computed. Two items in each scale were reverse scored (see **Table 1**, Items 4 and 5). After assessing normality of the distribution, by using the skewness and kurtosis method, the Independent Samples *t* Test was run to test the statistical difference between the means of female and male students' attitudes. Adapting from Narli (2010), student mean attitude scores were then divided into three groups: high; moderate; and low, based on the number of scales in the *STEM Semantic Survey* (i.e. five). As each scale was 7-point Likert type, group span value was calculated as $7/3 \cong 2.33$. Group interval values were calculated accordingly as presented in **Table 2**.

Table 2. Group boundary values

Interval boundary value (IBV)	1 – 2.99	1 – 4.99	5 – 7
Group	High	Moderate	Low

Students' responses to the open-ended item in the Survey were analysed by using both qualitative and quantitative data analysis methods. The intended career choices were grouped into two: STEM and non-STEM professions (see below). One Sample Chi-Square Test was utilised to test the statistical difference between the observed frequencies in STEM and non-STEM career intentions. To test the statistical association between the observed frequencies in STEM and non-STEM career intents (2 categories) and gender (2 categories), Fisher's Exact Test was used.

Analysis of open-ended item

Deductive content analysis (Elo & Kyngäs, 2007) was utilised for qualitative data analysis. Student responses to the open-ended item, about what career they would want to pursue after high school and why, were transcribed documented using excel spreadsheets and next translated into English. As noted earlier, expressed career choices (goals) (e.g., 'I want to study medicine') were grouped into two: STEM and non-STEM. Adapting from Grinis (2019), STEM careers were classified in this paper depending on the intensiveness of STEM courses in relevant undergraduate program. STEM careers were defined as the majors included in the instructional programs corresponding to sciences and quantitative disciplines involving biology, physics, computer sciences, mathematics, technology, and statistics. All other careers were classified as non-STEM.

In many student responses (n=74) only one career name was expressed, while in 21 responses, two (n=18) or three (n=3) career names were mentioned. The stated careers in these 21 responses were mostly separable. Thus, they were grouped either as STEM (e.g., *"Orthodontist or bio medical engineering because I have interest in [them]"* S69, grade 7, boy) or non-STEM careers (e.g., *"Design or Turkish language. I like fun subjects, find them easy"* S41, grade 7, boy). In two student responses, however, intended careers could be grouped both into STEM and non-STEM categories (e.g., *"Policeman [non-STEM] or surgeon [STEM] [career] interests me"* S94, grade 7, girl). Responses such as: *"I have not decided yet"* (S46, grade 8, girl); and *"I do not know"* (S73, grade 7, boy) (n=5) were also available. These responses, together two dichotomous ones, were grouped as 'Other' (n=7) and not included in the analysis. Based on the expressed STEM (f=71) and non-STEM (f=43) careers in the student responses, Wordles (**Figure 1** and **Figure 2**) were created in which font size indicates word frequency.

The student responses were categorised into SCCT's behavioural variables: self-efficacy; outcome expectations; interests; and goals. A summary table of these variables, together associated sub-variables and representative examples, was presented in Appendix A. As already noted, goals were expressed career choices and had two categories: STEM and non-STEM professions. Goal interests were liking/disliking or interest/lack of interest in careers, career-relevant activities, and/or career-relevant subjects. Self-efficacy referred to the perceived personal capacity regarding an expressed career intent and constituted career fit, career-relevant self-efficacy or capability, and aptitude for the expressed career. Outcome expectations involved anticipations that certain financial or distal rewards would follow pursuing particular careers. Three types of distal expectations were evident in student responses: expected long-term benefits; favourable conditions; and ultimate wishes. Within the latter group, altruistic and patriotic motives (both are central to Turkish culture) (Evason, 2017) were among the determinants of students' expressed career intents (e.g., providing a contribution to people and/or country).

In a total of 20 response, only the career goal was given such as: *"Doctor"* (S112, grade 8, girl) or *"President"* (S60, grade 8, boy), but no reason was provided. The 68 responses which provided a reason(s) for the intended career choice were analysed to ascertain determinants of students' career intentions. Where more than one reason was given, these responses were coded into more than one category to maximising the richness of the data. For example, *"I want to become a lawyer because I like defending others and can defend well"* (S5, grade 8, boy) was coded into

Table 3. Means and standard deviations of attitudes towards STEM disciplines and career

	N	Minimum	Maximum	Mean	Std. dev
Science	95	5.00	35.00	12.75	6.96
Mathematics	95	5.00	35.00	14.83	8.86
Engineering	95	5.00	35.00	16.51	8.98
Technology	95	5.00	35.00	14.58	8.84
Career	95	5.00	35.00	13.37	6.84
Valid N (listwise)	95				

Table 4. Attitudes towards STEM disciplines and career correspond to IBV and group

	IBV	Group
Science	2.55	High
Mathematics	2.97	High
Engineering	3.30	Moderate
Technology	2.92	High
Career	2.67	High

Table 5. Independent Samples t Test comparing female and male students' attitudes towards STEM disciplines and career

		n	$\overline{X}$	S	Sd	Sig	P
Science	Female	48	13.13	7.79	91	.33	.744
	Male	47	12.66	6.09			
Mathematics	Female	48	15.18	8.77	91	.34	.732
	Male	47	14.54	9.16			
Engineering	Female	48	19.71	8.35	91	3.47	**.001**
	Male	47	13.60	8.63			
Technology	Female	48	16.89	8.39	91	2.43	**.017**
	Male	47	12.53	8.89			
Career	Female	48	14.19	6.77	91	1.01	.317
	Male	47	12.75	6.97			

two sub-variables: 'career-relevant activity interest' and 'career-relevant self-efficacy'. Frequencies were calculated and presented in **Table 9** below.

RESULTS

An overview containing quantitative results regarding students' attitudes towards STEM disciplines and careers is given first. This is followed by an in-depth description of determinants of students' career choice intentions organised by the SSCT framework. The discussion of results follows this section.

Attitudes towards STEM Disciplines and Careers

The *STEM Semantic Survey* scale was rated from 1-Strongly agree to 7-Strongly disagree in this study. Lower mean values, thus, refer to more positive attitudes. The mean and standard deviation values for students are shown in **Table 3**. As shown in the table, students' attitudes towards mathematics (Mean=14.83) and technology (Mean=14.58) were very close. Among the four STEM disciplines, attitudes towards science were the most (Mean=12.75) while towards engineering were the least (Mean=16.51) positive. When grouped, students' attitudes towards science, mathematics, and technology were high, while towards engineering were moderate (**Table 4**).

Table 5 presents the differences between the means of female and male students' attitudes towards STEM disciplines and careers. As seen in the table, while the differences between the means for female and male students' attitudes towards science and mathematics were statistically insignificant, the differences towards engineering and technology were statistically significant. Female students scored higher on engineering ($\overline{X}$=19.71) and technology ($\overline{X}$=16.89) scales than male students ($\overline{X}$=13.60 and $\overline{X}$=8.89 respectively). These indicated that female students' attitudes towards engineering and technology were less positive than their male counterparts.

When grouped, both female and male students' attitudes towards science were found to be high. While male students' attitudes towards mathematics, engineering, and technology were similarly high, female students' attitudes towards those subjects were moderate (**Table 6**).

Table 6. Attitudes towards STEM disciplines and career correspond to IBV and group by gender

		IBV	Group
Science	Female	2.63	High
	Male	2.53	High
Mathematics	Female	3.04	Moderate
	Male	2.91	High
Engineering	Female	3.94	**Moderate**
	Male	2.72	**High**
Technology	Female	3.38	**Moderate**
	Male	2.55	**High**
Career	Female	2.84	High
	Male	2.55	High

Table 7. Intended career choice in whole sample

	Observed N	Expected N	Residual
STEM	54	44,0	10,0
Non-STEM	34	44,0	-10,0
Total	88		

$\chi^2 = 4.55$, sd = 1, p = .033

Table 8. Intended career choice by gender

		STEM	non-STEM	Toplam
Female	n	29	15	44
	%	65.9%	34.1%	100.0%
Male	n	25	19	44
	%	56.8%	43.2%	100.0%
Total	n	54	34	88
	%	61.4%	38.6%	100.0%

$\chi^2 = .77$, sd = 1, p = .512

Students' attitudes towards a STEM career were found to be the second most positive (Mean=13.37) (**Table 3**). The differences between the means for female and male students' attitudes towards a STEM career were statistically insignificant (**Table 5**). Both females and males had high attitudes towards a STEM career (**Table 6**). Additional statistical analyses confirmed students' positive attitudes towards a STEM career (see the next section).

Intended Career Choice

In their responses to the open-ended item, among 88 students, 54 of them referred to a STEM (e.g., engineer) and 34 of them to a non-STEM career goal (e.g., psychologist). One sample chi-square test result showed, among students, the difference between intending to pursue a STEM or non-STEM career was statistically significant (χ^2=4.55, p<.033) (**Table 7**). This showed that participant students would more intend on pursuing STEM careers than non-STEM careers.

The statistical association showing how students' STEM and non-STEM career intentions vary by gender is presented in **Table 8**. As seen in the table, while 34.1% of female students would want to choose a non-STEM career, 65.9% of them would prefer to pursue a STEM career. Male students similarly had more interest to STEM careers than non-STEM careers. While 43.2% of male students referred to a non-STEM career choice goal, 56.8% of male students mentioned a STEM career intent. The observed differences, however, were similar. The differences between female and male students' interest to pursue a STEM or non-STEM career were statistically insignificant (χ^2=.77, p<.05).

Determinants of Career Goals

The various descriptions of either STEM or non-STEM career goal reasons in the open-ended question pointed to interests (*f*=45, 55.56%) (**Table 9**). Students expressed that the career choice was made primarily based on interest to a particular career (*f*=19) and career-relevant activities (*f*=19) or subjects (*f*=7). Students often cited factors involving liking/interested in a certain career (e.g., *"Medicine because it interest me"* S106, grade 8, girl) and being interested in activities (e.g., *"Paediatrician because I have interest in both children and medicine"* S91, grade 7, girl) or liking/being good at specific subjects relevant to a career (e.g., *"Engineering, because I am interested in mathematics"* S15, grade 8, girl) as reasons for intending to pursue a career after graduating from high school.

Several descriptions corresponded to expected future outcomes (*f*=25, 30.86%). Ultimate wishes (*f*=21) were the most cited reasons as bases for choosing a career, together with, in a few instances, favourable conditions (*f*=2) and expected long-term (*f*=1) and financial (*f*=1) benefits. Among the responses where an ultimate wish were

Table 9. The frequency of student responses (*f* = 81) in SCCT variables

Expressed career goals	Behavioural variables	Sub-variables	Frequency	Total (%)
STEM	Interests	Career interest	12	30 (37.04%)
		Career-related activity interest	12	
		Career-related subject interest	6	
	Outcome expectations	Ultimate wishes	11	12 (14.81%)
		Long-term benefits	1	
	Self-efficacy	Career fit	3	4 (4.94%)
		Career-relevant self-efficacy	1	
Non-STEM	Interests	Career interest	7	15 (18.52%)
		Career-related activity interest	7	
		Career-related subject interest	1	
	Outcome expectations	Ultimate wishes	10	13 (16.05%)
		Favourable conditions	2	
		Financial benefit	1	
	Self-efficacy	Career-relevant capability	3	7 (8.64%)
		Career-relevant self-efficacy	2	
		Aptitude for the career	1	
		Career fit	1	

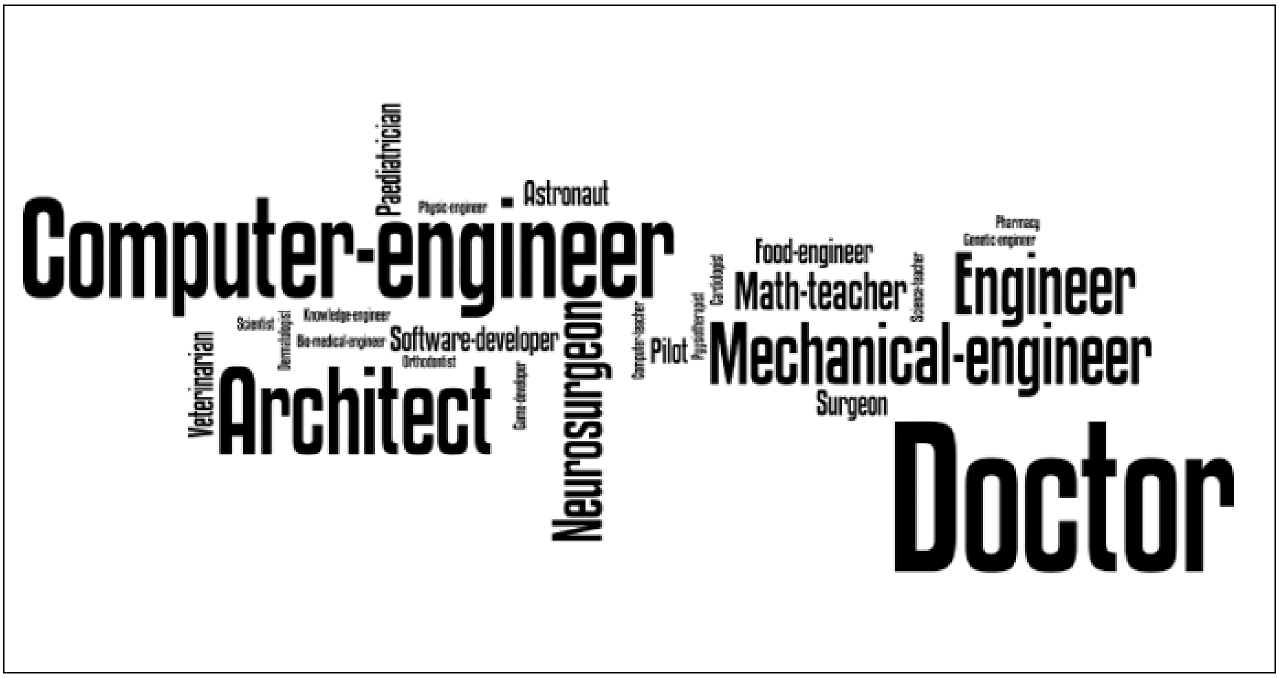

Figure 1. Wordle of expressed STEM professions in student responses (*f* = 71)

mentioned, the two drivers of Turkish culture were implicit in students' career choice motives: altruism (*f*=12) and patriotism (*f*=6). The most mentioned careers within this group were doctor (*f*=5), neurosurgeon (*f*=3), soldier (*f*=3), psychologist (*f*=2), and mechanical engineering (*f*=2). Typical examples involved: *"I want to become a psychologist, because helping people makes me happy. I know some people who have psychological problems. When I help them, I feel good"* (S55, grade 8, girl); and *"I want to become a mechanical engineer because I want to make helicopters, planes that is useful for our army, country"* (S71, grade 7, boy). One student wanted to become a mathematics teacher or a doctor because she wants *"to do useful work for the country"* (S104, grade 7).

Some other statements of career choice reasons referred to self-efficacy (*f*=11, 13.58%). Career fit (*f*=4), career-relevant self-efficacy (*f*=3) or capability (*f*=3), and aptitude for the career (*f*=1) were attributed with career intentions by some students. Role model influence in the students' career choice was negligible. Only in two responses, a possible role model impact was detected. One student wrote: *"Judge, to having the same profession with my grandpa and dad and do a useful job for my country and people"* (S13, grade 8, boy).

Figure 1 and **Figure 2** show Wordle analysis of the expressed careers in student texts, categorised into two groups: STEM and non-STEM professions. As depicted in **Figure 1**, the STEM professions most commonly identified included doctor (*f*=12), computer engineer (*f*=8), architect (*f*=7), engineer (*f*=5), mechanical engineer (*f*=5), and neurosurgeon (*f*=5). The most identified non-STEM professions were psychologist (*f*=5), policeman (*f*=5), judge (*f*=4), and lawyer (*f*=4).

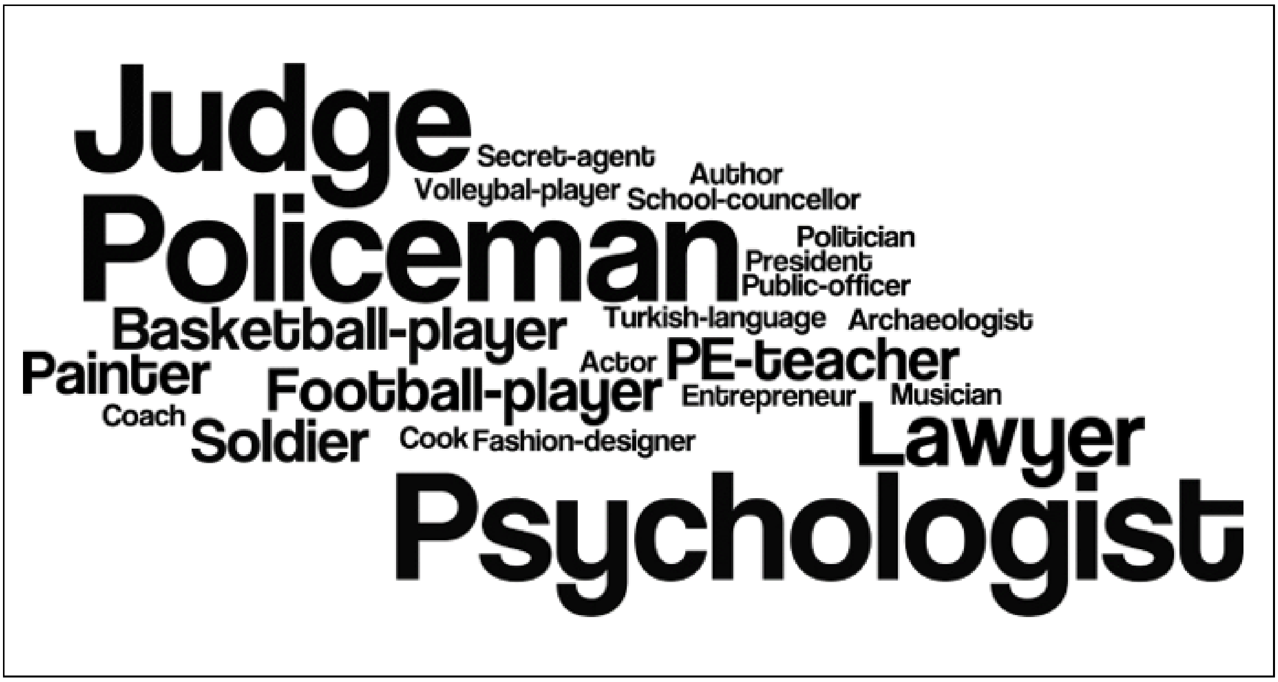

Figure 2. Wordle of expressed non-STEM professions in student responses ($f = 43$)

DISCUSSION, LIMITATIONS, AND IMPLICATIONS

This paper provides empirical support for claims about school students from developing countries having positive orientations towards science and mathematics (e.g., Hatisaru, 2020b; Mullis et al., 2016; Sjøberg & Schreiner, 2010; Thomas & Watters, 2015). Participant students from Turkey maintained highly positive attitudes towards science, mathematics, technology and STEM careers, and moderate attitudes towards engineering. More students expressed interest in pursuing STEM-related careers after high school than non-STEM careers. The gender difference in students' attitudes towards STEM disciplines and careers was negligible. Both female and male students were highly positive towards science and mathematics. While male students were similarly highly positive towards engineering and technology, female students were only moderately positive towards these two disciplines. The gender difference in STEM orientation literature presents mixed results. While these findings regarding the difference between female and male students' attitudes towards STEM disciplines were consistent with Christensen et al. (2014), Sadler et al. (2012) reported trends that female students were less likely to pursue STEM careers. Both studies were undertaken in developed countries; in this study conducted in Turkey, females' attitudes towards STEM disciplines and careers were positive. In fact, in TIMSS 2015, grade eight Turkish female students performed better than Turkish male students in science (Mullis, Martin, & Loveless, 2016).

This study highlights the possible influence of various factors related to when students make their educational or career choices. SCCT posits the role and importance of behavioural variables including self-efficacy, interests, outcome expectations, and goals in individuals' career decisions. Overall, one of the critical determinants of the participant students' career intentions was interests. Several students associated their interests with a specific career (e.g., mechanical engineering), or activities (e.g., making cars) and/or subjects (e.g., mathematics) related to that career. The results revealed that outcome expectations may play somewhat different roles in students' career choice process. Potential long-term benefits such as professional income, which were only mentioned by a few lower secondary students in this study, may be more influential on high school students' career interests and choices (Bahar & Adiguzel, 2016; Prieto & Dugar, 2017). While interests and outcome expectations were the main motivations for students' career choice after high school, consistent with previous research (e.g., Bandura et al., 2001; Prieto & Dugar, 2017), students' self-efficacy was also influential.

Where students expressed that it was their ultimate wish to choose a particular career, it was evident that societal and/or cultural factors influenced their career intentions. SCCT elaborates on how larger, societal context can influence career choice decisions. Specifically, several students' responses revealed that they wanted to become a doctor or psychologist to help others with their health or mental health issues. A few students wanted to assist the army by becoming a soldier or mechanical engineer. Implicit in the motives of these students' career choices are two drivers of Turkish society, altruism, and patriotism (Evason, 2017), which highlights the possible societal influence on their career goals. In the last *Teaching and Learning International Survey (TALIS 2018)*, teachers across the world attributed altruistic motivations such as, "teaching allowed [me] to influence the development of children and young people" for becoming a teacher (OECD, 2019, p. 123). Interestingly, in this study, few students (S9 and S104) mentioned wanting to become a teacher. In Turkish society, although all professions are valued, a career in medicine or engineering is viewed as more prestigious than a career in teaching. The students' lack of interest in a teaching career may again indicate that the context and social expectations influence students' educational choices (Bahar & Adiguzel, 2016).

In summary, the present study illustrates the suitability of the SCCT framework (Lent et al., 1994; 2000) for investigating the determinants of school students' STEM career intentions. According to SCCT, behavioural variables shape individuals' educational and occupational choices (Lent et al., 2010), and various important contextual variables such as culture and educational climate impact on these behavioural variables (Lent et al., 2000). Educational investments which take into consideration these variables have the potential to influence school students' attitudes towards and career choices in STEM. In particular, the influence of personal interests and societal factors on students' educational choices need to be considered in the development and implementation of STEM initiatives that aiming to impact students' orientations towards STEM.

Limitations

The aims of this paper were to investigate Turkish lower secondary students' attitudes towards STEM disciplines and careers, and the influence of behavioural, personal, and contextual variables on their career intentions in STEM. Interests and ultimate wishes, or altruistic motives, have been highlighted as important determinants of students' career goals. Nevertheless, these findings are not an exact measure of the influence of, for instance, early life experiences (Tai, Liu, Maltese, & Fan, 2006), academic achievement (Wang, 2013), perceived classroom learning experiences (Lyons, 2006), or influence of role models (Sasson, 2020) involving parents and teachers (Bahar & Adiguzel, 2016; Sjaastad, 2012). Answers to the open-ended item concerning the reasons of expressed career goals, represent the students' response at that point in time and within that classroom context. It is not possible to measure the precise range of behavioural or environmental influences on student choice, and intentions to pursue STEM careers may exist that were not mentioned by the students cannot be excluded. A second limitation relating to external validity also exists. It is not known whether the determinants of the students' career intentions found in this study are the result of the specific characteristics of students who participated in this study, or whether they are representative of a general trend in the population from which the sample has been drawn. Thus, the findings may not be generalisable to other schools in Ankara or to other regions in Turkey. Further research in this area including different and more in-depth research instruments, can be applied to meet these limitations. Nevertheless, the findings presented here provide valid and valuable insight into the motives that lie behind school students' career intentions in STEM. Together the quantitative data, students' responses to open-ended item, and the theoretical underpinnings of the research, all strengthen the validity of the study and to the conclusions drawn.

Implications

The findings reveal that behavioural SCCT variables operate as guides and motivators of students' career intentions and point to several implications. The diminishing inclination of school students to pursue STEM-related careers can be influenced by interventions that encompass and/or influence student interests. After school programmes and initiatives that provide students informal learning experiences in STEM such as robotics summer camps, media/toy design projects, and science fairs (e.g., Ayar, 2015; Gülgün, 2019; Karahan et al., 2015; Sirinterlikci et al., 2019) demonstrate how such educational investments might work. Considering the likelihood that educational experiences before high school may have an important influence on future occupational plans, early exposure to the sciences can increase student competence and interest in STEM careers (Sasson, 2020; Tai et al., 2006)

The attainment of STEM qualifications within Turkey's young population is ultimately important to the progress of the Turkish economy (Kivanc et al., 2017). As government aims to propel Turkey into the top ten largest economies in the world by 2023 (Istanbul Chamber of Industry, 2016), the country needs to enhance its competitiveness by building up its human resources (World Economic Forum, 2013). Even though students attribute importance to mathematics and science learning (e.g., Hatisaru, 2020b; Mullis et al., 2016), and express interest into studies in STEM (Ayar, 2015; Kearney, 2016), statistics show that the number of graduates and new admissions in technical and quantitative fields remain disproportionately low (Ayar, 2015). The current attrition in STEM degrees will ultimately result in skill shortages by 2023 (Kivanc et al., 2017). Student continuation in science and quantitative disciplines and progression towards careers in these fields (i.e. success) can only be achieved within an educational system where students' goals complement their career-relevant knowledge and skills. To achieve such a system, resources must be available at both institutional and programme level (Jolly et al., 2004). Effective ways to transform students' positive attitudes towards and interest in STEM disciplines and careers to success, need to be understood and followed by comprehensive approaches to creating the environment for student success (Jolly et al., 2004). It is especially important that students who commence university studies are better informed about the knowledge and skills required for entering certain STEM fields (Prieto & Dugar, 2017). Career guidance should be strengthened within the education system (Kearney, 2016), for "both to ensure that the country [in this case Turkey] has the skills its needs for the economy and to enable young people to make the best choices to meet their own future needs and aspirations" (Tripney et al., 2010).

This research has found the conceptualisation of behavioural, personal, and contextual factors in students' STEM career goals based upon the SCCT framework proposed by Lent et al. (1994, 2000) useful, for capturing the various ways in which these variables can be mediated to inspire school students' academic choices. Future research into STEM career interests and interventions needs to consider the contextual aspects of career choice behaviours (Lent et al., 2000), as in this study they were found to be operating as guides for students' future career plans. For example, there has been a significant decline in undergraduate mathematics enrolments in Turkey (Nesin, 2014), with the Council of Higher Education indicating that of the total undergraduate population (in 2019, it was over 2 million), only 1.12% enrolled in a mathematics major in 2015. In 2016 and 2017, there was a dramatic decline in enrolments (0.36% in 2016; 0.50% in 2017; 1.41% in 2018) possibly because in those years, mathematics graduates were not entitled to become school mathematics teachers. This example indicates that employment market conditions for mathematics graduates may influence students' decisions about whether to study mathematics and possibly their interest in mathematics.

The study reported here, in combination with the findings of the larger study (Hatisaru, in press), have implications for future research. These combined results suggest, albeit tentatively, that students' perceptions of teaching and learning practices in mathematics classrooms in Turkey (teachers transmit information and demonstrate correct solutions while students are passive recipients), play little role in the career intentions. This finding stimulates further research focussed on investigating the ways in which classroom learning experiences associate with the career choice process. Current research suggests that more open-ended and inquiry-based methods of learning are important for both 'screening' students who are truly inclined and committed to STEM disciplines (Thomas & Watters, 2015) and for improving the quality of learning and assisting studying STEM subjects at university level (Kearney, 2016). Hence, a thorough understanding of the ways in which such perceived teacher-centred instructional approaches affect educational choices and outcomes (e.g., Lyons, 2006) in the long term is necessary.

ACKNOWLEDGEMENTS

I am grateful to the schools and students for participating in this study. I thank Ismail Yolcu and Emily Morgan for their assistance in data collection and coding, and Ersoy Karabay for assisting with statistical analyses and thoughtful conversations.

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APPENDIX A: Determinants of student career choice corresponding to SCCT variables

Goals	Behavioural variables	Sub-variable	Example
Expressed STEM/ non-STEM careers	Interests	Career interest	"Software developer or computer engineering because I am interested in." (S83, grade 6, boy) "I want to study law and become a lawyer because it interests me." (S43, grade 8, girl)
		Career-related activity interest	"I will become a PE teacher because I like sport and want to make it my profession." (S27, grade 8, boy) "Pilot because I like planes much and [being a pilot] is a proud for my country. Painter, I have interest in paintings." (S18, grade 8, girl)
		Career-related subject interest	"I want to become a doctor because I like science and maths very much and feel happy when I succeed." (S36, grade 8, girl) "Engineering, I am interested in maths." (S15, grade 8, girl)
	Outcome expectations	Ultimate wishes	"After high school I want to become a Neurosurgeon. I like helping people. I want, after a surgeon, seeing that person becomes well." (S80, grade 6, girl) "I want to be a Soldier because I want defending my land, people very much." (S98, grade 7, boy)
		Favourable conditions	"Public officer. Job conditions are convenient: off weekend, no stress." (S90, grade 7, boy)
		Long-term benefits	"After completing high school, I like to become a computer engineering, which is a future profession and suits me." (S22, grade 8, boy)
		Financial benefit	"I will become a judge because they earn well. And it is nice." (S103, grade 7, boy)
	Self-efficacy	Career fit	"I want to be a psychologist or volleyball player because I find these professions suitable for me." (S63, grade 7, girl)
		Career-relevant self-efficacy	"Science teacher. I like science subject much and achieve. Veterinarian, I like pets and think succeed it." (S9, grade 8, girl)
		Career-relevant capability	"I want to become a basketball player. The reason is I am skilled in this area and believe can make a good career." (S37, grade 7, boy)
		Aptitude for the career	"Acting because I am good at memorising and I want to." (S102, grade 7, girl)

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European Journal of STEM Education,
2021, 6(1), 03
ISSN: 2468-4368

Investigating STEM Awareness of University Teacher Educators

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Citation: Abdioğlu, C., Çevik, M., & Koşar, H. (2021). Investigating STEM Awareness of University Teacher Educators. *European Journal of STEM Education*, 6(1), 03. https://doi.org/10.20897/ejsteme/6559

Published: January 15, 2021

ABSTRACT

The aim of this study is to determine the STEM awareness of academics working in education faculties and their STEM academic works affected by this awareness. The research was conducted according to a sequential explanatory design, which is one of the mixed research methods. In the quantitative part of the study, a relational type of screening model was used and in the qualitative part, a case study design was preferred. The sampling of the quantitative part was composed of 239 academics working in education faculties in Turkey within the scope of the appropriate sampling method, which was non-random. As a result of the analysis, a semi-structured interview form was prepared within the scope of 4 themes and the qualitative part was started. As a result of the research, it was determined that academics in education faculties had high mean scores for STEM awareness, and that there was no significant difference in terms of gender, professional area and department, but there was a significant difference in terms of age and title variables. In addition, the situations in which interviewed academics, whose awareness scores were high and low, were affected by STEM awareness were revealed and discussed.

Keywords: higher education, deviant case study, mixed method, STEM awareness

INTRODUCTION

In today's world, information and technology are rapidly developing and changing. Therefore, countries should constantly revise and develop their education systems and curricula based on the needs of the age in order to get ahead in their competition with others. In many countries, students are expected to acquire the knowledge and adapt it for real life in order to solve problems. Along with these expectations, 21st century skills have recently gained importance. For example, in the Turkish curricula updated in 2011, the Ministry of National Education highlights that it is aimed to educate individuals who can generate information and use it in their daily life, solve problems and think critically, be entrepreneurial and decisive, and have communication skills (URL-1). However, it may not be possible for students to develop these skills if the outcomes of each lesson are given separately (Akgündüz et al., 2015). Therefore, a multi-disciplinary approach is needed to achieve these goals. Consequently, STEM (science, technology, engineering and mathematics), one of the multidisciplinary approaches, has emerged as an effective approach in recent years.

STEM is an interdisciplinary approach that includes all the disciplines of science, technology, engineering and mathematics. STEM education underscores that STEM is at the center of developing ideas about effective teaching and learning. In this approach, teaching and learning goes beyond just emphasis on memorizing the contents and information in a specific discipline.

In order for countries to be successful in competition with their counterparts, great importance should be given to STEM education (Lacey & Wright, 2009). STEM education may help countries develop in industrialization, competition in the world market and fostering qualified individuals in new emerging business fields. Therefore, it is important to foster individuals' STEM literacy. Employing STEM-literate people in the industrial fields should be included among the objectives of the country to increase industrial and economic development (Çevik, Şentürk, & Abdioğlu, 2019). This is because STEM-literate individuals can understand science, technology, engineering and math concepts in complex problems, solve these problems and generate new solutions (Meng, Idris, & Eu, 2014). STEM literacy involves being able to use scientific methods or engineering design principles in designing new tools, and being able to evaluate and explain the impact of any finding on the real world, rather than memorizing the content of a specific discipline (Stephan, Pugalee, Cline, & Cline, 2018).

Awareness is defined in different ways in the literature. According to Çatak and Ögel (2010), awareness is a mind and body practice that involves focusing the attention on immediate experiences and observing inner experiences. Keleş (2007) expresses awareness as conscious and sensitive behaviours towards different factors in the individual's and society's life areas. Kabat-Zinn (2005) defines awareness as concentration on the moment in an unbiased and attentive way in line with a specific aim. According to Hutton and Baumeister (1992), by increasing awareness towards a certain field, attitudes and behaviours towards that field are also seen to be strengthened.

STEM awareness can be expressed as awareness of the relationship between the areas of STEM and the ability to make logical deductions (Gürbüz & Karadeniz, 2020). Deveci (2018) expresses STEM awareness as fostering high-level thinking skills in individuals through STEM education, ability to use the disciplines of science, technology, engineering and mathematics together, understanding that a problem can be solved in different ways, being self-confident, and awareness of providing the ability to collaborate and establish effective communication. On the other hand, according to Kovarik et al. (2013), STEM awareness is regarded as a precondition for individuals to interact, possess self-efficacy and develop themselves. Accordingly, studies in the literature on the subject of awareness and STEM awareness reveal the importance of high awareness of STEM in individuals, besides their readiness for STEM.

Since STEM education constitutes the main technological foundations for the developed countries, the need for individuals specialized in the STEM area is constantly increasing (Meng, Idris, & Eu, 2014). Therefore, in order to increase the number of people specialized in thee STEM field, importance should be given to STEM education (Öner, Capraro, & Capraro, 2016). In order to achieve the desired outcomes, teachers from pre-school to university have a great responsibility. Among other educators, teacher educators have the biggest responsibility for fostering STEM awareness. Teacher educators, who educate pre-service teachers, should be aware of what STEM education is and why it is needed in socio-economic contexts. Because teacher educations greatly influence the perspectives of pre-service teachers who will educate the next generations, teachers educators' STEM awareness is worth examining.

Importance of the Research

In order to educate students in the field of STEM education, teachers, who implement the curricula at schools, should have sufficient knowledge, skills and equipment in the field of STEM. Regardless of their specialization, teachers are expected to have attitudes, knowledge and skills related to at least one STEM discipline (Akgündüz et al., 2015). These attitudes, knowledge and skills depend not only on their own efforts but also on their undergraduate education. Thus, it is clear that teacher educators, who are responsible for training prospective teachers, play an important role.

In the literature, there have been many studies investigating the STEM awareness of teachers and teacher candidates. Studies have examined STEM awareness in preservice teachers' (Kızılay, 2016), chemistry and mathematics teachers (Aslan-Tutak, Akaygun & Tezsezen, 2017) and primary school, mathematics and science teachers (Bakırcı & Karışan, 2017).

This study was drawn on recent articles on STEM education by categorizing the research into seven inductively-developed purposes, including understanding STEM preservice teacher learning and development, understanding teacher educators and their practices, and five others. In this study, questions such as "Who is being studied, and who is doing the research?", "What are the methods that have been used?", etc., were included. Bell, Gitomer, Savage and McKenna (2019) reviewed a sample of 174 recent papers on STEM teacher preparation and identified fourteen studies focusing on teacher educators, but they concluded that none of these studies paid attention to teachers educators beliefs about STEM. This study elaborates on STEM teacher preparation and contributes especially to the knowledge on teacher educators' STEM awareness."

In order to achieve satisfactory outcomes in STEM education, STEM education in faculties at university and especially education faculties should be of good quality too. Teachers implement STEM programs at the schools. One way to increase their STEM awareness and to equip them with the necessary STEM skills is to ensure that teacher educators cooperate with some other faculties from different disciplines to both diversify and enrich teacher education (Akgündüz et al., 2015). For doing this, first of all, teacher educators should be familiar with the STEM approach and have the requirements for this approach. With the development of this awareness, how STEM awareness effects their teaching is another important issue. Kovarik et al. (2013) argued that individuals' ability to interact, their self-efficacy and their possession of content knowledge were prerequisites in the development of STEM awareness. Also Hutton and Baumeister (1992) emphasized that as the level of awareness increases, the relationship between attitude and behavior also becomes stronger. On the other hand, the advocates of theories of the cognitive-behavioral approach state that it is possible to increase the level of awareness about the feelings and thoughts that guide the behavior of the individual (Engin & Çam, 2005). In this context, it is thought that STEM awareness may influence teacher educators' readiness, interest, attitude, participation in activities and following current developments in the STEM field. Bybee (2010) emphasized that STEM awareness may relate to communication, decision-making, social and self-management skills. Therefore, teacher educators who have significant STEM awareness can train pre-service teachers who have self-efficacy for the scientific and technological needs of the age and are equipped with 21st century skills. These needs underscore that STEM awareness have a possible influence on other aspects of teacher education, which is a multi-dimensional phenomenon.

Examination of teacher educators' views on educational method has an important place in any phenomenon related to education. In the literature, studies have investigated teacher educators' views and emphasized the importance of examining their opinions. For example, Dağtekin and Zorluoğlu (2019) studied teacher educators' views on the updated science teacher education program and emphasized the importance of their views in revealing the advantages and disadvantages that the programs can provide to prospective teachers. Yılmaz (2010) emphasized that the views of teacher educators were one of the most efficient ways to unveil the problems encountered in the field of teacher education.

When the literature is examined, it is seen that individuals whose STEM awareness is investigated have also been examined as to whether this awareness varies according to variables such as age, gender, and department (field/area of expertise). For example, in their study examining STEM awareness in preschool, science and mathematics teacher candidates, Bakırcı and Karışan (2017) revealed that while there was no significant difference between genders, there was a significant difference between certain departments. In a study that examined the reasons why women were underrepresented in STEM professions, Xu (2015) revealed that there was a significant deviation in earning profiles between women and men in the first ten years of employment. Moreover, the findings showed that the incomes of women in STEM professions were lower in concurrence with their increasing family obligations (Xu, 2015). In another study, in which gender differences in science and mathematics achievement and competence were investigated, it was revealed that gender differences in science and mathematics may be indirectly related. On the other hand, there are no single or simple answers to the complex questions about gender differences in science and mathematics (Halpern et al., 2007). As can be seen from these studies in the literature, variables such as gender, age and department are examined in studies related to STEM. However, in the context of these studies, no study can be found in which STEM awareness of academics employed in education faculties is examined in depth according to variables like gender, age and department.

Therefore, it would be beneficial to examine the STEM awareness of teacher educators. With this purpose of the study, answers to the following questions were sought:

1. What level of STEM awareness do teacher educators have?
2. Does STEM awareness of teacher educators differ based on their gender, ages, titles and specialty areas?
3. What factors affect the STEM awareness of teacher educators?

METHOD

Research Model

A mixed methods research approach, in which quantitative and qualitative methods were used together, was utilized to examine the STEM awareness levels of teacher educators. Creswell (2012) defined a mixed methods research model as collecting and analyzing quantitative and qualitative data together. The research was carried out with sequential explanatory mixed methods. In this study, quantitative data were collected, and then qualitative data were collected to explain the quantitative data (Creswell & Plano Clark, 2014). This method was used to strengthen the results of the study by eliminating the weaknesses of a single quantitative data analysis, so that both research perspectives support each other to give strong evidence about the phenomenon under investigation (Suhonen, 2009). The research was carried out in two stages. In the first stage, quantitative data were collected. At this stage, a cross-sectional model was utilized. Cross-sectional models include selecting a sample that represents the population to reach a general conclusion (Karasar, 2007). In addition to this, a correlational research model was used to examine the relations between variables (Cohen, Manion & Morrison, 2000; Karasar, 2007). In the second stage of the research, participants who had lower and higher scores in the STEM awareness scale were

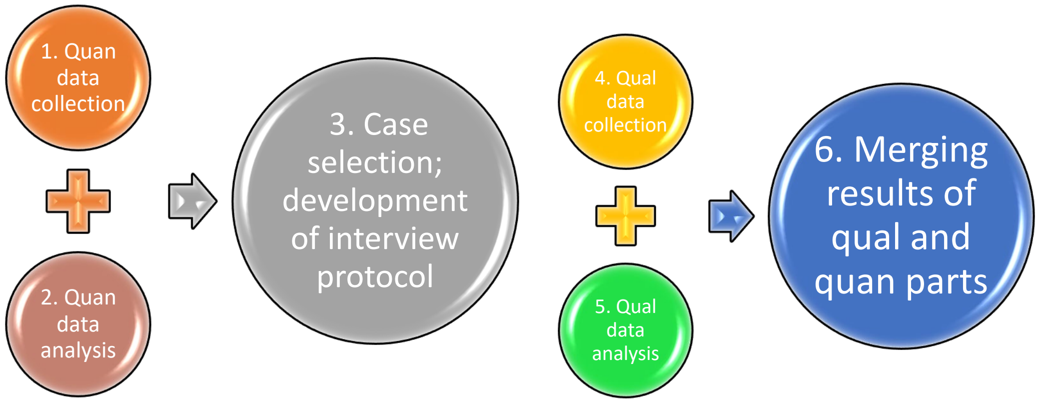

Figure 1. Sequential explanatory mixed methods research model diagram, (Creswell & Plano Clark, 2014)

Table 1. Descriptive characteristics of participants included in the quantitative part

		f	%
Gender	Female	134	56.1
	Male	105	43.9
Age	20-30	35	14.6
	31-40	104	43.5
	41-50	72	30.1
	51-60	21	8.8
	61-70	7	2.9
Department	Elementary science and mathematics	86	36 0
	Primary teaching	63	26.4
	Secondary science and mathematics	39	16.3
	Educational sciences	32	13.4
	Computer and educational technology	14	5.9
	Turkish and social education	3	1.3
	Art education	2	0.8
Title	Research assistant	75	31.4
	Lecturer	5	2.1
	Assistant professor	80	33.5
	Associate professor	39	16.3
	Professor	40	16.7
Total		**239**	**100**

included to examine the factors causing differences in STEM awareness. The data collection stages are shown in Figure 1.

In the quantitative methods coming before the qualitative methods, participants' scores on the quantitative part can be used as the sampling strategy (Sandelowski, 2000). Criterion sampling is a type of purposeful sampling used to select participants based on predetermined criteria, such as scores on the instrument. One type of sampling can also be called extreme or adverse case sampling (Sandelowski, 2000). In this method, successful or unsuccessful cases, extraordinary or unique examples are generally selected (Marshall & Rossman, 2014). The purpose of an extreme or deviant sampling strategy is to obtain different perspectives on the same phenomenon from dramatic or extraordinary cases (Liamputtong, 2013). It can be used to obtain extreme outputs to address the research questions based on contradictory situations (Charmaz, 2011). In the qualitative part of the research, data collection was carried out with the interview method. With the semi-structured interview form prepared according to the determined themes, questions were sent to participants via email due to COVID-19, and then interviews that could not be conducted face-to-face were carried out digitally by conducting them by video with the WhatsApp application. The obtained data were then analyzed.

Research Group

Participants in the quantitative part of the study were selected using the convenience sampling method. A total of 455 teacher educators were contacted by email to voluntary participate in this study, and 239 teacher educators replied positively. This sampling method brought speed and practicality to the research (Yıldırım & Şimşek, 2006). Descriptive information about the participants is given in Table 1.

Of the participants, 134 (56.1%) were female and 105 (43.9%) were male. Most participants were in the age range between 31-40 (43.5%) while the fewest were in the age range between 61-70 (2.9%). The majority of the

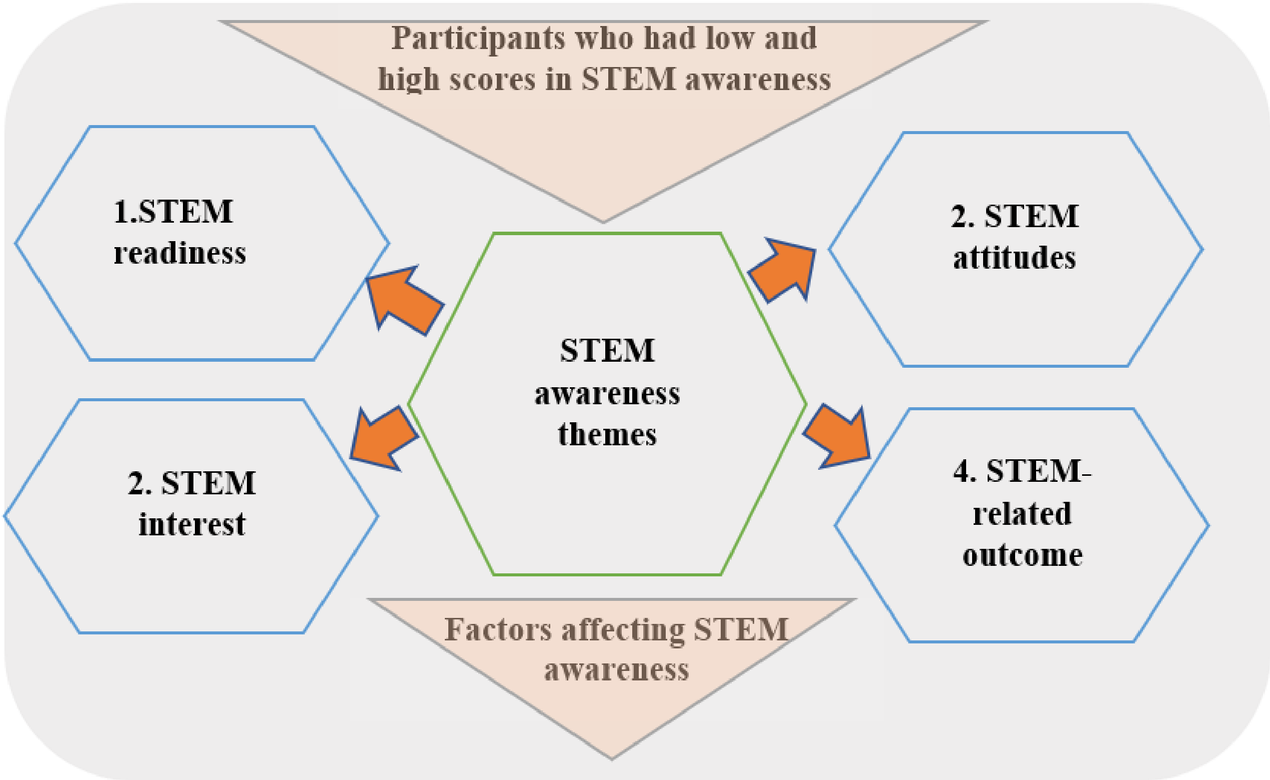

Figure 2. Diagram of the qualitative stage

participants were specialized in elementary science and mathematics (36.0%). Regarding the academic titles of the participants, assistant professors were in the majority (33.5%).

Data Collection Tools

Detailed information on the qualitative and quantitative survey tools is given below.

STEM awareness scale: The STEM awareness scale was developed by Çevik (2017) to determine teachers' STEM awareness. It consists of 15 items in three sub-dimensions, named as *effects on students* (six items), *effects on the course* (five items) and *effects on teachers* (four items). (For scale items, see Appendix). Likert-type ratings are "Totally Agree," "Agree," "Not Sure," "Disagree," and "Totally Disagree." Scale items are scored from 5, which refers to "Totally Agree," to 1, which refers to "Totally Disagree." The overall Cronbach alpha coefficient of the scale was reported to be .86 (Çevik et al., 2017). Cronbach alpha coefficients for sub-dimensions were .89, .71, and .70, respectively. A Cronbach alpha coefficient higher than .70 is generally considered sufficiently reliable (Pallant, 2007). Goodness-of-fit indices of the scale revealed that the model was confirmed and that that this structure was valid for measuring STEM awareness ($\chi 2$= 156.87, d=247, $p < .01$, GFI= 0.92, AGFI=0.90, SRMR= 0.057, NFI= 0.94, NNFI= 0.96, CFI=0.97, IFI=0.96). The STEM awareness scale was administered to 89 participants in paper-and-pencil form and 145 participants in online form through Google Forms.

STEM Awareness Interview Preparation Process: In the light of the findings obtained from the analysis of the quantitative data, 4 themes were determined. Based on the previous studies, a semi-structured interview form was developed for in-depth examination in the four themes identified regarding STEM awareness. The interview protocol consisted of eleven questions. The first five questions were descriptive questions. There were two questions regarding STEM readiness, two questions on STEM attitude, one question on STEM interest and one question on STEM-related outcomes. In the preparation of the interview protocol, the focus was on clear, descriptive questions, refraining from directing, and developing alternative questions (Yıldırım & Şimşek, 2006). Once the interview protocol was developed, the opinions of one expert in science, one expert in mathematics and one science teacher were obtained and the form was finalized based on their feedback. The development of the interview protocol is shown in **Figure 2**.

Table 2. Normality test results regarding the STEM awareness scale sub-dimensions

Sub-Dimensions	Kolmogorov-Smirnov		Skewness		Kurtosis	
	Statistics	p	S	S. E.	K	S.E
Effects on students	.12	.09	-.67	.15	.70	.31
Effects on the course	.09	.07	-.20	.15	-.28	.31
Effects on teachers	.13	1.0	.22	.15	-.02	.31
Total score	.05	2.0	-.27	.15	.58	.31

p > .05, S. E.: Standard error

Table 3. Arithmetic means of the scale used in the interpretation

Score Range	Mean Score (P. range of items)	Scale	Evaluation
1.00-1.79	15-26	Totally disagree	Very low
1.80-2.59	27-38	Disagree	Low
2.60-3.39	39-50	Not sure	Middle
3.40 -4.19	51-62	Agree	High
4.20 -5.00	63-75	Totally agree	Very high

Table 4. Mean scores related to STEM awareness

Sub-Dimensions	N	Score range		Min	Max	ss
Effects on students	239	4.29	25.79	12	30	3.45
Effects on the course	239	3.78	18.94	10	25	2.99
Effects on teachers	239	3.89	15.56	10	20	2:06
Total scale	239	4.02	60.30	32	74	6.97

Analysis of Data

First, the normality test was used to determine whether the collected data were normally distributed. The normality test was performed for the whole scale and for each sub-dimension. It is suggested that for data consisting of more than 50 cases, it is appropriate to use the Kolmogorov-Smirnov test to evaluate the normality (Büyüköztürk, Çokluk & Köklü, 2010). Kolmogorov-Smirnov test values for the scale are given in **Table 2**. All quantitative analyses were made with SPSS 24.0 software.

The Kolmogorov-Smirnov tests were statistically non-significant for the scores of each sub-dimension and the overall score of the STEM awareness scale. If the calculated p values are higher than .05, it is interpreted that the scores do not differ from normal distribution (Büyüköztürk, 2012). In addition to this, the skewness and kurtosis values for each sub-dimension were between +1 / -1. Skewness and kurtosis values within ± 1 limits are considered as evidence for normal distribution (Tabachnick & Fidell, 2013). Therefore, parametric tests were preferred in the data analysis. Frequency analysis, independent t-test and one-way ANOVA were used in the data analysis. In the determination of the levels, mean scores of 1.00-1.79 were considered as “totally disagree”, 1.80-2.59 as “disagree”, 2.60-3.39 as “not sure”, 3.40-4.19 as “agree”, and 4.20-5.00 as “totally agree” (See **Table 3**).

The scales given in **Table 3** guided the interpretation of participants’ STEM awareness. Content analysis was used in the analysis of qualitative data. Content analysis is used to summarize the qualitative data with smaller parts that have similar meanings (Büyüköztürk, Çokluk & Köklü, 2010). Content analysis requires the data collected to be quantized and analyzed in depth. It allows hidden themes and codes to be revealed. To provide evidence regarding the themes, direct quotations of the participants are presented and interpreted as illustrations.

Qualitative data analysis was checked by two different independent researchers. The number of codes on which agreement was reached was 35, while agreement was not reached on 5 codes. The coder reliability was computed by using the formula: Agreement = [Number of Agreements/(Number of Disagreements + Number of Agreements) X 100](Miles and Huberman, 1994). This was determined as ((35/35 + 5) * 100) = 87%. Later, the 5 disputed codes were discussed and re-evaluated, and the disagreements were solved after obtaining a third expert’s opinion. Codes were grouped in themes and data were presented with their frequencies and percentages.

RESULTS

In this section, results regarding the research questions are presented.

1. Findings related to the research question of “What level of STEM awareness do teacher educators have?”

Teacher educators’ STEM awareness mean score for effects on students was found to be 25.79 with a range of 4.29 (See **Table 4**). It can be said that teacher educators’ STEM awareness towards effects on students was very

Table 5. Results of t-tests by gender

	Gender	N	Mean	ss	t	p
Effects on students	Female	134	25.73	3.46	.26	.79
	Male	105	25.85	3.47		
Effects on the course	Female	134	19.04	2.94	.57	.56
	Male	105	18.81	3.06		
Effects on teachers	Female	134	15.55	1.95	-.07	.93
	Male	105	15.58	2.21		
Total scale	Female	134	60.34	6.68	.09	.92
	Male	105	60.25	7.36		

Table 6. Results of ANOVA by age

Sub-Dimensions of the Scale	Age range	N	Mean	ss	sd	F	p	Scheffe Test	Levene F Test
Effects on students	20-30	35	24.82	3.93	234	2.06	.08		p > .05, $F_{student}$ = .74, sd = 234 p = .56
	31-40	104	26.23	3.39					
	41-50	72	25.81	3.35					
	51-60	21	24.61	3.00					
	61-70	7	27.28	3.09					
Effects on the course	20-30	35	25.79	3.45	234	4.27	.00*	20-30 / 31-40 20-30 / 61-70	p < .05, F_{course} = 5.89, sd = 234, p = .07
	31-40	104	17.91	3.28					
	41-50	72	19.56	2.68					
	51-60	21	18.52	3.23					
	61-70	7	18.19	2.44					
Effects on teachers	20-30	35	21.42	1.39	234	.57	.68		p > .05, $F_{teacher}$ = 2.11, sd = 234, p = .14
	31-40	104	18.94	2.99					
	41-50	72	15.34	2.33					
	51-60	21	15.75	2.02					
	61-70	7	15.40	2.04					
Total scale	20-30	35	15.42	1.50	234	3.14	.01*	20-30 / 31-40 20-30 / 61-70	p < .05, $F_{overall}$ = 1.32, sd = 234, p = .50
	31-40	104	16.14	3.13					
	41-50	72	15.56	2.06					
	51-60	21	58.08	7.95					
	61-70	7	61.54	6.57					

* *p <.05*

high. The STEM awareness mean score for effects on the course was 18.84 with a range of 3.78, indicating that the STEM awareness towards effects on the course was high. The mean score for STEM awareness for effects teachers was 15.56 with a range of 3.89, showing that teacher educators had a high level of STEM awareness for effects on teachers. It was found that the overall mean score of the STEM awareness that teacher educators had was 60.30 with a range of 4.02. This finding show that teacher educators had a high STEM awareness. While the highest mean score was for effects on students, the lowest mean score was for effects on the course.

2.a) Findings related to the research question of "Does the STEM awareness of teacher educators differ in terms of gender?"

Findings regarding the STEM awareness mean score of teacher educators in terms of gender are given in **Table 5**. As seen in **Table 5**, there was no significant difference between female and male teacher educators' STEM awareness scale mean scores for the three sub-dimensions or the whole scale.

2.b) Findings related to the research question of "Does the STEM awareness of teacher educators differ in terms of age?"

Findings regarding the STEM awareness mean score of teacher educators in terms of age are given in **Table 6**. The mean values show that teacher educators' STEM awareness varied in one sub-dimension and the total score based on their age. ANOVA was run to test whether this difference was statistically significant. As a post-hoc test, the Scheffe test was used to determine the direction of the difference. The Scheffe test was developed to compare all possible linear combinations between groups. This method is generally considered as a flexible post-hoc type of test that can keep the α margin of error under control (conservative) when there are many groups to be compared, and does not take into account the assumption that the number of observations in the groups are equal (Scheffe, 1959). In the sub-dimension of effects on the course, the test resulted in a statistically significant difference between the 20-30 and 31-40 age groups in favor of the 31-40 age group, and between the 20-30 and 61-70 age groups in favor of the 61-70 age group [F_{course} = 5.89, sd = 234, p = .07]. In the sub-dimensions of

Table 7. Results of ANOVA by academic title

Sub-Dimensions of the Scale	Titles	N	Mean	ss	sd	F	p	Scheffe Test	Levene F Test
Effects on students	Res. Asst.	75	25.41	3.93	234	1.08	.36		p > .05, $F_{student}$ = 2.26, sd = 234 p = .06
	Lecturer	5	25.60	2.88					
	Asst. Prof.	80	26.43	2.81					
	Assoc. Prof.	39	25.38	3.97					
	Professor	40	25.62	3.15					
Effects on the course	Res. Asst.	75	18.64	3.15	234	2.33	.04*	Res. Asst.- Asst. Prof. Asst. Prof.- Assoc. Prof.	p < .05, F_{course} = 1.77, sd = 234, p = .13
	Lecturer	5	19.60	3.78					
	Asst. Prof.	80	19.71	2.57					
	Assoc. Prof.	39	18.20	3.04					
	Professor	40	18.62	3.11					
Effects on teachers	Res. Asst.	75	15.37	2.23	234	1.32	.26		p > .05, $F_{teacher}$ = .95, sd = 234, p = .43
	Lecturer	5	16.00	2.44					
	Asst. Prof.	80	15.97	1.88					
	Assoc. Prof.	39	15.23	2.15					
	Professor	40	15.40	1.93					
Total scale	Res. Asst.	75	59.42	7.72	234	2.25	.06	20-30 / 31-40 20-30 / 61-70	p > .05, $F_{overall}$ = 2.11, sd = 234, p = .08
	Lecturer	5	61.20	8.16					
	Asst. Prof.	80	62.12	5.90					
	Assoc. Prof.	39	58.82	7.56					
	Professor	40	59.65	6.28					

* *p <.05*

Table 8. Results of ANOVA by specialty area

Sub-Dimensions of the Scale	Source of Variance	Total Squares	sd	Mean Squares	F	p
Effects on students	Between	265.50	22	12.06	1.01	.45
	Within	2582.03	216	11.95		
	Total	2847.54	238			
Effects on the course	Between	92.78	22	4.21	.44	.98
	Within	2037.50	216	9.43		
	Total	2130.29	238			
Effects on teachers	Between	61.87	22	2.81	.63	.89
	Within	956.73	216	4.42		
	Total	1018.61	238			
Total scale	Between	646.73	22	29.39	.58	.93
	Within	10935.97	216	50.62		
	Total	11582.70	238	12.06		

effects teachers and effects on students, no significant difference was found [($F_{student}$ = .74, sd = 234, p = .56) and ($F_{teacher}$ = 2.11, sd = 234, p = .14)]. Regarding the overall scale, a statistically significant difference was found between the 20-30 and 31-40 age groups in favor of the 31-40 group, and between the 20-30 and the 61-70 age groups in favor of the 61-70 age group [$F_{overall}$ = 1.32, sd = 234, p = .50].

2.c) Findings related to the research question of "Does the STEM awareness of teacher educators differ in terms of their academic title?"

ANOVA results are given in **Table 7**. The Scheffe test was chosen as the post-hoc test. Analysis showed that in the effects on the course sub-dimension, there were statistically significant differences between research assistants and assistant professors in favor of assistant professors, and assistant professors and associate professors in favor of assistant professors p<0,[Fcourse = 1.77, sd = 234, p = .13]. No statistical difference was found between groups in the effects on teachers and effects on students sub-dimensions, or total scale scores p>0, [($F_{student}$ = 2.26, df = 234 p = .0 6), ($F_{teacher}$ = .95, df = 234, p = .43) and (F_{total} = 2.11, sd = 234, p = .08)].

2.d) Findings related to the research question of "Does the STEM awareness of teacher educators differ significantly based on their specialty area?"

ANOVA results are presented in **Table 8**. As seen, no statistical significance was found between groups in all sub-dimensions ([($F_{student}$ (1.01) =. 45, p> .05, F_{course} (.44) =. 98; p> .05, ($F_{teacher}$ (.63) =. 89; p> .05 and ($F_{overall}$ (.58) =. 93; p> .05)].

Table 9. Results of ANOVA by department

Sub-Dimensions of the Scale	Source of Variance	Sum of Squares	sd	Mean Squares	F	p
Effects on students	Between	116.23	6	19. 37	1.64	.13
	Within	2731.30	232	11. 77		
	Total	2847.54	238			
Effects on the course	Between	51.94	6	8. 65	.96	.44
	Within	2078.34	232	8. 95		
	Total	2130.29	238			
Effects on teachers	Between	21.11	6	3. 51	.81	.55
	Within	997.50	232	4. 30		
	Total	1018.61	238			
Total scale	Between	453.27	6	75. 54	1.57	.15
	Within	11129.42	232	47. 97		
	Total	116.23	238			

2e) Findings related to the research question of "Does the STEM awareness of teacher educators differ significantly based on their department?"

In **Table 9**, ANOVA results are given. As seen, no statistical significance was found between groups in all sub-dimensions ([($F_{student}$ (1.01) =. 45, p> .05, F_{course} (.44) =. 98; p> .05, ($F_{teacher}$ (.63) =. 89; p> .05 and ($F_{overall}$(.58) =. 93; p> .05)].

3. Findings related to the research question of "What factors affect the STEM awareness of teacher educators?"

In the quantitative stage, the STEM awareness mean score of the participants was 60.30. This result shows that teacher educators had high STEM awareness. However, some participants scored very low and some scored high. To examine in-depth why they had different STEM awareness scores, interviews were conducted with the participants, who were selected through the extreme or deviant sampling strategy, which included cases with high scores and low scores. A semi-structured interview form was developed by the researchers. The form consisted of five themes, namely STEM readiness, STEM attitudes, importance of STEM, STEM interest and STEM-related activity. The themes were determined to guide revealing of the factors in the development of STEM awareness. Once the opinions of an expert in STEM were obtained, and one of the themes, "importance of STEM", was removed. The final version of the interview protocol included four themes. Some of the questions in the interview form were:

1. Could you give information about STEM education?
2. Do you think that STEM education should be included in Turkey?
If yes, how should it be? If no, why not?
3. Have you been involved in any STEM projects / activities?
If yes, what was your job description in the project / activity?
4. Do you read about STEM?
If yes, what kind of texts do you read? If no, can you briefly explain why?
5. On what sub-dimension of education, student, course or teacher, do you think the STEM approach has the most influence? Please list these from most to least important.

14 participants who had a STEM awareness score higher than 70.0 and 13 participants who had a STEM awareness score less than 26 were identified. Because of the Covid-19 pandemic, face-to-face interviews were not able to be conducted. Instead, the interview form was sent to the 27 participants though Google Forms, and 5 participants in the low group and six in the high group responded to the form. Regarding the responses given by the 11 participants, video interviews were conducted separately by means of the WhatsApp program, making it possible for in-depth discussion of some questions (for example, discussions were made in relation to the question, "Do you think that STEM education should be included in Turkey?"). The duration of the meetings ranged between 15-20 minutes. The final form of the data obtained through the interviews was recompiled and analyzed by the researchers. Participants with high scores were assigned to group H and those with lower scores to group L. Demographic information about the participants included in the qualitative stage is given in **Table 10**.

Table 10. Demographic information about interviewed participants

Gender	**f**	**%**
Female	5	45.5
Male	6	54.5
Academic title		
Professor	3	27.3
Assoc. Prof.	2	18.2
Asst. Prof.	2	18.2
Res. Asst.	4	36.3
Department		
Elementary Mathematics and Science Education	3	27.3
Secondary Science and Mathematics Education	4	36.3
Primary Education	3	27.3
Educational Sciences	1	9.1
TOTAL	11	100

Table 11. Codes related to teacher educators' views on the "STEM" approach

	Themes	**Codes**	**f**
High awareness group	STEM Readiness	Up-to-date	6
		Daily life	3
		Educational Value	1
		Contribution to teaching	1
		Other	1
Low awareness group	STEM Readiness	Up-to-date	4
		Daily life	3
		Educational Value	2
		Contribution to teaching	1
		Other	2

Table 12. Frequency of views on necessity of STEM in Turkish Curriculum

	Themes	**Codes**	**f**
High awareness group	STEM Requirement	Yes	5
		No	0
		Both yes and no	0
		Conditional	1
Low awareness group	STEM Requirement	Yes	3
		No	0
		Both yes and no	1
		Conditional	1

5 interviewees were female and 6 were male. Of these, three were full professors, four were research assistants, two were assistant professors and one was an associate professor. Four participants were working at secondary mathematics and science departments, three were at elementary mathematics and science departments, and three were at primary teaching departments.

The first question on the interview protocol designed to explore participants' views on STEM was "Could you give information about STEM education?". The frequency distribution of the responses they gave is displayed in **Table 11**.

These findings show that participants with high scores had high STEM readiness while participants with low STEM awareness had little prior knowledge about STEM. The following quotes from the participants can be given as examples of this interpretation:

H1: "STEM, by forming education with an interdisciplinary approach, helps students acquire the 21st century skills. With STEM education, students can further internalize knowledge."
H4: "… it is a teaching approach that aims to train STEM staff that will be needed in the future."
H5: "It is an approach that integrates science education with technology, engineering and mathematics to learn by doing."

L1: "A teaching approach that I think is exaggerated and that spreads like fashion, and is used for advertising and commercial purposes, rather than its scientific aspect ..."
L4: "I do not have much information about STEM. Although it may seem like something new, I think it is the approach that we have been talking about for years as interdisciplinary work and project production and that we want to foster in students."

The distribution of the participants' responses to the question of whether STEM education should be a part of the Turkish national curriculum is given in **Table 12**.

Table 13. Responses related to involvement in STEM projects

	Themes	Codes	f
High awareness group	STEM Activity	I am involved	4
		I'm not involved	1
Low awareness group	STEM Activity	Not at our university	1
		I am involved	1
		I'm not involved	4

In **Table 12**, while all of the participants with high STEM awareness stated that STEM was a need for the current curriculum, some of the participants with low awareness answered in the same way. Quotes from the participants are as follows:

H1: "Yes, it should definitely be. STEM is important and efforts to find its value and spread it in the national curriculum should be made. However, it is seen that all the necessary steps for STEM have not been taken yet. The priority of the Council of Higher Education in Turkey should be to ensure all STEM academics receive the necessary education to sustain the STEM approach (coding, Arduino, design, etc.), apply STEM activities and know how to act with the disciplines required for STEM, and to be able to prepare a lesson plan. But unfortunately, our academics were not prepared in this field and sufficient training was not given."
H3: "Yes, it should be taught as a 2-hour course at middle schools and high schools."
L3: "Both the Ministry of National Education and teacher education curricula should be reviewed. A spiral program should be adopted. STEM can be taught as a separate course in order to demonstrate the relationship between the disciplines. STEM should be started from primary school."
L5: "I think we are at the very beginning of STEM education right now. There is a tendency towards robotics fields in particular, but I don't think STEM logic is fully understood."

The participants' views on how STEM should be conditionally implemented in schools are as follows:

H5: "Although I think this approach is applicable in our education system, I do not think it is suitable for all age groups. Although learning by doing-living is an indispensable part of preschool education, which is my area of expertise, I believe that the basic field of engineering poses a problem in the application process in this approach. Considering the roles of families in the process, especially in the performance assignments applied in primary school, it can be said that this approach causes problems with expectation for the target audience."
L1: "I do not think it should be exaggerated, but rather it should or should not take place. If it is used correctly and nicely and it will work, of course it should be used."

Views of the participant who said both yes and no about the necessity of STEM are given below:

L2: "Yes, because I think it will contribute to students' knowledge of the engineering profession and to their scientific creativity, and it will be useful in schools as it will show all disciplines together as in daily life.
No, because I think both the readiness levels of the students and the teachers' knowledge of designing the necessary activities are not sufficient. There are a lot of misconceptions in the literature, and unfortunately, teachers' opinions are not clear on this subject."

The distribution of participants' responses to the question of whether they participated in any STEM project or activity at their university, and if they did, what their job descriptions were, is shown in **Table 13**.

According to **Table 13**, it is seen that the participants with high awareness participated in activities related to STEM while the participants with low STEM awareness mostly said they were not involved in STEM-related activities.

Some of responses of the participants were follow:

H2: "We worked on TUBITAK projects and postgraduate studies related to STEM."
H5: "TUBİTAK 4004 Project Instructor."
H6: "TUBİTAK 4004 Project Coordinator."
L2: "During my graduate education, I managed STEM workshops and worked as an educator in STEM teacher trainings supported by National Education Directorates."

One participants stated that no STEM project was carried out at the university where she worked, so he participated in STEM projects that different organizations carried out. Her quote is as follows:

H1: "Unfortunately, no STEM project has been carried out at our university. However, I was involved in STEM projects organized by the Ministry of National Education."

Table 14. Responses of the academics regarding the status of reading about STEM

	Themes	Codes	f
High awareness group	STEM Interest	Yes	5
		No	1
Low awareness group	STEM Interest	Yes	5
		No	0

Table 15. Participants' responses about having a STEM-related publication

	Themes	Codes	f
High awareness group	STEM Product	Yes	4
		No	2
Low awareness group	STEM Product	Yes	0
		No	5

Table 16. Answers about which of the training sub-dimensions the STEM approach contributed most to

	Student	Teacher	Course / Teaching	f
High awareness group	1st	3rd	2nd	4
	2nd	3rd	1st	2
Low awareness group	2nd	3rd	1st	2
	1st	3rd	2nd	2
	2nd	1st	3rd	1

* 1 = maximum, 2 = medium, 3 = minimum

In order to determine the interest of teacher educators in STEM, they were asked if they read any materials in the STEM field. The frequency distribution of the responses is shown in Table 14.

As seen in Table 14, five participants (83 %) with high awareness stated they read various sources related to STEM, while one participant said he did not read about STEM. Also, all of the participants with low awareness (100%) reported that they read about STEM. Some of their responses are presented below:

H1: "I follow articles for STEM. I also read the books on the market and use them for my classes. As a participant, I also follow videos to improve myself, articles on which activities are developed, and trainings organized by the National Ministry of Education for teachers."
H4: "… I follow the publications in academic journals. I also follow the books about the new STEM."
H6: "I still do STEM+ reading in curriculums developed for the STEM approach."
L1: "I follow the news about articles and STEM events. It doesn't interest me much."
L3: "I am trying to follow the relevant literature. I care about STEM. I read articles. I read activity books."
L5: "I read articles about application examples and projects abroad."

The response of the participant who stated that he did not read about STEM is as follows:

H3: "I did not feel the need to be too interested in STEM, a concept that emerged in the last years of my professional life."

Teacher educators were asked whether they had any publications on the STEM approach, and the frequency distribution is shown in Table 15.

In Table 15, findings indicated that participants with high STEM awareness had work related to STEM published, whereas those with low awareness were not involved in any STEM-related publication. Some of the responses of the participants are given below:

H1, H2: "Yes, I have one publication on STEM."
L4: "Yes, I have four STEM publications."
L6: "Yes, I have ten STEM-related publications."

The frequency distribution of responses about ranking the benefits of the STEM approach in the student, teacher and course / teaching sub-dimensions from most to least important are given in Table 16.

Four participants with high STEM awareness stated that STEM education would positively influence students, the course and teaching, and teachers, in that order. Two participants with high STEM awareness ranked the positive effects as the course and teaching, students and teachers, respectively. Two participants with low STEM awareness stated that STEM education contributed first to the course and teaching, then to the student, and lastly, to the teacher. Two teacher educators in the low group ranked the contributions as the student, the course and teaching, and the teacher, in that order. One participant with low STEM awareness stated that STEM education contributed mostly the teacher, then the student, and lastly, the course and teaching. These findings show that teacher educators with high STEM awareness believed that STEM education contributes more to students and the course and teaching, whereas teacher educators with low STEM awareness did not have any agreement on this issue.

CONCLUSION AND DISCUSSION

As a result of this research, it was determined that the participants of this study all had high levels of STEM awareness. This result is consistent with the results of Çolakoğlu and Günay-Gökben's (2017) study, in which they identified the STEM work of teacher educators with the deans of education faculties. Çolakoğlu and Günay-Gökben (2017) underlined that although the teacher educators' STEM awareness was high, their work on STEM was not sufficient. In this study, parallel with this finding, despite their high STEM awareness, teacher educators' STEM-related publications, projects and seminars were not at a satisfactory level. Studies that found teachers' STEM awareness to be high reported that the reason for the high STEM awareness was that in the content teaching course in the teacher education program, new teaching methods in the literature were emphasized (Çevik, Danıştay & Yağcı, 2017; Karakaya, Ünal, Çimen & Yılmaz, 2018). Because these courses were taught by teacher educators that were the subject of this study, it can be said that the results of this study were indirectly parallel with the findings of previous studies. By supporting the quantitative findings, the qualitative findings of this study underscored that teacher educators with high STEM awareness believed that STEM education was up-to-date and valued its educational importance rather than its popularity.

Additionally, in the study we examined whether teacher educators' STEM awareness differed according to their gender. However, parallel to the findings of studies with teachers (Bakırcı & Karışan, 2017; Çevik, Danıştay & Yağcı, 2017) and teacher candidates (Demir Başaran & Temircan, 2018; Karakaya & Avgın, 2016; Kırılmazkaya, 2017; Lin & Williams, 2016), no difference was found between female and male teacher educators' STEM awareness. However, there was a significant difference in teacher educators' awareness based on their age. Analysis showed that this difference was between teacher educators in the 20-30 and the 31-40 age groups, in favor of the 31-40 age group, in the sub-dimension related to the effects on the course. Also, it was found that teacher educators aged 61-70 had a higher awareness than those aged 20-30. These results are consistent with studies conducted with school principals and teachers (Ciğerci, 2020; Nadelson & Seifert, 2013). The results indicated that participants who had high STEM awareness had more work experience in the field of their study. As Margot and Kettler (2019) stated, age, gender and teachers' STEM experiences are the factors affecting their expectations from STEM education. In the qualitative part of the study, it was determined that the majority of the teacher educators with high awareness were more experienced ones. This case also supports the result of the quantitative part. It was also determined that the STEM awareness of the teacher educators was significantly different according to their academic titles. Further analysis revealed that assistant professors had higher awareness than research assistants and associate professors. The reason for this can be that the assistant professors may closely follow new approaches, teaching methods and techniques in the literature during their doctoral studies and their tenure track. Gökgöz and Ünsar (2009) reported that the habit for hard work that they gained during their doctoral studies, and their requirements to be appointed as assistant professors and to keep up with their colleagues caused assistant professors to engage in intensive work in their desire to advance their careers. In the literature it was reported that because research assistants do not have a course workload and are less experienced than faculty members, they will have different professional development needs (Moeini, 2003). Also, since research assistants are still at the beginning of their academic life and their interests are newly formed, they may not be willing to devote extra time to new approaches including STEM, as they are more likely to focus on master's or doctoral studies, and therefore, their awareness may be less than that of faculty members. As for associate professors, they may have a decrease in their awareness compared to assistant professors because they are no longer in the tenure tracking and read more on a specific field. It was also found that STEM awareness of teacher educators did not significantly differ based on their departments.

Bers and Postmore (2005) underscore that teacher candidates should be trained in using new methods and techniques effectively during their studies in undergraduate education. In this regard, it is necessary for teacher candidates to be taught the engineering process in teacher education programs, especially in science and technology teacher programs (Marulcu & Sungur, 2012). In this context, we found that participants with high STEM awareness stressed that STEM education needed to be included in the curriculum, whereas those with low STEM awareness did not. In the STEM Research Report published by the Ministry of National Education (2016), it is highlighted that STEM course activities should be integrated into the curriculum. Interdisciplinary integration is essential because of the 21st century requirements and problems requiring a multiple perspective. Therefore, it is important to develop educational programs by integrating the right disciplines (Bahar, Yener, Yılmaz, Emen &

Gürer 2018). At this point, it is a vital requirement that in the curriculum of STEM education, qualified teachers who implement a multi-disciplinary approach should be involved (Ramaley, 2007; Wang, 2012). In this study, it was found that STEM awareness was influenced by participation in STEM-related projects or activities and publishing scientific work on STEM. STEM awareness is a prerequisite for self-efficacy, interaction and self-improvement (Kovarik et al., 2013). This will influence the training of qualified preservice teachers who have 21st-century skills in teacher education programs. The National Institute of Education (2009) emphasized the characteristics of being innovative and entrepreneurial among the teacher competencies needed for the 21st century. It can be inferred from the results of this study that STEM awareness indirectly affects the entrepreneurship characteristics of pre-service teachers (Deveci, 2018).

On the contrary, preservice teachers' disinclination to use information in an integrated way causes disconnection between theory and practice (Gürsoy & Çinici, 2019). This disconnection may be rectified with STEM education, which allows them to use math and science concepts in engineering design and technology (Chamberlin & Pereira 2017). To make this happen, teacher educators who are responsible for the training of teacher candidates play a bridge role in the context of STEM.

One finding of this study indicated that teacher educators with high STEM awareness believed that the STEM approach contributed more to students and the course / teaching. As a matter of fact, Eroğlu and Bektaş (2016) stated that science teachers who have received STEM education are effective in improving student creativity with STEM-based lesson activities. On the other hand, participants with low STEM awareness did not clearly have any consensus about the effect of STEM education. Their low STEM awareness can be a reason for this disagreement.

LIMITATIONS

This study was carried out with 239 teacher educators working at 54 state universities in seven different regions of Turkey. Further studies can be carried out with more participants. Also, studies can investigate the STEM awareness of faculty members who work at different colleges, such as colleges of science or engineering, since STEM is a multi-disciplinary approach. It was left to the participants selected by the convenience sampling method to be included in the study. This may be one of the weak points of the study. It is because those who are interested in STEM research wanted to participate and this may have affected the result. However, there are also those with very low STEM awareness among those included in the study. In a different study a different method may be used to select the participants. In this way, the scientific quality of the study can be further strengthened. The objective of this study was to determine STEM awareness, and further studies can be extended to STEM attitudes, interest and skills. One limitation of this study was that in-depth face-to-face interviews could not be done due to the COVID-19 pandemic. Instead, answers were received with digital forms and discussions were made on these answers via WhatsApp.

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APPENDIX

STEM AWARENESS SCALE FOR TEACHERS

	Totally Agree	Agree	Not Sure	Disagree	Totally Disagree
Effects on Students					
1. STEM education contributes to the increase of hand skills of students.					
2. STEM education improves students' analytical thinking skills.					
3. STEM education motivates students for the lesson.					
4. STEM education increases students' problem-solving skills.					
5. STEM education practices increase students' self-confidence.					
6. STEM education supports students for gaining a critical perspective.					
Effects on The Course					
7. It is inevitable that STEM education will cause the lesson to be reflected on daily life.					
8. STEM training requires high-level materials.					
9. STEM education practices negatively affect class dominance.					
10. STEM education activities waste a lot of time in the lesson.					
11. STEM education activities should be included in the curriculum.					
Effects on Teachers					
12. STEM education makes it necessary for teachers to use technology in the lesson.					
13. STEM educational practices are an opportunity for teachers to improve themselves.					
14. Teachers should take an active role in STEM education activities.					
15. Teachers can easily plan STEM education for in-class / out-of-class activities.					

* The scale was developed by Çevik (2017).

EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 04
ISSN: 2468-4368

Infusing Computational Thinking in an Integrated STEM Curriculum: User Reactions and Lessons Learned

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Citation: Yang, D., Baek, Y., Ching, Y.-H., Swanson, S., Chittoori, B., & Wang, S. (2021). Infusing Computational Thinking in an Integrated STEM Curriculum: User Reactions and Lessons Learned. *European Journal of STEM Education*, 6(1), 04. https://doi.org/10.20897/ejsteme/9560

Published: January 15, 2021

ABSTRACT

This study describes the design and implementation of an integrated STEM + computational thinking (CT) curriculum, which was guided by project-based learning, for integrating CT in after-school programs. The study examined teachers and students' reactions to the curriculum and the challenges in implementing such a curriculum. Results show that most students and teachers reacted positively toward the curriculum. Main challenges to implementing such a curriculum were also identified. Lessons learned from the curriculum implementation are discussed. The study contributes to the integration of CT and development of CT in students. It also contributes to teacher professional development regarding CT integration.

Keywords: computational thinking (CT), integration of CT, integrated STEM, curriculum design, project-based learning (PBL), after-school programs

INTRODUCTION

What is Computational Thinking and Why is it Important?

Computational thinking (CT) is a fundamental skill that involves problem formulation, problem-solving, and scientific reasoning (Wing, 2006). CT is also a metacognitive process that involves sub-skills and dispositions for regulating complex problem-solving and modeling unobservable phenomena (Dwyer et al., 2014). Therefore, CT is considered the "third pillar" of scientific practice (PITAC, 2005) and is a fundamental 21st century skill (PCAST, 2010).

The integration of CT in K-12 for science, technology, engineering and mathematics (STEM) learning has the potential to improve science learning and increase student engagement in STEM learning via CT-embedded scientific inquiry (Yang et al., 2018). Integrating CT into the classroom helps prepare students for the future by encouraging creativity and problem solving (Fessakis et al., 2013). Although researchers have studied K-12 student mathematical thinking and scientific reasoning extensively (Bicer et al., 2015), the development of CT in K-12 students has received much less attention (Lye & Koh, 2014). The practice of CT in K-12 STEM learning is rarely studied (Sengupta et al., 2018). Moreover, currently CT is widely missing in K-12 STEM education (NRC, 2011). The question that researchers and educators in STEM education are facing is not *why* we need to integrate CT, but *how*. Therefore, it is critical to examine productive ways to integrate CT in K-12 STEM education.

LITERATURE REVIEW

CT is relatively new for many K-12 researchers and educators. However, the fundamental skills emphasized in CT are vital for STEM learning because of their relationship with the STEM disciplinary processes of modeling, reasoning, and problem solving (Sengupta et al., 2013). The STEM subjects also provide a natural context for CT learning (Grover & Pea, 2018). The Next Generation Science Standards (NGSS) recognized CT as a key scientific practice (NGSS Lead States, 2013), which has prompted various attempts to integrate CT into K-12 classrooms based on limited research (Stanton et al., 2017). Moreover, the National Science Board (2010) has also supported teaching CT in K-12 education. In addition, the review of CT integration in several European countries and the United States has shown that including "CT aspects in the curriculum is relevant in all countries" (Mannila et al., 2014, p. 9).

Integrating CT in K-12 Education

Recent attempts to integrate CT into K-12 education fall into three categories: a) the stand-alone addition of programming activities that support little to no subject content learning (Lye & Koh, 2014); b) integration that supports subject content learning "as ways to describe, make comparisons between, and test predictions about systems" in problem-solving (Wilkerson & Fenwick, 2016, p. 186); and c) integration aligned with the practice of STEM professionals showing students how professionals practice CT (Winthrop et al., 2016). Although different CT integration approaches have been reported (Israel et al., 2015), researchers generally agree that instructional support should be offered during the process (Sengupta et al., 2013).

Coding and programing activities are some of the popular integration approaches at the K-12 level. Scratch, a visual programming language, has been integrated into many classroom instructional activities to teach computing and programing to lower level elementary students, whereas Java or Python may be used to develop programming skills in older students (Israel et al., 2015). Research indicates that the integration of visual programming languages in K-12 classrooms can improve students' CT and computational practices (e.g., experimentation and iteration). However, the use of programming as the learning context in CT integration has led to the confusion that CT equates with programming, or that CT practice has to at least involve programming (Voogt et al., 2015).

More recent CT integration has focused supporting subject content learning, which is reflected in the view of CT as a necessary transdisciplinary skill (Wing, 2008). In practice, some science educators have had students focus on an ecosystem using CT to conduct experiments, whereas others have advocated the use of modeling physical phenomena to teach CT. Students can also be exposed to the work of STEM professionals which can help them apply CT skills, reflecting another view of CT that considers the human experience and creativity in CT integration (Wing, 2008).

Most previous CT integration in K-12 education has shown that CT was embedded in only one or two subject areas. More recently, researchers have adopted an integrated STEM education approach to solve problems (Yang et al., 2018). At the same time, in order to train teachers, researchers have started to include teacher professional development (PD) in their approach toward integrating CT in K-12 science inquiry (Elby et al., 2015). However, most teacher PD does not immerse teachers and students together in inquiry experiences (Wilson, 2013). As a result, critical teacher-student interactions are missing, which runs counter to the strengths of inquiry-based learning (Linn & Hsi, 2000).

Research indicates that CT can be effectively integrated into K-12 STEM education and inquiry (NRC, 2011). Most pedagogical approaches, such as problem-based hands-on inquiry, trial and error within science experiments, and guided arguments, are all used to integrate CT into K-12 education, and have been recommended for formal learning environments (NRC, 2011). However, these pedagogies can also be adopted in informal ones. In fact, running structured STEM projects in informal settings can provide a suitable learning environment to explore the integration of CT in STEM disciplines because both teachers and students have the time and opportunity for thoughtful and reflective engagement in complex projects (NRC, 2011).

After-School vs. In-School Programs

Formal (in-school) programs are structured and planned curriculum activities that are led and facilitated by trained personnel while informal (after-school) programs are less structured activities that often have no pre-designed learning objectives (Czerkawski & Hernandez, 2011). The systematical structure with pre-designed learning objectives of formal curricula entails the quality and complete coverage of subject content. The facilitation of the formal curricula by well- trained instructors is also a major advantage compared with that of the informal programs and curricula. Thus students can be expected to systematically learn and master fundamental subject content mapped to well established content standards with formal programs and curricula. However, all stakeholders including students, teachers, as well as industries have called for the reforms in formal curricula for the lack of changes accompanying the advances of the society (Stocklmayer et al., 2010). For example, the reform within a formal curriculum such as the implementation of a student-centered learning approach like the project-based learning for real world problem solving has always been challenging and faced with resistance (Marx et al., 1997). One reason for such challenge and resistance lies in the teachers' lack of time and expertise to explore innovative practice to implement the needed changes within a formal curriculum (Stocklmayer et al., 2010). The challenge in providing students with relevant problem solving and learning activities often results in an outdated curriculum that fails in equipping a workforce with desired skills.

Informal programs and curricula are highly adaptable and are an ideal context for bridging both formal and informal programs for STEM learning (Braund & Resiss, 2007; Fallik et al., 2013) while offering a semi-structured environment for hands-on, immersive, and authentic learning to occur. For an informal program and curriculum, its loose structure without pre-designed learning objectives nor the mandate for meeting the standard testing allows both teachers and students to explore a topic in a more relaxed way (Linn & Hsi, 2000). Thus informal programs and curricula provide an ideal learning context for experimenting interventions and innovative practice (Braund & Resiss, 2006). Researchers and practitioners are increasingly focusing on bridging informal and formal programs as both have advantages and disadvantages (Braund & Resiss, 2006; Fallik et al., 2013). Eshach (2007) suggested that bridging formal and informal curricula can be achieved by recognizing the advantages and disadvantages of both curricula and implementing the desired learning experience accordingly.

In after-school venues, students have the time to engage in complex projects that are better suited to nurturing CT than during the narrow windows of opportunity in formal settings. An after-school program is well suited to integrate CT in STEM learning, allowing students and teachers to work as partners so that everyone is learning collaboratively (Linn & Hsi, 2000). Community centers are particularly well-suited to informal learning as they offer a setting in which learning activities are typically expected over a sustained period of time. After-school settings also give teachers the freedom to experiment and not worry about class time being taken away. Additionally, there are too few K-12 students who are exposed to CT in non-school programs (PCAST, 2010). Thus, an informal, after-school setting could be the most appropriate, as well as needed for implementing a complex curriculum integrated with CT.

Productive CT Integration Environments

Productive CT integration lies in the design of the integration, whether it be the design of an activity, a lesson, or curriculum. As discussed in the NRC's (2011) report, most students find it highly motivating to work in teams with teachers and peers on a project, and students often develop the ability to communicate concepts with others, share resources, and develop the products with their peers. Therefore, the appropriate environment for integrating CT should support social interactions, cooperation, and collaboration (Chowdhury et al., 2018).

Project-based learning (PBL) is a constructivist instructional method that engages students in constructing knowledge and learning skills with teachers and their peers through "an extended inquiry process structured around complex, authentic" questions (BIE, 2017, para. 4). The PBL approach is also consistent with best practices for STEM learning such as providing students with opportunities that are authentic (i.e., participating in "real" science), inquiry-based, relevant to them as learners, and supportive and collaborative (NRC, 2005). PBL can guide the design and development of a productive learning environment and curriculum in terms of delivering the content and fostering the development of CT in elementary students with social interaction, teacher scaffolding, and hands-on activities in STEM learning. The PBL approach enables the design of hands-on activities that allow students to investigate relevant topics or problems and to learn through the active creation of final products. In PBL, all learning activities and objectives are driven by an overall guiding question. At the end of a unit, students showcase their final products, often through a competition or an exhibition.

Previous research has shown the advantage of engaging students in an integrated STEM learning environment that requires the application of multiple STEM concepts and skills as opposed to focusing on discrete subject areas (Wang et al., 2011). Teachers also benefit from such an integrated learning environment since it can serve to complement and even reinforce their existing curriculum. By designing inquiry environments in which CT is integrated with multiple STEM topics, teachers are less likely to feel that they are pulling time or materials away from other subjects, and by contrast they are helping solidify student learning comprehensively. Therefore, an integrated STEM+CT learning environment guided by PBL inquiry, which requires students to learn, explore, and apply more than one discipline to solve problems, would be productive for integrating CT for K-12 students. This is consistent with the claim that for K-12 students to develop CT literacy and competency, they must gain not only CT skills, but also a deeper knowledge of where CT is relevant, including disciplinary practice (Grover & Pea, 2018).

METHODS

Purpose of the Study

This study presents the design and development of a project-based STEM+CT curriculum for integrating CT in an after-school program as a backdrop and subsequently explores the users' (teachers and students) reactions to the curriculum. Two research questions were formed: How would teachers and students react to (think and feel about) the project-based integrated STEM+CT curriculum in an after-school setting? What would the challenges be when implementing such a STEM +CT curriculum in an after-school setting?

The PBL Guided STEM+CT Curriculum

The curriculum design team consisted of a group of interdisciplinary faculty members in educational technology, mathematics education, engineering, and a former NASA astronaut, as well as a school district STEM content supervisor.

The STEM+CT curriculum consisted of several PBL projects, which with a project topic and overview, a driving question and sub-questions, learning objectives and outcomes, student activities, and required resources. The driving question and sub-questions helped guide the learning process and hands-on inquiry. Content wise, the STEM+CT curriculum projects were designed for upper elementary (4th to 6th) grade levels since those students are developing abstract thinking (Inhelder & Piaget, 1958).

Table 1 illustrates two STEM+CT project-based projects. One is Life on Mars and the other is the Bridge Design. The Life or Mars and Bridge Design topics were chosen because both were relatively easy to integrate with different STEM subject content, were motivating (such as learning about Mars), or related to students' physical surroundings like building a bridge for a river in the students' local community, an active earthquake area. Both projects lasted eight-weeks and required students to integrate STEM subjects with CT to solve the overall driving question. The following table lists the essential components of each project in the form of the PBL-guided inquiry.

Table 1. STEM+CT Projects Guided by PBL

Projects	Life on Mars	Bridge Design
Description	Students research different forms of life and the Martian environment, design and assemble a robot to detect life on a simulated Mars.	Students research earthquakes and bridges, design an earthquake resistant bridge, and build and test their bridges under simulated earthquake conditions.
Outline	Week 1 to 4: Research forms of life and Mars; assemble a robot; learn to program; Week 5 to 8: Assemble, program, and test a robot; final competition	Week 1 to 4: Research earthquakes and bridges; Week 5 to 8: Design, build, and test a bridge; final competition
Learning Objectives	Students investigate life on Mars and how it can be detected; design and build a robot to detect life on Mars.	Students investigate bridges and earthquakes; design and build a bridge and test it under simulated earthquake conditions.
Driving Question	How can we detect life on Mars using a robot?	How can we build a strong bridge for the Mountain River to resist earthquake forces?
Final Product	An assembled/programmed robot	A bridge built with specified criteria
Sample Hands-on Activities	Assembling and programming a robot	Designing, building and testing a bridge
Assessment	Final competition in which robot detects life in the shortest time.	Final competition on which bridge is the strongest in resisting earthquake forces.
Resources Needed	Mindstorms LEGO (EV3) set; Laptops; etc.	K'Nex building kits; Laptops; etc.

The STEM+CT projects also included final learning outcomes, student activities, assessment, and required resources (**Table 1**). Both projects were designed for small groups of four to six students based on the sharing of project materials such as Lego Mindstorms kits, as well as the project tasks and available time. Both projects covered multiple STEM subjects and provided learning objectives based on the guiding question and its sub-questions. The overall driving questions were: How can we detect life on Mars using a robot? and How can we build a bridge for the Mountain (pseudonym) River that is strong enough to resist earthquake forces?

Learning Activities

The Life on Mars project was designed to engage students to practice and apply CT and integrate science, math, engineering, computer science, and technology through robotics and programming. Scientific knowledge and concepts (e.g., forms of life, the planet Mars) and robotics and programming concepts were introduced in the first four weeks. Students assembled robots using Lego Mindstorms kits and programmed the robots with Mindstorms EV3 software. The purpose of programming the robot was to find "water" (a green dot) on a surface that simulated

Figure 1. Assembled and programmed robot and simulated Mars

Mars, since water is most likely where life would be found. **Figure 1** shows a robot that was assembled and programmed by students.

The CT integration in this project was beyond the stand-alone addition of programming or coding. It supported students' learning of STEM concepts related to the Martian environment in order to solve the problem of how to use a robot to detect life on Mars. At the start of the fifth week, students assembled and programed robots, which were showcased in week eight in a race to detect life (the green dot in **Figure 1**). The team that found "life" in the shortest amount of time, won.

The Bridge Design project was designed to have students apply CT and integrate STEM through engineering design and bridge building. At the core of the engineering design process were: defining and identifying a problem; developing possible solutions; designing and testing prototypes; and making revisions (Chabalengula & Mumba, 2017). In this project, scientific knowledge and engineering concepts (e.g., earthquakes, bridges) were introduced in the first four weeks. Engineering design concepts (e.g., developing possible solutions and building prototypes) were introduced in later weeks while students were designing and building bridges. Starting in the fifth week, students built an earthquake-resistant bridge with K'Nex kits and prepared for a final competition. Each of the K'Nex pieces had an associated price tag, which the students used to keep track of bridge costs for the final competition. In the eighth week, students competed for the best bridge design judged by design specifications (width of at least 2 feet, height of at least 1.5 feet, having two towers, and meeting the pre-determined earthquake testing criteria) plus the cost.

Embedded with CT

To facilitate the integration of CT, the research team highlighted some CT components for student hands-on inquiry and problem-solving based on an extended review of literature (e.g., Brennan & Resnick, 2012; Grover & Pea, 2013, 2018). Subsequently, 11 CT components displayed in **Table 2** were embedded in both projects based on our curriculum's learning objectives and activities (see **Table 1**).

The STEM+CT curriculum focused on students' ability (e.g., practices) to solve problems using CT (Grover & Pea, 2018). The vocabulary and terminology (**Table 2**) focuses on student computational literacy and the use of appropriate CT terminology while communicating their thoughts and actions during scientific inquiry. CT vocabulary and terminology usage can overlap with math and science in a STEM+C learning environment. The majority of the CT components focuses on student ability to form and communicate problems (Grover & Pea, 2018) as well as solve problems (Wing, 2006). Specifically, abstraction, algorithms, conditional logic, data structures, analysis and representation, decomposition, and heuristics focus on the thought process and logic in problem solving. CT components of data collection, data structures, analysis and representation, pattern recognition, and simulation and modeling focus on students communicating and dissecting problems while creating and generating different questions, as well as resolving those questions. Communication focuses on both oral and written descriptions of student inquiries, usually supported by visuals, graphics, or simulations. Since the PBL approach emphasizes the importance of providing reflection and students voices, communication is one of the CT components highlighted and embedded throughout the curriculum design. **Table 2** also includes some curricular examples of each embedded CT components.

The following screen capture is an example of how CT components were embedded in student inquiry activities.

As shown in **Figure 2**, students collected data about Mars' environment via watching videos and reading websites (e.g., What Is Mars? by NASA) that were selected by the researchers. Students were also guided by questions during data collection and took notes about their findings. In one part of the curriculum, students worked independently and in groups of two to three in collecting data on Mars' environment. Students' data collection in this project involved gathering and obtaining data, and more importantly organizing them in the form of drawings or student-produced graphics. This organization was to identify the key characteristics and patterns of the data to answer a research question such as what the environment of Mars looks like. Finally, students presented their findings, along with the data they collected, to their peers (CT communication). The presentations were also

Table 2. CT Embedded in the STEM+CT Curriculum

CT Component	Description	Example of Embedded CT
CT vocabulary	Variables, data, modeling, testing and debugging, iterative, etc. (Brennan & Resnick, 2012; Lye & Koh, 2014)	Test, analyze, debug, retest, solution
Abstraction	Reducing complexity and generalizing from specific instances to make sense of things (An & Lee, 2014; Lee et al., 2011)	Identifying each of the characteristics of strong bridges
Algorithm	Applying specific set of tools or sequence of steps (processes) to solve problems (Yadav, Zhou, Mayfield, Hambrusch, & Korb, 2011)	Programming the Lego Mindstorms EV3's software blocks, testing and repeating until a task is competed
Communication	Written and oral descriptions supported by graphs, visualizations, etc. (Astrachan & Briggs, 2012)	Presenting research finding via Google slides or other visuals
Conditional logic	Using strategy such as an "if-then-else" construct to clarify problems and solutions (Wing, 2006)	Programming a robot using the if- then command/block
Data collection	Gathering data to define or solve a problem (Grover & Pea, 2013)	Gathering and analyzing the simulated Mars area to determine what path the robot should take
Data structures, analysis and representation	Exploring data to find patterns, causes, trends, or results to facilitate the knowledge construction and problem solving (Grover & Pea, 2013; CSTA, 2009)	Using distance and speed to determine the time a robot should move in a specific direction
Decomposition	Simplifying problems or specifying steps to solve problems (Catlin & Woollard, 2014)	Determining which Lego Mindstorms EV3's software blocks are needed for a robot to turn left or right, then programming the blocks, testing and repeating until the task is competed
Heuristics	Applying experience-based strategy that facilitates problem solving (Yadav et al., 2011)	Using the trial and error strategy while programming and testing
Pattern recognition	Recognizing repeated patterns such as iteration or recursion (Grover & Pea 2013, 2018)	Identifying the same characteristics of strong bridges from the data collected from different sources
Simulation and modeling	Manipulating data or concepts through controlled programs or exercises or creating such programs for data manipulations (CSTA, 2009)	Using an online program to simulate the strength of a bridge while varying the values of the input variables

CT component embedded in student activities:

- Data collection: Student collect data on the environment of Mars.
- Abstraction: Students identify main characteristics of the environment of Mars.
- Communication: Students present their findings on the environment of Mars.

Figure 2. Embedded CT components in the Life on Mars project

followed by a discussion to reach a consensus on the common key characteristics of the Mars' environment. Students applied the CT components of data collection, data structure, abstraction and communication to answer the research questions in the STEM+CT curriculum. In these activities, CT components of data collection, data structures, analysis and representation as well as CT communication were embedded through the curriculum design.

Another example of embedded CT in the curriculum is student practice of CT in problem solving. For example, students had to translate the measurements of distance or degrees into input values while programming a robot to go forward or to turn left or right. At the same time, the students had to interpret a physical action of a robot into programming languages such as using the if- then command, which helped students develop CT skills and logical thinking. The integrated STEM+CT curriculum provides student a learning context which was quite different than what they usually practiced in the classrooms. The integration of CT and the design of the curriculum, such as the built-in guiding questions and relevant resources for answering them, also supported student learning of science and problem solving. Descriptions of CT and more examples of embedded CT components in the curriculum can be found in **Table 2**. The examples of student practice of CT are centered on problem solving and engineering design activities.

Implementing the STEM+CT Curriculum

The implementation of the STEM+CT curriculum was led by in-service teachers working with small groups of students in community centers' after-school programs over eight weeks (two 90-minute sessions per week) for a total of 16 sessions. All STEM+CT curriculum materials were available via a Google site and shared with all teachers prior to the implementation.

The curriculum was implemented at two community centers' after-school programs. The community centers helped recruit 18 4^{th} to 6^{th} grade students for each of the projects on a first come, first served basis and a total of 36 students participated. The community centers were adjacent to a Title I (at least 45% of its students receive free or reduced lunches) elementary school. The community centers' staff escorted the students to the classrooms of their Title I schools where the project team and teachers would meet around 3:40 pm on the project days (Mondays/Wednesdays or Tuesdays/Thursdays).

Implementation Led by Teachers

The research team worked with the local school district, which helped recruit six teachers (three per project per location) to facilitate the implementation of two STEM+CT projects. Two weeks prior to implementing the projects at the community centers, the research team led two, three-hour PD sessions on CT, PBL, and the subject content of each project. In addition, a brief preview of the project's weekly sessions was provided. The teachers were directed to facilitate and guide the students during the implementation of the curriculum. The teachers assumed various roles such as a helper, motivator, facilitator, resources provider, co-learner, and a problem-solving guide. The teachers received a stipend, as well as two PD credits, from the researchers' institute for their participation and facilitation of the project. At least two researchers of the curriculum design team were present at each location during the eight-week period to facilitate them.

Data Collection and Analysis

Teachers were asked to write a weekly reflection after leading two sessions. The teachers were provided with specific prompts to guide their reflections and solicit their experience with the curriculum, students' reactions to it, and implementation challenges. The reflection prompts varied slightly from week 1 to week 8 as the project progressed but all six teachers in both projects had the same prompts. Each teacher's weekly reflection ranged from half to one and a half pages (single-spaced) with an average of 266 words.

Student focus group interviews were conducted at the end of the implementation to examine their reactions. Four focus group interviews (one interview with 3 students for the Life on Mars project and three interviews with 12 students for the Bridge Design project) were conducted. 14 students (11 boys and four girls) participated in four focus groups. **Table 3** presents an overview of the participants as well as the data sources.

Table 3. Participants and Data Sources

Participants	Projects		Total	Data Sources		Total
	Life on Mars	Bridge Design		Life on Mars	Bridge Design	
Teachers	3	3	6	Weekly Reflection (19)	Weekly Reflection (20)	39
Students	18	18	36	Focus Group (1)	Focus Group (3)	4

The focus group interviews were transcribed and prepared for analysis in Nvivo by one graduate research assistant. Teachers' reflections were imported into Excel for data analysis by another graduate research assistant. The two graduate research assistants then conducted a thematic analysis to examine the teacher reflections and student focus group interviews for themes by "identifying, analyzing and reporting patterns within data" (Braun & Clarke, 2006, p. 79) independently. The data analysis was then reviewed and roughly 30% of the reflections and interviews were analyzed by a faculty researcher. An inter-rater reliability of 96% based on the shared coding for the reflections, and a similar inter-rater reliability of 88% for the interviews were found, which were higher than the minimum acceptable threshold of 75% (Graham et al., 2012).

RESULTS

Student Practice of CT

Before presenting the research findings, we would like to share two examples of student work and student reasoning to further illustrate student practice of CT components, which aims to serve as a backdrop for understanding the teachers and students reactions to the curriculum as well as lessons learned from the curriculum design and implementation. The first example is a screenshot of a student's codes for programming the robot to follow a path leading to the "life" on a simulated Mars. In this example, students had to use or practice various CT components such as conditional logic (the if-then command) and heuristics (trial and error and debugging) to accomplish the task.

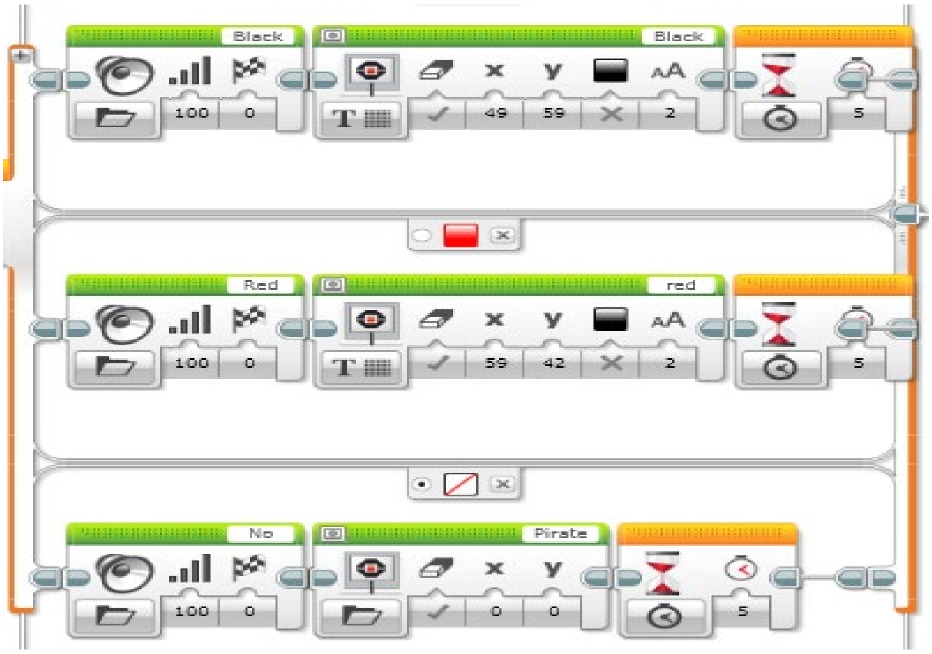

Figure 3. Student codes of programming a robot to follow a path

The second example provides a small vignette of student reasoning that took place during the discourse of problem solving. A student was testing his robot and seemed frustrated that it was not working after trying the same approach several times. A facilitator stepped in to find out what was going on and had the following conversation.

Facilitator: Okay, so read the problem. So, you're making the robot move straight at a speed of 60. That was… it's doing right there?

Student: I'm gonna put a speed of 100.

Facilitator: Now, what's the problem? Is it 60 or 100?

Student: 100.

Facilitator: No.

Student: I want it to be 100 because ...I'll know myself.

Even though this student was not following the written instructions to make the robot move at a speed of 60, he persisted in trying his own value and engaged in thinking on his own. The student had to reason abstractly and quantitatively while interpreting the physical action of a robot and translating the measurements of speed into programming. The trial-and-error approach gave him the space to test his own reasoning. More student work and artifacts demonstrating CT practice can be found in our recent report on elementary school students' CT practice in a bridge design challenge (Yang et al., 2019).

Teachers' Reactions to the Curriculum

Teachers in the Life on Mars project reflected that they mostly had positive experiences. For example, one teacher wrote, "*I was also impressed by the students. … It was great to see that some students had background knowledge on either life or robots. I loved seeing most of them excited and eager to get started on the project. The collaboration, discussion, and work ethic made me proud to be a teacher at their school.*" The teachers liked that all of the curriculum materials were online and readily accessible. For example, one teacher wrote, "*It helped … with the links [of the curriculum materials] readily available. It made transitions much smoother.*"

In the Bridge Design project, the teachers reported that students were more interested in doing the hands-on activities, rather than reading and researching. One teacher observed, "*Students are coming from a full day of learning (reading, writing, researching) at school and they want to participate in hands-on activities and have a REALLY hard time engaging in reading, researching and notetaking.*" The teachers also recognized acquiring foundational knowledge through researching was important for students to design and build an earthquake-resistant bridge. Due to students' low interest in research, a couple teachers proposed using videos instead texts. One teacher wrote "*… if students have to do research, then videos would be more engaging for students than reading heavy with words.*"

In the Life on Mars project, all three teachers described the beneficial outcome of their participation in the project from different perspectives. One teacher emphasized that she gained more confidence in teaching STEM concepts as a result of her participation. Another teacher stated that the project broadened her horizon on how much technology could be used in facilitating STEM teaching and learning. The third teacher would like to add more STEM activities and facilitate them in her classroom. In the Bridge Design project, all three teachers reflected that they would incorporate similar hands-on activities in their own classrooms. One teacher wrote, "*This experience enhanced my skills in STEM and CT. I will bring this teaching experience to my third grade classroom. I learned a lot and [my learning] will transfer to many areas*."

Students' Reaction toward the Curriculum

In the Life on Mars project, all three teachers reflected that students were very excited and engaged in the activities, especially the robot activities. One teacher pointed out that the introduction of the driving question (see **Table 1**) had helped students realize the importance of having background knowledge before they conducted hands-on activities.

In the Bridge Design project, the teachers reported that students were not fully engaged in the discussions and readings in the first session. One teacher provided a possible reason for the students' low engagement as "*Session 1 was incredibly rushed, as there was no time allowed in the lesson plans to meet/greet the new students and then the rest of the readings and discussions were rushed*." However, all teachers pointed out that the students were more engaged in conversations among themselves and enjoyed exploring different types of bridges in the second session.

In the Life on Mars project, students expressed positive reactions through an interconnected set of themes ranging from coding, building robots, learning about Mars, making new friends, working in teams, and having fun in the focus group interview. Even when students' efforts did not go according to plan, they still had fun participating in the activities as one student said "*I also liked the obstacle course we had to run through, even though we failed*." Another student appreciated the experience of learning how to code, "*I didn't know how to code before and I got to try something new*." Another expressed that what they (their peers) enjoyed most "*was learning how to use programming and making a robot move and sense things*." In the Bridge Design project, students similarly expressed having fun, enjoying the hands-on activities, and making new friends. Students described their experience as "*It's just fun playing with the K'NEX kit and building something with it*." All the students who were interviewed expressed that they had fun and hoped that they would be able to participate in similar projects again in the future.

In the Life on Mars project, students expressed frustrations with insufficient time in the sessions and noted how, consequently, they felt being rushed in the focus group interviews. One student stated, "*what I didn't like was that I was rushed in the last [activity]*." Other students explicitly commented on the timeframe, stating that they did not like "*how short it [each session] wa*s."

In the Bridge Design project, some students explicitly stated their views on research, "*I just think there is a breaking point of too much research*" and "*If you don't include the research, it is very fun*." In addition, students felt that the timing of the Bridge Design project was less than ideal because "*it was right after school. … it was hard to sit down to do the research….*"

Challenges in the Implementation

Insufficient Time

Throughout the implementation, the teachers kept reflecting that the time was insufficient to finish all the planned activities. The teachers often had to cancel the recommended 10 minute break in the middle of each session to make up time for the planned activities. For example, one teacher wrote, "*I believe the amount of tasks outlined in the lesson plans are still too ambitious and our group rushed through again to try and achieve all 3 challenges. The students were not given a break at all, …let alone the recommended ten minutes of break*." Similarly, another wrote: "*I think our biggest challenge with the project thus far has been time. I think the amount of material we're trying to squeeze into 90 minutes is really difficult*." The lack of time was also corroborated by observations from the researchers present at each session. After a few sessions, both the teachers and research team realized the issue of insufficient time. The teachers started to work on reducing some activities while keeping the learning objectives intact with the research team's help.

Complex Lesson Plans

As the curriculum was designed to weave together multiple disciplines, facilitating the sessions was challenging. The complexity of the lesson required teachers to go out of their comfort zone and sometimes to learn together with the students, which the teachers were not necessarily prepared for, or used to doing. Teachers from the Life on Mars projects pointed out this challenge, "*The biggest challenge was not being familiar with the [Mindstorms EV3] software. Next time, I would want to be able to … learn how to code myself. It would have helped me facilitate and support the students more effectively*." One teacher approached this challenge differently, however still not from the perspective of learning together with the students, as she wrote, "*I used my teaching skills to guide students through the activity. I encouraged them to* *use the resources available .... Although I didn't feel like I had much knowledge about the programming to help them, I was at least able to guide them to the correct resources so they could attempt to figure it out on their own.*"

The complex curriculum was also challenging for teachers facilitating the Bridge Design project. One teacher wrote, "*My biggest challenge was in figuring out how the K'Nex pieces work, but luckily, I had many students who could take that on easily.*" Similarly, another teacher reflected, "*I feel that the lesson plans are a bit complex (too many activities, too many readings) to accomplish during the allotted time, students and teachers feel rushed.*"

Students' Low Interest in Research

The low interest in research largely manifested in the first several weeks when the curriculum focused on the necessary background knowledge for solving problems later on. That was when students did not have many opportunities for hands-on activities. In the Bridge Design project, one teacher reflected at the end of the third week, "*I do feel like the students are starting to feel like this is not what they signed up for. I think they thought that there would be much more building involved (hands-on activities) and not so much reading and writing.*" Similarly, another teacher reported, "*I have a hard time motivating my students to read and write [taking notes for discussions] when they just spent an entire school day doing that. While we realize that this is essential, this amount of reading and note taking may be a better format for an engineering class during school hours, rather than an after school program.*" The same challenge appeared in the Life on Mars project:

> I gave them [the students] a choice of presentation materials to generate more interest, I tried questioning them as they worked and presented to see if they could clarify concepts…we did talk about being a critical reader and I showed them how to use the illustrations and headings on the websites to quickly find the information that they needed. Some of them were quite overwhelmed with the amount of information they needed to read through.

DISCUSSION

The hands-on activities in both projects focused on learning and applying CT, and learning STEM content as well as solving problems. For example, students learned about earthquakes, the engineering aspect of bridge design, and then designed earthquake resistant bridges based on the STEM knowledge acquired in the Bridge Design project. Similarly, students applied measurement skills (e.g., of angles, rotations, distance, and time) to program their robots in the Life on Mars project. One student summarized this succinctly when asked what he learned from his participation, "… *I learned that, I didn't know that you had to incorporate math and, uh, science and engineering. I thought it would be just building the bridge.*"

The curriculum inquiry was also supported by technology and tools. As technology-supported learning can enable students to engage in scientific practices, when students use the tools, technology, and computational techniques that real scientists use, students engage in career exploration and preparation. The design and development of a STEM+CT curriculum paves the way for future research on what CT looks like within and across disciplines, which is critical for CT integration in K-12 classrooms.

Finally, the implementation involved multiple stakeholders from higher education, the school district and schools, and community centers, which helped "build a broad base of leadership and ownership" to amass all necessary and resources (Stanton et al., 2017, p. 5); the involvement of multiple stakeholders also leads to long-term sustainability of CT integration across K-12 education.

Overall, the teachers in both projects had positive reactions to the curriculum and viewed their experience facilitating the curriculum as highly beneficial despite of some challenges presented herein regarding the design and implementation of such a complex curriculum. The students interviewed also reacted positively to the curriculum and expressed their desire to participate in a similar project in the future. Data analysis regarding the effectiveness of the curriculum in terms of students' learning of CT and STEM knowledge is ongoing.

CONCLUSIONS

Lessons Learned

As the curriculum design team (research team) was present at both implementation sites, they saw first-hand the challenges in implementing the curriculum. To overcome the time issue and ensure a relatively relaxing environment for both teachers and students, the researchers focused on the essential readings and materials for providing necessary knowledge while revising the curriculum following the first around of implementation. The overall structure of the curriculum (such as learning objectives and time frame) remained the same. During the revisions, some learning activities were fine-tuned and efforts to reduce reading materials and increase more hands-on activities were sought.

The research team also specifically allocated time for team building and icebreaking as well as time to introduce the overall guiding question for each project at the beginning of the revised curriculum. This helped ensure that the students and teachers would have the time to get to know each other and have an overall picture of the project before working with each other, regardless of the facilitator. The introduction of the project and the overall guiding question is very important to provide the background to students so that they would be motivated to do the necessary reading and research, rather than only wanting to do the activities.

For students' low interest in reading and research, in addition to the up-front introduction of the overall guiding question, the researchers also provided more videos and replaced some text materials with videos or graphics in both projects. While working with the teachers during the implementation, the researchers became more conscientious about making the curriculum materials "kid friendly" (e.g., more visuals) and more aligned to students' reading levels.

To help the teachers better lead such a complex curriculum/lesson plans, the research team made it clear that teachers were not expected to be subject experts; instead they could and should assume the various roles of learners, facilitators, or learners. Teachers were also encouraged to use materials outside of the curriculum to help students solve the guiding question. The research team also added specific questions for research and inquiry activities in different sessions so the learning objectives could be more focused on CT.

The research team also learned that it was really beneficial to be present during the implementation to provide timely assistance for the teachers and students. However, access to the research team and content experts would not be scalable. To help transfer and maintain the presence of content experts during the curriculum implementation in other settings, the researchers have added facilitation prompts/questions in hands-on activities provided by the experts during the curriculum revisions. The additional facilitation questions/prompts were intended to help teachers better facilitate hands-on activities while students were exploring and solving various problems.

Communicating CT: The Problem-Solving Process Chart

One critical lesson the research team learned was that it was necessary to explain and communicate what CT was to teachers so that they could better facilitate the integration of CT in STEM learning. In revising the curriculum, the researchers created a problem-solving process (PSP) chart mapped with CT components (**Figure 4**) and included it as part of the curriculum (Yang et al., 2018). The PSP chart was based on the K-12 engineering design processes of identifying and researching problems, developing and selecting solutions, building prototypes, testing, evaluating and redesigning the solutions as needed (Chabalengula & Mumba, 2017). The PSP chart helped the researchers communicate with the teachers, and relate CT to the problem-solving processes for practice so that teachers shared the same understanding of CT and its affordance in STEM learning. Specifically, the PSP chart would serve three purposes: 1) helping researchers share common ideas on what CT was among

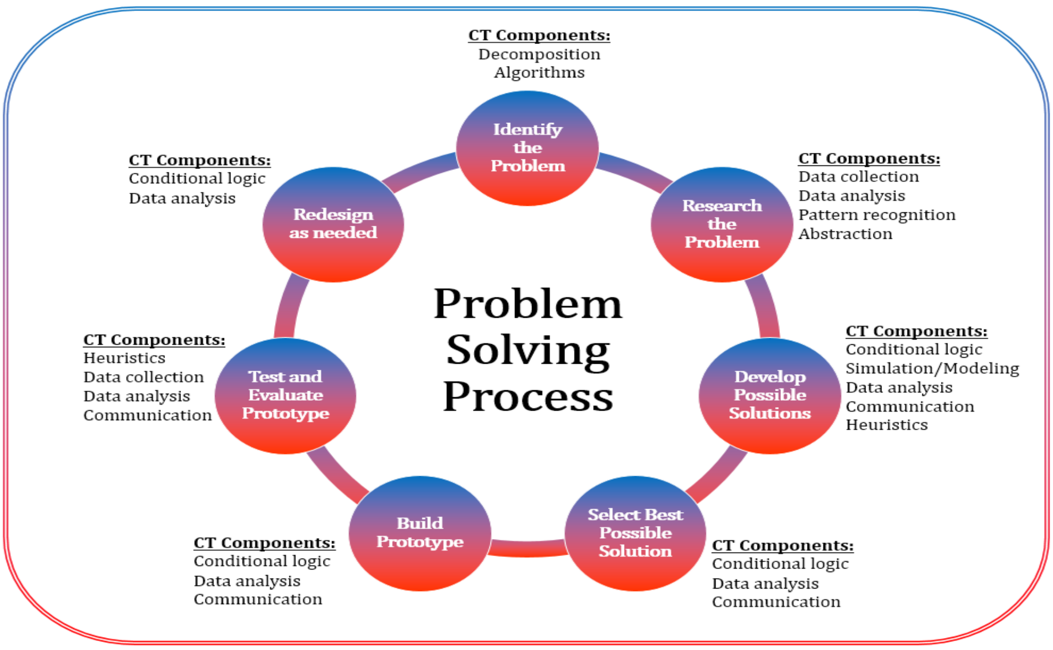

Figure 4. The PSP chart

themselves and with teachers; 2) helping teachers understand what CT was and how to explain CT to students; and 3) providing a means for students to reflect and recognize what CT applications and practice were in learning the STEM content and solving problems.

In **Figure 3**, 10 CT components, such as decomposition, abstraction and conditional logic that focus on forming and solving problems, were mapped on to one or more engineering design processes based on engineering practice and engineering design thinking (NRC, 2010). However, it should be pointed out that the mapping of one CT component on to a specific engineering design process does not mean that this CT will not be used in other processes. From our observations and preliminary findings (Yang et al., 2018), the manifestation of CT practices is very much dependent on the specific tasks at hand. During the implementation, the teachers would pull out the chart and direct students to talk about and discuss what they had learned and practiced by referring to it at the end of each session. The following screen capture shows the guiding questions the teachers used to help students reflect on their learning in the revised curriculum (**Figure 5**).

End of Session Reflection and Debriefing: 5-10 minutes

Teacher briefly explains the computational thinking (CT) skill embedded in the problem solving process. Using the Problem Solving Process diagram, the teacher will ask students to identify what kind of problem solving skills/process/computational thinking they used in this session and explain how they used it. The following are some sample questions that can guide the debrief.

- What did I learn today?
- What problem solving skills/processes or CT components I used today in this diagram?
- How did you use the problem solving skills/processes/CT components?

Figure 5. Guided reflection and debrief

For K-12 students to develop CT literacy, they had to learn to use CT and recognize the applications of CT across disciplinary domains, which the PSP chart could serve as a tool helping achieve this purpose.

This paper contributes to the design and development of CT-rich STEM programs for K-12 students and the effort to develop CT in students in terms of "positioning CT in the curriculum" (Voogt, et al., 2015, p. 722). Specifically, it provides a curricular example for integrating CT in cross-disciplinary practices. The integrated approach could also help make CT integration in K-12 classrooms and STEM curriculum more sustainable by learning and covering several content areas and standards simultaneously. The paper also contributes to teacher training and PD for CT integration involving various stakeholders.

However, there are some limitations associated primarily with the context of the study. First, the findings and lessons learned resulted from an informal context in a community centers' after-school program and may not apply to formal classroom settings. Second, the lessons learned involved various stakeholders (teachers, students, researchers, and community partners) which all impacted the findings, and thus they may not be able to inform other programs that involve different stakeholders. That being said, the researchers speculate that similar challenges could persist in formal settings and time would always be an issue, as well as the teachers' challenges in facilitating such a complex curriculum. Third, different or additional coding categories might emerge in the data analysis if the diversity in study contexts were increased. Therefore, additional research regarding the design and implementation of a STEM+CT curriculum in different contexts of study and participants is needed. Future research on what CT and computational practices may look like in different areas of STEM professional practice for K-12 students is recommended. Studies on how technology and tools can support the application of CT and development of CT in students, as well as research on evolving approaches to assessing CT are highly recommended.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 05
ISSN: 2468-4368

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Hybrid and Online Synchronous Delivery of Environmental Engineering During COVID-19 Pandemic: A Comparative Study on Perception, Attitude, and Assessment

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Citation: Karim, M. A. (2021). Hybrid and Online Synchronous Delivery of Environmental Engineering During COVID-19 Pandemic: A Comparative Study on Perception, Attitude, and Assessment. *European Journal of STEM Education*, 6(1), 05. https://doi.org/10.20897/ejsteme/9688

Published: February 7, 2021

ABSTRACT

Hybrid and online synchronous delivery of courses is a time-demanding approach to teaching and learning systems that is designed to engage students in investigations of authentic concepts or problems without coming to the pre-assigned classrooms two or three times a week. This study presents perceptions and attitudes of students that attended a hybrid course in environmental engineering that suddenly converted to an online synchronous delivery due to COVID-19. It also presents an assessment of the hybrid and online synchronous delivery approach on the final exam scores as well as the final grades of the same course. The course, 'Introduction to Environmental Engineering', was developed as an online course for Civil and Environmental Engineering program students and delivered with hybrid and online synchronous options due to COVID-19 pandemic for several semesters to test the concept. In the hybrid delivery set up, all the quizzes and homework assignments were online while the midterm and final exams were in-class. For spring 2020 the final exam was online and for summer 2020 both the midterm and final exams were online due to COVID-19 adjustment. At the very end of the semesters, an online anonymous survey was conducted with five questions to understand the students' perception and attitude on exam taking options and learning environment. Students' perceptions and attitudes about online synchronous delivery approach compared to hybrid delivery approach, as well as the learning outcomes, appeared at face value not to be favorable. However, statistical analysis revealed that differences between online synchronous delivery and the Pre-COVID-19 hybrid delivery were not significant, indicating that, at least for these engineering students, online synchronous delivery is a justifiable option.

Keywords: hybrid, online synchronous delivery, COVID-19 adjustment, students' perception and attitude

INTRODUCTION

Internet-based and online teaching and learning is becoming popular and was needed during COVID-19 pandemic. The relatively recent advent of Learning Management Systems (LMS), such as blackboard, Desire2Learn (D2L), eCollege, Moodle, and WebCT, and systems for offering lectures via MS Teams, Zoom and other platforms in the undergraduate setting in educational institutions has made it easy to provide online education, that is, web-based enhancement to traditional (face-to-face) classroom instruction (Rutter & Matthews, 2002). This online, hybrid or other mixed delivery approach allows instructors to combine the advantages of online class learning with the benefits of face-to-face interaction with relatively limited technological requirements on their part (Edling, 2000). The addition of a hybrid/online approach to the existing hybrid or face-to-face lecture-centric environmental engineering course is not supposed to reduce the quality of teaching and learning and would be welcomed and well received by students (Karim, 2016; Black, 2002). Preliminary reports suggest that the hybrid approach provides significant benefits for students and instructors, regardless of their level of technological expertise (Black, 2002; Brakels et al., 2002) and regardless of whether the classroom is hard-wired for live Internet access (Bento & Bento, 2000). Despite frequent use of an LMS for course administration purposes (content and lecture delivery), the instructors do not appear to be harnessing the full pedagogical potential of web-based augmentation via LMSs. The potential of LMS tools along with other online and mobile technology platforms to increase course administration/lecture delivery efficiency and maximize or enhance learning in traditional settings is an important educational issue that must be fully authenticated from both instructor and student perspectives (Papadakis et al., 2017; Papadakis et al., 2018; Woods et al., 2004). However, combining multiple modalities for online content delivery with a *pot pouri* of hybrid learning exercises that appeal to several learning styles may precipitate higher overall learning outcomes (McCray, 2000).

Theoretical Background

Traditional perception of teaching and learning in all levels is usually a face-to-face approach. Due to advancement of technology and internet connectivity teaching has evolved. In order to keep up with the technological advancement and new generations' mindset traditional teaching moved away and web-based teaching found its way in the past decades. Although course delivery using either a hybrid or online approach may increase time demands and, in some cases, result in a loss of control, many instructors enjoy this approach because it allows for significant flexibility and benefits in instructions. Due to COVID-19 in March 2020 course delivery for many institutions worldwide had to change to online synchronous and/or asynchronous formats, and exams had to be administered online and/or use an alternative assessment process.

This study was designed to answer two questions: (1) What are the students' perceptions and attitudes about the online synchronous course delivery along with online exam-taking options and online platforms as a learning environment? (2) Is there any effect of course delivery approach changes due to COVID-19 pandemic on students' performance levels?

To answer the above questions, two objectives of this study were formulated. The first objective was to understand the students' perceptions and attitudes about online synchronous course delivery along with online exam-taking options and online as a preferable learning environment for future environmental engineering courses. The second objective was to see the effect of COVID-19 change in the students' performance levels. The first objective was accomplished via an anonymous online survey and the second objective was accomplished with statistical analysis of final exam scores, weighted average GPA, and the overall course grades. The goal of this study was to understand the overall effect of COVID-19 pandemic on students' perceptions and attitude about an online synchronous course delivery and to assess the performance level, as well as to compare the performance levels between hybrid (Pre-COVID-19) and online synchronous (Post-COVID-19) course delivery options. The following sections outline the intervention, study methodology, instruments used, data collection and analysis, results and discussions, and finally conclusions and recommendations.

Intervention

Intervention simply means purposeful actions by a human agent to create and implement change. As we all know that end of 2019 and early in 2020, a pandemic of coronavirus (COVID-19) broke out in China and then spread globally. In the USA, spring semester starts in January and ends in May. Due to public health advisory and presidential Corona virus taskforce guidance, the education institutions in the USA had to make several changes in the course delivery in order to limit the spread of COVID-19. Within two weeks of this advisory, the educational institutions had to come up with an approach that would meet the guidance (6-ft social distance, washing hands, and face covering) without interruption of education. Several options were thought out such as converting all the courses to 100% online, either asynchronous or synchronous. Asynchronous delivery calls for video recording of lecture sessions and posting them in LMS. Since all faculty were not trained to be online instructors, synchronous option was chosen, with some training sessions for the faculty how to use MS Teams, Zoom, or Blackboard Collaborate for online synchronous delivery platform. That is how our university ended up delivering all courses online synchronous since mid-March 2020. The parameters for optimum group forming strategy, content design, effectiveness measurement, meta-analyses, impact of technology on PBL, implementation framework, alternative assessment in PBL, and other procedures for optimum learning that are acceptable to students and instructors were elaborated from the literature (Albanese & Mitchell, 1993; Berkson, 1993; Blumenfeld et al., 1991; Diehl et al., 1999; Frank et al., 2003; Karim, 2015; Krajcik et al., 1994; Moursund, 1999; Mills & Treagust, 2003; Ravitz &

Blazevski, 2014; Strobel & Van Barneveld, 2009; Thomas et al., 1999; Vernon & Blake, 1993; Watson & Fang, 2012; Boubouka & Papanikolaou, 2013).

METHODOLOGY

The course, 'Introduction to Environmental Engineering', was developed as an online course for Civil and Environmental Engineering program students but taught as a hybrid (50% time in-class lecture and 50% time online self-paced) before COVID-19 (Pre-COVID-19) pandemic and online synchronous during COVID-19 (Post-COVID-19) pandemic for several semesters, to test the concept. In the hybrid course set up, all the quizzes and homework were online while the midterm and final exams were in-class. The spring 2020 final exam was online and during summer 2020 both midterm and final exams were online due to COVID-19 adjustment. The following two subsections outline the type of instruments used and the type of data collected and analyzed to accomplish the objectives of this study.

Instrument

To understand the effect of COVID-19 on the perceptions and attitudes of students learning (the first research question), an online anonymous survey via D2L was conducted at the end of the semester with five questions. The survey questions are presented in **Figure 1**. The first two questions were meant to investigate the students' perceptions and attitudes about the course content and alignment delivered with online synchronous approach although no changes were made in the course content and other alignment. The third question probed an alternative assessment process using technologies and investigated students' perceptions and attitudes about the challenges of conducting online closed book exams using a lockdown browser and webcam, as most of the traditional students were not familiar with these technologies. The fourth and fifth questions were to understand the students' perceptions and attitudes about several test taking options (alternative assessments) and levels of learning. The second instrument used investigated the final exam scores, weighted average GPA, and the overall course grades to assess the students' performance level and to compare the students' learning environment between hybrid (Pre-COVID-19) and online synchronous (Post-COVOD-19) delivery (the second research question).

Q.1. Did tests reflect material covered in the class? ☐ Yes ☐ No

Q.2. Is there a good agreement between the course outline and the course content?
☐ Yes ☐ No

Q.3. Do you like the Online Midterm and Final Exam Through D2L using Lockdown Browser and Webcam (5 being the highest)?
O 1 O 2 O 3 O 4 O 5

Q.4. Do you want the Midterm and Final Exam be as?

- **Option 1**: Get the questions from D2L, print it, take it, scan, and submit it in Submission Folder without proctoring
- **Option 2:** Take home exam for a day or two
- **Option 3:** 100% online with Multiple Choice Questions like a quiz
- **Option 4:** 100% online and get the questions in D2L like a quiz, take the exam like quiz and do the detail work in papers proctoring with webcam, scan the papers in pdf and submit the papers in submission folder

Q.5. What kind of learning perception do you have due to the change of the course from face-to-face to online due to COVID-19?

- **Option 1:** Learned same as hybrid/face-to-face
- **Option 2:** Learned more in online than hybrid/face-to-face
- **Option 3:** Learned less in online than hybrid/face-to-face

Figure 1. Survey questionnaire for hybrid/remote offerings of Environmental Engineering

Data Collection and Analysis

The data collected through the online survey was analyzed to understand students' perceptions and attitudes about the course content and alignment, online exams using technologies, the exam-taking alternatives, and the degree of learning. The data that was collected and used to assess the performance levels was the final exam scores (maximum minimum, and average) and the overall course grades (Letter grades and weighted average GPA considering A = 4.0, B = 3.0, C = 2.0, and D = 1.0). F-grade was not included in the assessment as the students only receive an F-grade when they stop coming to the class or drop out after the deadline. The data was collected for the spring and summer 2020 semesters as online synchronous delivery and compared with data from the summer and fall 2019 semesters as hybrid delivery. There was a total of 34 students enrolled in summer 2019, 35 in fall 2019, 48 in spring 2020 (2 sections), and 33 in Summer 2020 semesters. Overall, 76 (about 51%) students participated in the survey for all 4 semesters. Nine students (about 26%) participated in the survey for summer 2019, 15 (about 43%) in fall 2019, 29 (about 60%) in spring 2020, and 23 (about 70%) in summer 2020. Seventy-four (74) students (about 49%) did not take the survey because the survey was not mandatory, and no incentive/grade points was given for taking the survey. Final exam scores, weighted average GPA, and the overall course grades were statistically analyzed and compared for differences between Pre-COVID-19 and Post-COVID-19 delivery. The analysis of data was performed with simple statistical tools and excel using goodness-of-fit tests such as ANOVA, χ^2-tests, student *t*-tests, and *F*-tests, as necessary. The results of the data analysis are illustrated in the following section and in **Figure 2** through **Figure 6**. Some of the responses to questions/options/choices, as seen in the figures, do not sum up to 100% as a few students did not respond to all questions or select all options or choices.

RESULTS AND DISCUSSIONS

Course Content and Alignment

For Q.1, overall, about 92% agreed that tests materials reflected what was covered in the class (**Figure 2**), both before and during the COVID-19 situation. The highest score was for the summer 2020 class (96%), followed by spring 2020 (93%), summer 2019 (89%), and fall 2019 (87%).

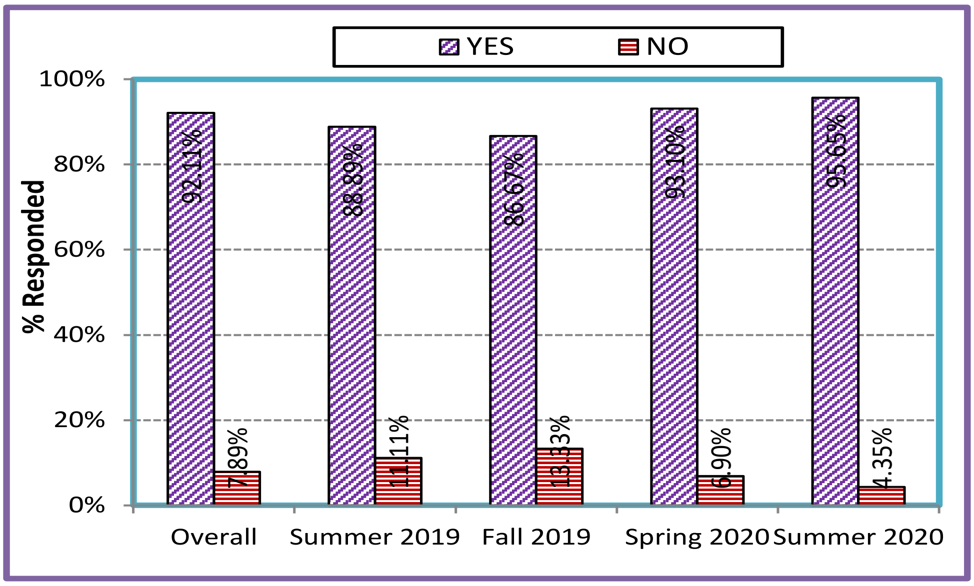

Figure 2. Distributions of responses for Q.1

The distributions of Q.2 responses are presented in **Figure 3**. It can be seen that, overall, about 93% of the students, participating in the survey, agreed that is there is a good agreement between the course outline and the course content, with the highest score (100%) for summer 2019, followed by fall 2019 and spring 2020 (93%), and summer 2020 (91%). It is apparent that students' perceptions and attitudes about the course content and the alignment were consistent and similar for the Pre-COVID-19 and Post-COVID-19 situation.

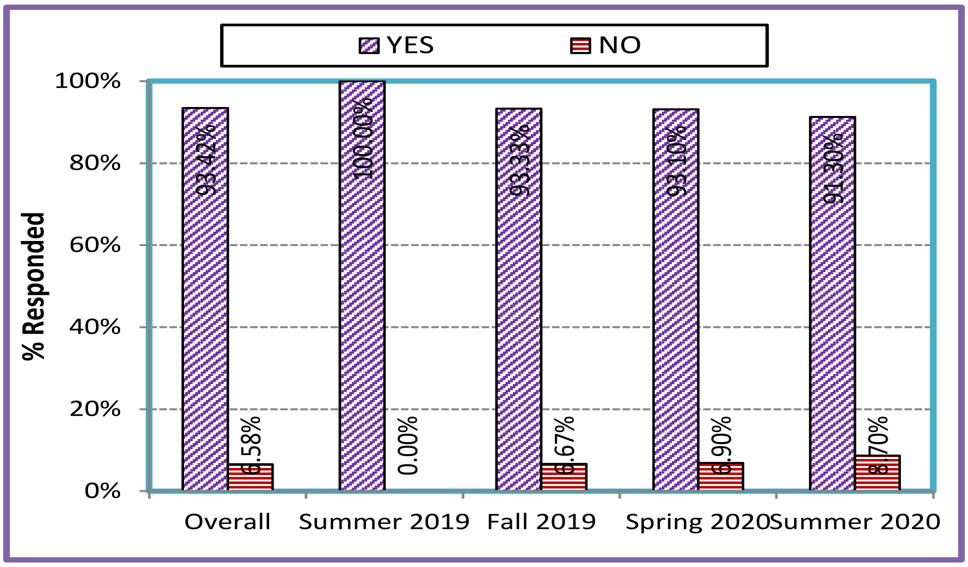

Figure 3. Distributions of responses for Q.2

Online Exam Using Technologies

The weighted average response to Q.3, as to how the participants liked to take online midterm and final exams through D2L using Respondus Lockdown Browser and Webcam, was 2.83, which is close to the middle, with only a minority (25%) of students being positive and declining from spring to summer 2020. (see **Figure 4**; there were of course no values for summer 2019 and fall 2019). About 7% of the participants did not answer this question. It is clear that online examination with lockdown browser and webcam is not popular, presumably because it can be cumbersome to make the lockdown browser and webcam work, depending on the computer and the individual knowledge of computer operations.

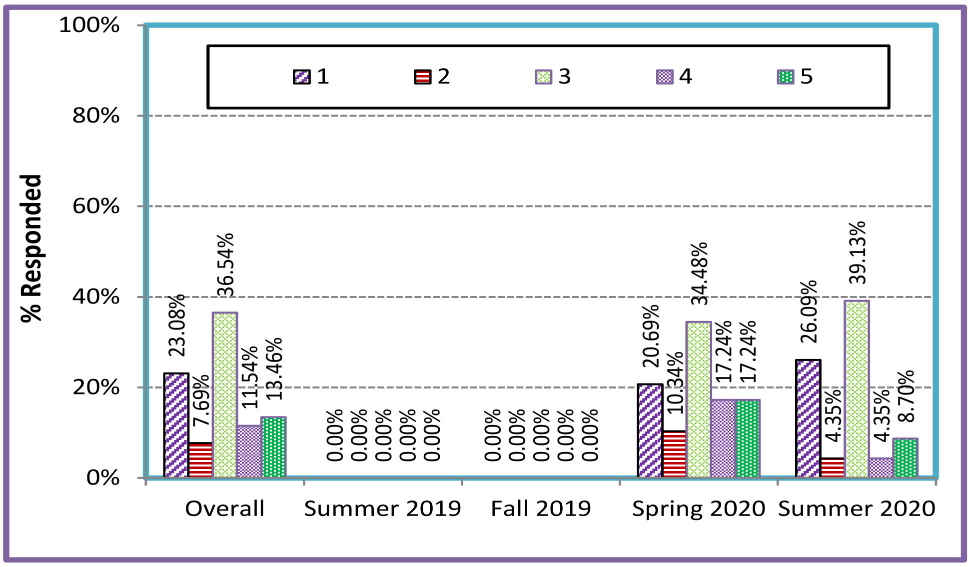

Figure 4. Distributions of choices of the participants for Q.3

Alternative Evaluation and Learning

Regarding Q.4 on preferences for the midterm and final exams, 17% of the participants chose option 1: "Get the questions from D2L, print it, take it, scan and submit it in submission folder without proctoring", 37% chose option 2: "Take-home exam for a day or two", 13% chose option 3: "100% online with Multiple Choice Questions like a quiz", and 25% chose option 4: "100% online that is get the questions in D2L like a quiz, take the exam like quiz and do the detail work in papers proctored using webcam, scan the papers in pdf and submit the papers in submission folder" (see **Figure 5**). About 8% participants did not answer this question. Option 2 (take-home exam) has the highest score, whereas students' preference for online quizzes seem to decline from spring to summer.

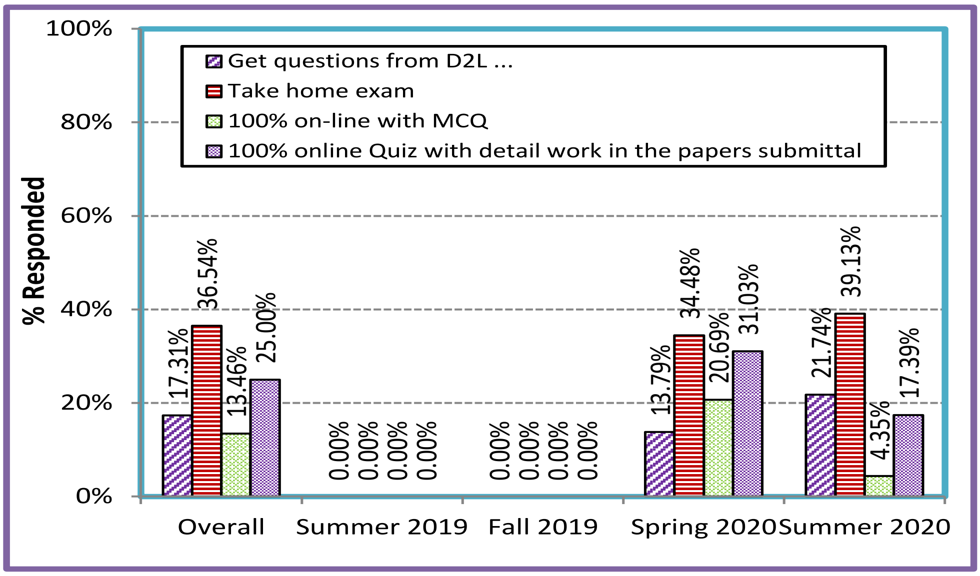

Figure 5. Distributions of responses of the participants for exam delivery options (Q.4)

This could indicate that the students prefer to complete the test in their own time with the possibility of external help, as it has to be open book; and that this creates less anxieties than being watched by someone or a webcam. However, this cannot be confirmed until a take-home exam is conducted and evaluated.

To check the face-value outcomes above, a chi-square goodness-of-fit test was performed to validate or reject the null hypothesis "no differences from semester to semester and among four exam-taking options". The chi-square test data are shown in **Table 1**. From the chi-square test, a p-value of 0.2913 was obtained, which is greater than both 0.05 (α = 5%) and 0.01 (α = 1%). A χ^2-value of 3.7371 was also obtained. For a degree of freedom of 3, the critical values for χ^2 are 7.81 (for α = 5%) and 11.3 (for α = 1%). The chi-square (χ^2) value is less than the critical values of both the significance levels. So, the null hypothesis cannot be rejected, and it cannot be concluded that the differences from semester to semester and among the four exam taking options are statistically meaningful.

Table 1. Chi-square goodness-of-fit test for Q.4 data

Semester	Observed Values					Expected Values				
	Option 1	Option 2	Option 3	Option 4	Total	Option 1	Option 2	Option 3	Option 4	Total
Spring 2020	4	10	6	9	**29**	5.438	11.479	4.229	7.854	**29**
Summer 2020	5	9	1	4	**19**	3.563	7.521	2.771	5.146	**19**
Total	**9**	**19**	**7**	**13**	**48**	**9**	**19**	**7**	**13**	**48**

p-value = 0.2913; χ^2-value = 3.7371; DF = 3, χ^2-critical = 7.81 (for α = 5%) and 11.3 (for α = 1%)

To verify this, a single factor ANOVA was performed, and the data is presented in **Table 2**. Since $F < F_{critical}$ (in this case, 2.1538 < 6.5913), the null hypothesis indeed cannot be rejected.

Table 2. ANOVA for Q.4 data

Group	Sum	Count	Average	Variance	*Source*	*SS*	*DF*	*MS*	*F*	*p-value*	*F-crit*
Option 1	9	2	4.5	0.5	*Between group*	*42*	*3*	*14*	*2.154*	*0.2362*	*6.591*
Option 2	19	2	9.5	0.5	*Within group*	*26*	*4*	*6.5*	---	---	---
Option 3	7	2	3.5	12.5	*Total*	*68*	*7*	---	---	---	---
Option 4	13	2	6.5	12.5							

Regarding Q.5 on learning, 29% of the participants chose option 1: "Learned same as hybrid/face-to-face", 15% chose option 2: "Learned more online than hybrid/face-to-face", and 48% chose option 3: "Learned less online than hybrid/face-to-face". About 8% participants did not answer this question. The distributions of Q.5 responses are presented in **Figure 6** and it seems obvious that students think they learned less online than in the hybrid or face-to-face conditions.

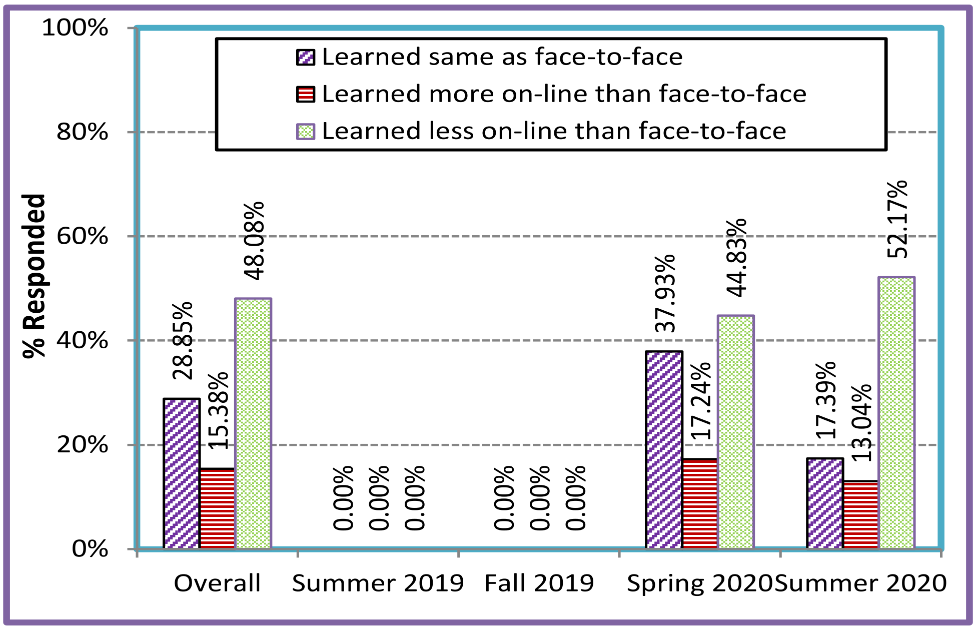

Figure 6. Distributions of responses of the participants for learning materials options (Q.5)

To see the variations of the three learning options for spring 2020 and summer 2020 (summer 2019 and fall 2019 were not included as these semesters were not a part of the remote offerings), a chi-square goodness-of-fit test was performed to validate or reject the null hypothesis "no differences from semester to semester and among three learning options". The chi-square test data are shown in **Table 3**. The *p*-value is too high and the χ^2-value is too low to reject the null hypothesis, so the differences between the semesters and among the three learning options are not statistically significant.

Table 3. Chi-square goodness-of-fit test for Q.5 data

Semester	Observed Values				Expected Values			
	Option 1	Option 2	Option 3	Total	Option 1	Option 2	Option 3	Total
Spring 2020	11	5	13	**29**	9.063	4.833	15.104	**29**
Summer 2020	4	3	12	**19**	5.938	3.167	9.896	**19**
Total	**15**	**8**	**25**	**48**	**15**	**8**	**25**	**48**

p-value = 0.4063; χ^2-value = 1.8015; DF = 2, χ^2-critical = 5.99 (for α = 5%) and 9.21(for α = 1%)

To verify this, a single factor ANOVA was performed, and the data are presented in **Table 4**. Since $F < F_{critical}$ (in this is the case, 4.0555 < 9.5521), it was confirmed that the null hypothesis cannot be rejected.

Table 4. ANOVA for Q.5 data

Group	Sum	Count	Average	Variance	*Source*	*SS*	*DF*	*MS*	*F*	*p-value*	*F-crit*
Option 1	15	2	7.5	24.5	*Between group*	*73*	*2*	*36.5*	*4.055*	*0.1403*	*9.552*
Option 2	8	2	4.0	2.0	*Within group*	*27*	*3*	*9.0*	---	---	---
Option 3	25	2	12.5	0.5	*Total*	*100*	*5*	---	---	---	---

Assessment

The analysis of assessment outcomes was based on the final grades for hybrid (summer 2019 and fall 2019) and online (spring 2020 and summer 2020) exam options. The data are presented in **Table 5**. From the chi-square test, a *p*-value of *0.0401* was obtained, which is less than 0.05 (α = 5%) but greater than 0.01 (α = 1%). A χ^2-value of *17.5994* was also obtained. For a degree of freedom (DF) of 9, the critical values for χ^2 are 16.9 (for α = 5%) and 21.7 (for α = 1%). Therefore, with α set at 1%, the null hypothesis cannot be rejected but when α is set at 5%, it can. So, with some uncertainty, it can be concluded that the differences in the final grades from semester to semester and between hybrid and online exam options are significant.

Table 5. Assessment based on final grades using Chi-square Goodness-of-fit test

Exam Option	Semester	Observed Grades					Expected Grades				
		A	B	C	D	Total	A	B	C	D	Total
Hybrid (Pre-COVID-19)	Summer 2019	10	14	7	3	**34**	8.04	14.01	9.65	2.30	**34**
	Fall 2019	9	18	5	1	**33**	7.80	13.60	9.36	2.23	**33**
Online (Post-COVID-19)	Spring 2020	9	13	22	4	**48**	11.35	19.78	13.62	3.24	**48**
	Summer 2020	7	16	8	2	**33**	7.80	13.60	9.36	2.23	**33**
	Total	**35**	**61**	**42**	**10**	**148**	**35**	**61**	**42**	**10**	**148**

p-value = 0.0401; χ^2-value = 17.5994; DF = 9, χ^2-critical = 16.9 (for α = 5%) and 21.7 (for α = 1%)

A second analysis of assessment was based on the weighted average GPA for hybrid and online exam semesters. The data is presented in **Table 6**. From the chi-square test, a *p*-value of *0.9974* was obtained which is greater than both 0.05 (α = 5%) and 0.01 (α = 1%). A χ^2-value of *0.0459* was also obtained. For a degree of freedom of 3, the critical values for χ^2 are 11.1 (for α = 5%) and 15.1 (for α = 1%). The chi-square (χ^2) value is less than the critical values of both 7.81 (α = 5%) and 11.3 (α = 1%). Therefore, the null hypothesis cannot be rejected so the differences in GPA from semester to semester and between hybrid and online exam options are not statistically significant. A *t*-Test and an *F*-Test performed for this parameter confirmed this.

Table 6. Assessment based on weighted average GPA using Chi-square Goodness-of-fit test

Exam Option	Semester	Observed GPAs	Expected GPAs	
Hybrid (Pre-COVID-19)	Summer 2019	2.9118	2.8458	*p-value = 0.9974*
	Fall 2019	3.0606	2.8458	
Online (Post-COVID-19)	Spring 2020	2.5625	2.8458	*χ^2 value = 0.0459*
	Summer 2020	2.8485	2.8458	
	Total	**11.3834**	**11.3834**	

The third analysis of assessment was based on the final exam Minimum, Average, and Maximum scores obtained by students in the hybrid and online delivery semesters. The analysis is presented in **Table 7**. From the chi-square test, a *p*-value of ***0.9959*** was obtained which is greater than both 0.05 (α = 5%) and 0.01 (α = 1%). A χ^2-value of ***1.3995*** was also obtained. The critical values for χ^2 are 12.6 (for α = 5%) and 16.8 (for α = 1%) for a degree of freedom of 6. The chi-square (χ^2) value is less than the critical values of both significance levels. Therefore, the null hypothesis cannot be rejected, and it cannot be concluded that differences between exam scores from the semester to semester and between hybrid and online exam options are significant.

Table 7. Assessment based on the final exam scores using Chi-square Goodness-of-fit test

Exam Option	Semester	Observed Values				Expected Values			
		Min	Avg	Max	Total	Min	Avg	Max	Total
Hybrid (Pre-COVID-19)	Summer 2019	30	58	88	**176**	30.05	56.98	88.96	**176**
	Fall 2019	30	67	100	**197**	33.64	63.78	99.58	**197**
Online (Post-COVID-19)	Spring 2020	35	55	95	**185**	31.59	59.90	93.51	**185**
	Summer 2020	30	57	87	**174**	29.71	56.34	87.95	**174**
	Total	**125**	**237**	**370**	**732**	**125**	**237**	**370**	**732**

p-value = 0.9659; χ^2-value = 1.3995; DF = 6, χ^2-critical = 12.6 (for α = 5%) and 16.8 (for α = 1%)

The summary of the goodness-of-fit test analyses is listed in **Table 8** for four different types of data. Based on the goodness-of-fit test and ANOVA it was apparent that students' perceptions and attitudes about the four different exam-taking options and three different learning options did not differ significantly, although face-value analysis of the responses suggested otherwise. The analyses of the final exam scores (maximum, minimum, and average), weighted average GPA, and the overall final grades confirmed that the observed differences were not big enough to say that outcomes differed significantly. The only value that proved significant (and only at the 5% level) was the difference between the final grades for the hybrid (2019) and the online (2020) exams.

Table 8. Summary of Goodness-of-fit test analyses

Data Type: χ^2-*Test*	*p-value*	χ^2-*value*	*DF*	*Critical Value* *0.05*	*Critical Value* *0.01*	χ^2-**Test Comment**
Students' choices for four exam options (Survey – Q.4)	0.2913	3.7371	3	7.81	11.3	*p*-values are greater than both 0.05 (α = 5%) and 0.01 (α = 1%) and χ^2-values are less than the corresponding critical values. The differences are not significant.
Students' choices for three learning options (Survey – Q.5)	0.4063	1.8015	2	5.99	9.21	
Weighted average GPA	0.9974	0.0459	6	12.6	16.8	*p*-values are greater than both 0.05 (α = 5%) and 0.01 (α = 1%) and χ^2-values are less than the corresponding critical values. The differences are not significant.
Final exam scores (Min., Avg, Max.)	0.9659	1.3995	6	12.6	16.8	
Final Grades	0.0401	17.5994	9	16.9	21.7	*p*-value is less than both 0.05 (α = 5%) and greater than 0.01 (α = 1%) and χ^2-value is greater than 16.9 (α = 5%) and *p*-value is greater than 0.01 (α = 1%) and χ^2-value is less than 21.7 (α = 1%). Differences are significant at the 5% uncertainty level.
Data Type: *t-Test*	*p-value*	*t-value*	*DF*	$t_{critical}$ *(two tail)*		*t*-**Test Comment**
Weighted average GPA	0.2237	1.7413	2	4.3026		Since *t-value* is within $-t_{critical}$ and $+t_{critical}$, the null hypothesis cannot be rejected. The observed values are not big enough to conclude that differences are significant.
Data Type: *F-Test*	*p-value*	*F-value*	*DF*	$F_{critical}$ *(one tail)*		*F*-**Test Comment**
Final Grades	0.3055	0.2708	1	0.0069		Since *F-value* > $F_{critical}$, the null hypothesis is rejected. Therefore, variances of the two populations, hybrid and online exam options, are NOT equal.
Data Type: *ANOVA*	*p-value*	*F-value*	*DF*	$F_{critical}$		*ANOVA* **Comment**
Students' choices for four exam options (Survey – Q.4)	0.2362	2.1538	3	6.5914		Since $F < F_{critical}$ (in this is the case, 2.1538 < 6.5914), therefore, the null hypothesis cannot be rejected. The four exam taking options are statistically equal.
Students' choices for three learning options (Survey – Q.5)	0.1403	4.0555	2	9.5521		Since $F < F_{critical}$ (in this is the case, 4.0555 < 9.5521), therefore, the null hypothesis cannot be rejected. The three learning options are statistically equal.

CONCLUSIONS AND RECOMMENDATIONS

From the data of this study, it can be concluded that a project-based or problem-based learning (PBL) course with alternative assessment options without physical contact, such as oral assessment or take-home exam can be introduced and implemented during COVID-19 without harm to the students' learning and performance. In this study, an effort was made to understand the students' perceptions and attitudes with regard to the learning environment as well as their performance levels in environmental engineering for the changes in the course offerings due to COVID-19 in the middle of spring 2020. Students agreed that the course content in the online format was aligned with the content of assessment, but their perceptions and attitudes about learning in online environment and taking online exams using technologies (respondus lockdown browser and webcam) appeared to be not favorable. Students' choice was the take-home exam. Fortunately, it could not be proved by statistical analysis that the online synchronous approach significantly degraded the level of students' performance, although face value analysis suggested that online synchronous delivery approach does not maintain the same level of students' performance. It is the author's opinion that PBL delivery with take-home exam, as preferred by the students in this study, along with other alternative evaluation processes (cf. Boubouka & Papanikolaou, 2013) can be adopted to maintain the students' learning and performance at pre-COVID-19 levels.

STUDY LIMITATIONS

A source of bias for this study could be the fact that the author was the only person who designed this study, conducted the survey, collected the semester end data, analyzed the data and had, as a teacher, an interest in a positive outcome. Another limitation is that all students were in the same engineering program, making it unclear whether the outcomes would be the same for other STEM students. The last limitation is the number of students involved to test the hypotheses. Perhaps, with a larger sample, face value differences do become significant.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 06
ISSN: 2468-4368

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The Development and Evaluation of a Tool to Determine the Characteristics of STEM Activities

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Citation: Okulu, H. Z. and Oguz-Unver, A. (2021). The Development and Evaluation of a Tool to Determine the Characteristics of STEM Activities. *European Journal of STEM Education*, 6(1), 06. https://doi.org/10.20897/ejsteme/10894

Published: May 8, 2021

ABSTRACT

STEM activities integrate various disciplines and are organized around domain-specific concepts and skills. What is achieved in terms of learning is related to how well the important STEM education characteristics are reflected in the implemented and integrated activities. This study aims to develop and evaluate a measurement tool for determining the characteristics of STEM activities by using a case study method. The STEM Activity Evaluation Form was developed based upon a literature review and experts' opinions. The observation-based form was applied to 21 different STEM activities, grouped in four categories: curiosity arousing activities, encouraging and upskilling activities, research and design projects, and one science fair. Students in science education partook in the activities in an eight-month period. The evaluation form has four categories: STEM learning environment, activitation of students, STEM content and practices, and connecting STEM. Application of the form revealed that the tool is useful to determine the appropriateness of activities with respect to the nature of STEM education.

Keywords: STEM education, STEM activity, STEM activity evolution form

INTRODUCTION

STEM (Science, Technology, Engineering, and Mathematics) education plays a significant role in the economic development for both developed and emerging countries (Kennedy and Odell, 2014). It not only supports the development of a STEM-capable workforce (Honey, Pearson, and Schweingruber, 2014) but also has the potential to increase inventiveness, scientific discovery, and efficiency in STEM disciplines (Modi, Schoenberg, and Salmond, 2012).

Many instructional approaches and practices like inquiry-based learning, project-based learning, argumentation and reasoning, digital learning, computer programming, and cooperative learning are used in STEM education as well as in the STEM disciplines themselves (Bender, 2016; McDonald, 2016). Scientific inquiry is an essential element of those practices. It reflects how scientists come to understand the natural world and how students learn science (National Science Teachers Association [NSTA], 2018). In science education, scientific inquiry is defined as a way of thinking that includes content knowledge and procedural processes. Over time, the definition has expanded and evolved a structure that includes knowledge and hands-on/minds-on approaches (National Research Council [NRC], 2000).

The integration of disciplines is also critical for STEM education. As the highest level of integration, the transdisciplinary approach aims to shape learning experience and combines knowledge and skills from at least two STEM disciplines to apply to real-world problems and projects (English, 2016). Engineering has a unique role among discipline integrations in STEM education. Moore and Smith (2014) defined STEM integration as participating in engineering design and developing technologies that require meaningful input from mathematics and/or science. The potential benefits to students of engineering integration in STEM education are (1) fostering science or/and mathematics learning and achievement, (2) better understanding of engineering as a discipline, (3) increasing the ability to engage in engineering design, (4) supporting engineering as a career, and (5) increasing technological literacy (National Research Council [NRC], 2009). Design-based engineering integration includes domain-specific concepts and skills and promotes engineering habits of mind (Honey et al., 2014). Engineering design-based practices contribute to the development of problem-solving skills (Morrison, 2006). It increases students' understanding of how things work and supports their ability to use technology (Bybee, 2010). STEM education which includes all these elements is high-quality STEM education (Bybee, 2013; Kelley and Knowles, 2016). High-quality STEM education has a great impact on students' achievement, disciplinary knowledge, and ability to make connections between disciplines (Honey et al., 2014).

In summary, high-quality STEM education makes ample use of scientific inquiry and engineering design practices, supports technology usage, integrates knowledge and skill from various disciplines around real-world problems, and shapes the student learning experience.

Using this description of high-quality STEM education as a framework outlines the characteristics of STEM activities. A STEM activity is a tool to transfer this framework to learning outcomes through teaching processes. Studies evaluating the effects of STEM activities on the learning outcomes are frequently found in the literature (e.g., Ball, Huang, Cotton, and Rikard, 2017; Barrett, Moran, and Woods, 2014; Damar, Durmaz, and Onder, 2017; Tippett and Milford, 2017; Torres-Crespo, Kraatz, and Pallansch, 2014; Yamak, Bulut, and Dundar, 2014; Wendell and Rogers, 2013). Barrett et al. (2014) reported significant increases in meteorology and engineering knowledge among high school students in the interdisciplinary STEM modules. Damar et al. (2017) investigated how robotics-based STEM activities affect middle-school students' attitudes towards STEM. Pre- and post-test results showed that the activities had a positive effect on students' attitudes. Yamak et al. (2014) demonstrated a significantly higher level of scientific process skills and attitudes towards science for middle-school students who attended the design activities. The reviewed studies provide evidence that STEM activities have great potential for achieving the learning outcomes. However, since STEM typically is integrated and holistic, it is not clear which of the many aspects of STEM education cause this positive impact on learning. An effective method to meet this challenge is to develop and use a diagnostic observation-based protocol (Yohalem, Wilson-Ahlstrom, Fischer, and Shin, 2009). Observation-based protocols typically include observation forms are can be used to evaluate specific elements, such as engagement in activities or reflection on learning (Schultz and Pecheone, 2015). However, the number of observation-based evaluation forms available for STEM activities is limited (Shah, Wylie, Gitomer, and Noam, 2018). Considering this limitation, the current study aims to develop and evaluate an activity evaluation tool that is compatible with the nature of STEM education.

METHOD

The case study method was used in this study. According to Merriam (2009), a case study is an in-depth description and analysis of a bounded system such as a single person, a program, a group, or an institution. In the current study, STEM activities were identified as the case. The research design is shown in **Figure 1**.

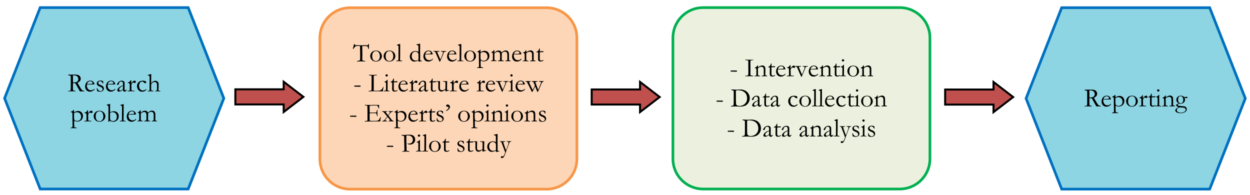

Figure 1. Research Design

Development of the STEM Activity Evaluation Form

In order to develop the STEM Activity Evaluation Form, the first step was examining studies in the literature that provide answers to the following questions: (1) What are the basic or constituting elements of STEM education? (2) How is the overall quality of STEM education measured? (3) How are STEM/science education programs elaborated into activities, such as projects? (4) How are STEM/science activities evaluated? and (5) Which classroom observation protocols are used to evaluate teaching and learning?

Table 1. Categories and Sub-Themes of the STEM Activity Evaluation Form

Category	STEM learning environment	Activation of students	STEM content and practices	Connecting STEM
Sub-theme	Organization Materials	Learning objectives Participation Engagement Evaluation	STEM disciplines STEM practices and scientific inquiry Reflection	Connection to real-life 21st century skills and attitudes

Table 2. Descriptions of Categories

Category	**Description**
STEM learning environment	The space and the materials should be available and organized to achieve learning objectives (Peters and Stout, 2006). The required time for the activity is an essential factor (Ainley, Pratt, and Hansen, 2006). Besides, a proper flow of activity steps prevents gaps, which negatively affect learning (Martin, Sexton, Franklin, and Gerlovich, 2014). Suitable materials for learning objectives should be accessible and complete for all participants (Harris, Miske, and Attig, 2004).
Activation of students	What students do in an activity is determined by the learning objectives. Students should be enabled to participate (Ainley et al., 2006). Each participant should be actively involved for effective STEM education (National Research Council [NRC], 2011). The activity should ensure that participants are involved both minds-on and hands-on (Fibonacci, 2013; PEAR, 2014; Pri-Sci-Net, 2014). The activity should be accompanied by formative assessment and evaluation techniques (Fibonacci, 2013).
STEM content and practices	Discipline integration plays an essential role in STEM education (Bybee, 2010). The engineering design process is essential in STEM activities (Basham and Marino, 2013). Mistakes are not negative. They are a vital part of learning (Hodson, 1988). Reflection on what the participants have learned provide evidence on the effectiveness of the activity. Thus, students should be encouraged to reflect (Harlen and Lena, 2013; PEAR, 2014). If the activity includes integrated engineering, artifact design is expected (Basham and Marino, 2013; Bybee, 2010). Scientific inquiry is one of the most common elements of STEM education. Activities can engage students in posing scientific questions, evidence-based thinking, and developing skills to identify existing ideas and analyzing and interpreting data. In this process, participants are expected to be aware that there is no ultimate solution to research problems. The participants should share their ideas and the evidence with peers and draw evidence-based conclusions (Harlen, 2014; Harlen and Lena, 2013; NRC, 2000).
Connecting STEM	STEM activities are connected to real-life situations and student are enabled to experience the relations between the activity, daily life problems and STEM solutions (Tseng, Chang, Lou, and Chen, 2013). Hence, the activity influences students' interest in STEM (Honey et al., 2014; Maltese and Tai, 2010). STEM activities can promote 21st century skills that are essential to the STEM workforce (Trilling and Fadel, 2009).

The first two questions meant to determine the characteristics of STEM education and evaluation of STEM education on the level of the curriculum or program. The third and fourth questions comprised the studies relevant for the development and evaluation of STEM/science education activities within specific programs or courses. The last question is even more detailed and focuses on concrete observation.

According to the literature, discipline integration plays an essential role in STEM education (Bybee, 2010). STEM education should include engineering design challenges of relevant technologies to develop students' problem-solving abilities and higher-order thinking skills (Moore, Johnson, Peters-Burton, and Guzey, 2016). Scientific inquiry promotes learning and success in STEM education (McDonald, 2016). STEM education studies focus often on learning outcomes such as attitudes (Wendell and Rogers, 2013), knowledge (Cotabish, Dailey, Robinson, and Hughes, 2013), and STEM interest (Mohr-Schroeder et al., 2014).

Pri-Sci-Net (2014), Fibonacci (2013), and The Partnerships in Education and Resilience (PEAR) Institute (2014) projects were prominent long-term and large-scale research projects focusing on the evaluation of STEM or science activities. The project outcomes contained many teaching materials and assessment tools relevant for this study. Pri-Sci-Net was a European Union (EU) funded project aiming to promote inquiry-based learning on a large scale in Europe and to develop inquiry-based science activities (Pri-Sci-Net, 2014). Fibonacci, a three-year project, aimed at dissemination of inquiry-based science and mathematics education throughout the EU. The project provided observation-based formative assessment tools for teaching practices (Harlen and Lena, 2013; Fibonacci, 2013). PEAR (2014) designed the Dimensions of Success (DoS) observation tool to evaluate the quality of out-of-school STEM programs. These dimensions are features of the learning environment, activity engagement, STEM knowledge and practices, and youth development in STEM. The observation-based protocols can be used to evaluate domain-specific teaching and learning in STEM/science activities (Schultz and Pecheone, 2015; Shah et al., 2018).

In the second step, the basic elements of science activities and STEM education were categorized into themes and sub-themes that were mentioned in the literature. Two researchers of science education independently classified the categorizes and sub-themes and worked out a consensus framework (see **Table 1**).

Table 1 represents the four categories and eleven sub-themes that resulted from the literature analyses and constitute the framework for the STEM Activity Evaluation Form. The first category or theme is 'STEM learning environment', which contains and organizes the space and the materials to be used. Hence, two sub-themes were defined: organization and materials. The second category is 'activitation of students' and describes how actions are related to learning. Hence, the sub-themes are learning objectives, participation, engagement, and evaluation. The third category is on 'STEM content and practices.' STEM teaching has a topic with multidisciplinary aspects; it evokes practices such as scientific inquiry, and students need to reflect in order to improve their learning. Hence, the sub-themes are STEM disciplines, STEM practices and scientific inquiry, and reflection. The fourth category is on 'connecting STEM.' STEM activities connect real-life problems to STEM approaches and solutions, which may develop more generic, or 21st century skills and attitudes of students. Hence, the sub-themes are connection to real-life and 21st century skills and attitudes. The descriptions of the categories are shown in **Table 2**.

Table 2 represents essential elements and characteristics of STEM activities that evolve from an analysis of the literature.

In the next step, these descriptions were transformed into 29 items to be used in the evaluation tool. The items were modified into a 4-point (0 to 3) observation scoring scale following the rubric specified by PEAR (2014). The criteria are presented in **Table 3**.

Table 3. Scoring of the STEM Activity Evaluation Form

Score	Scoring criteria
0	This quality has never been observed in the activity.
1	There is weak evidence that this quality is supported in the activity.
2	There is clear evidence that this quality is supported in the activity. However, the quality is not fully reflected in the activity, or it is not adequate to get 3 points.
3	This quality is observed in the activity based on compelling/consistent evidence.

After this step, the activity evaluation form was prepared for the pilot study. In this pilot, the form was applied by two researchers to two STEM activities. The Inter-Rater Reliability (IRR) value was calculated for the pilot study data. IRR refers to the degree of consistency between the scoring of two or more raters based on their observations of the same situation (Aiken, 2000). IRR values were 89% and 93% for the two activities, respectively. We concluded from these values that the STEM Activity Evaluation Form was reliable (Miles and Huberman, 1994). Thus, the activity evaluation form took its final version (see **Appendix A**). STEM education researchers and implementers/teachers are the target audience of the STEM Activity Evaluation Form. Users can evaluate STEM activities by observations. In this way, the limits and strengths of the activities can be revealed. Users of course need to have certain competencies with respect to STEM education to utilize this form validly. For example, two criteria in the STEM Activity Evaluation Form are "the activity includes STEM integration." and "the activity includes the engineering design process." In order to observe and score these two criteria validly, users should have sufficient understanding of STEM disciplines and the engineering design processes.

Participants

The data were obtained from STEM activities that occurred within the scope of an astronomy education course, conducted with 67 third grade science teacher candidates during eight months at a university in the Western Anatolia Region. The participants were divided into two groups as A (N=34) and B (N=33). All STEM activities were carried out in two groups. The research data were obtained by observing each activity in groups A and B. The purpose of performing the observations repeatedly for each activity was to improve the consistency of the research data.

Intervention

STEM education activities selected for investigating the STEM Activity Evaluation Form were chosen according to two criteria. First, the activity should be relevant to the learning objectives of astronomy according to the science curriculum as prescribed by the Turkish Ministry of National Education. Second, another STEM discipline, next to astronomy, is needed in the activity. In total, 21 activities were selected and categorized in four modules: curiosity arousing activities (1), encouraging and upskilling activities (2), research and design projects (3), and one science fair (4).

The module of *curiosity arousing activities* focused on astronomy, the known universe, and the connections between astronomy and STEM disciplines. It introduced students to naked eye and telescope observations and included trips to research laboratories and replica museum activities. These activities aimed to contribute to an understanding of the importance of scientific methods in astronomy, the use of advanced observation tools such as telescopes and other techniques and devices, and the relevance of social sciences for communication with STEM experts.

The *encouraging and upskilling activities* aimed to teach students about the design of artifacts such as basic observation tools, rockets, and holograms that are used in astronomy. The primary purpose was to foster STEM

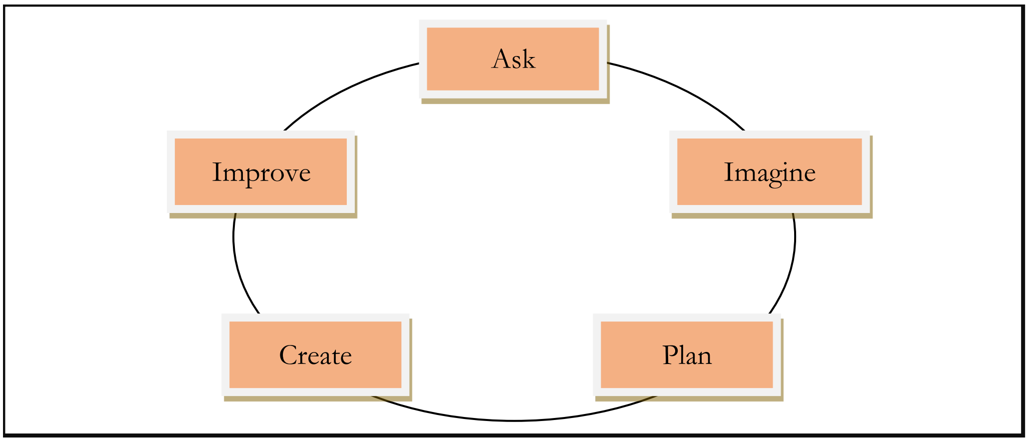

Figure 2. The engineering design process performed in encouraging and upskilling activities

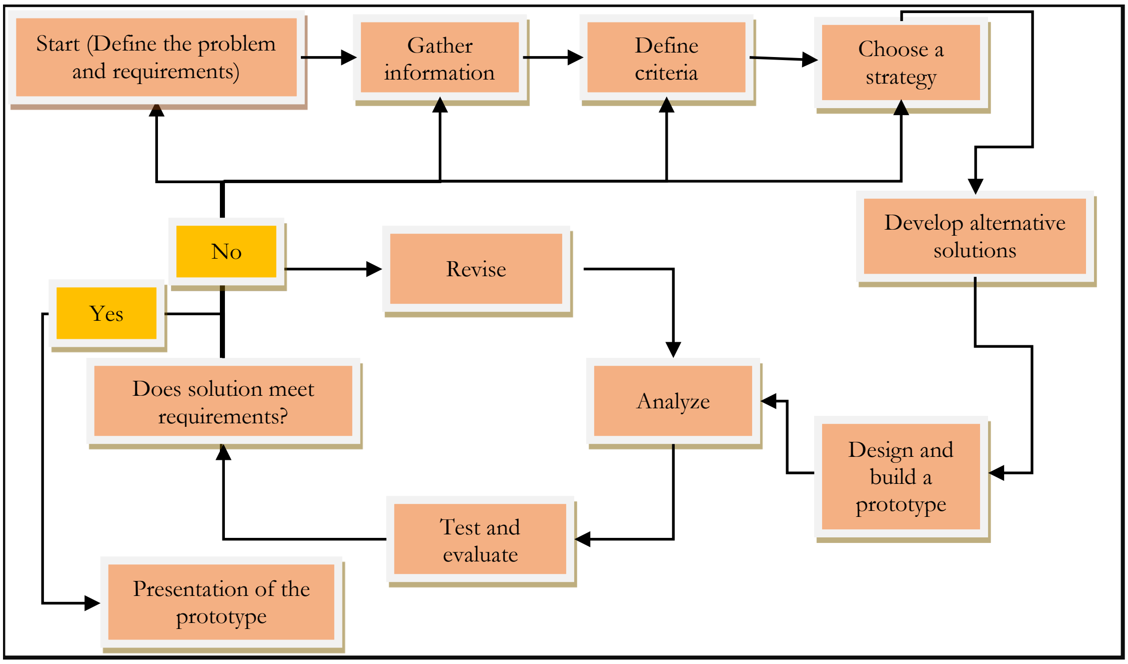

Figure 3. The engineering design process performed in research and design projects

skills of the participants using the engineering design process as proposed by Tayal (2013). A teaching format, this engineering design process is appropriate for a single one hour-long activity as well as for projects that last for several class periods (see **Figure 2**).

The engineering design process can be summarized as follows: In the first step ('ask'), the participants define the engineering problem, determine the requirements and constraints, and gather scientific knowledge essential for the solution. In the second step ('imagine'), the participants' ideas for the solution of the problem are expressed and discussed. The solution that best meets the requirements and constraints is selected. The third ('plan') step includes sketching the design and determining the material required for making a prototype. A prototype is constructed and tested in the fourth ('create') step. In the last ('improve') step, the prototype is redesigned and reconstructed according to the test results. This ends when the prototype meets the requirements. In this module, activities are organized individually or in group workshops using simple and inexpensive materials. The aim here is that the participants develop their STEM skills and also gain self-confidence by designing functional artifacts. As an example, the Telescope activity is presented in **Appendix B**.

The *research and design projects* focused on solving an engineering problem which was given by the teacher, or identified by participants in previous activities. In these activities, it is essential that participants use the necessary STEM skills gained in previous modules. For these medium and long-term projects, the engineering design approach recommended by Kampe and Oppliger (2012) was used. Participants were divided into teams and encouraged to use this approach in their projects (see **Figure 3**).

The steps in this design cycle can be summarized as follows. At the start, the problem is defined. Information about the problem is collected from various sources such as books, websites, or previous designs. The criteria, limitations, and restrictions are determined. Thus, the essential features of the design are determined. A flow plan,

Table 4. An Example of the Scores on Two Items for Two Activities

Activity	Item	Score	Observation, evidence, or example
Balloon Rocket	The activity includes the engineering design process.	3	In the activity, participants were given the task that they should carry a cargo (duster) 8 m away, using the thrust of the air within the shortest time. Participants performed all the steps of the engineering design process, such as defining the problem, revealing ideas for solutions, choosing a solution, drawing sketches, constructing a prototype, testing and evaluating the prototype, improving, redesigning, retesting, and re-evaluation the prototype. For example, after the implementer confirmed the sketches of the design, it was possible to create the prototype. Designing and sketching steps were the most time-consuming parts of the activity for participants.
Naked Eye and Telescope Observations	The activity focuses on artifact construction.	0	The activity focused on discovering the sky using a telescope. There was no artifact-oriented strategy in the activity.

including steps and strategies to be followed, is formed. Alternative solutions are developed and discussed. The solution that is most rational according to the criteria is chosen. A prototype is constructed. The prototype is analyzed to confirm compatibility with the design and is tested. After the test, the prototype is evaluated whether it meets all requirements and solves the engineering problem. If the criteria are met, the prototype has reached the final version and is ready for presentation. Otherwise, the prototype is revised, analyzed, tested, and evaluated, or the students fall back to one of the previous steps of the design process.

The *research and design projects* included student workshops and design challenges. The engineering problems of the projects were on how science works in space, how time can be measured in alternative ways, how we can reach space, how holograms work, and how we observe space. These problems do not have a single solution and encourage participants to use scientific research and design processes. It was essential to use STEM integration and collaborative teamwork to deal with these challenging problems. Moreover, the participants had to define the research and design stages and organize the design plan by themselves. The teams were given eight weeks for research and design projects. At least one discussion meeting was held with each team per week.

The *science fair* module included only one activity. The main aim here was to gain self-confidence through sharing designed artifacts in previous modules through interactive presentations and workshops.

Data Collection Process

A researcher collected data during the activities by taking the role of an external observer (Lodico, Spaulding, and Voegtle, 2010). The focus of the observations was the activity itself, not the activity plan or the competence of the teacher. The observer was a Ph.D. student experienced with classroom observation protocols in science teaching and had been in the same learning environment with the participants for three weeks.

Data Analysis

Activities were scored on the 11 items (the sub-themes as described above) on a four-point Likert scale (0, 1, 2, and 3). The arithmetic means of the scores were calculated and transformed into charts. Additional qualitative information was gathered by note taking during the observations. An example of the scores on two items for two activities is presented in **Table 4**.

RESULTS

Results for the Curiosity Arousing Activities

The results obtained for the five activities in the Curiosity Arousing module are presented in **Figure 4**.

What draws the attention in **Figure 4** are the relatively low scores for STEM content, scientific inquiry, and engagement. All other sub-themes were scored at a high level. We provide some details and qualitative observations to illustrate the scores for one of the activities, called Discovering the Universe.

The learning environment was appropriately arranged. The classroom layout had a U-shaped desk arrangement that encourages discussions, and the participants could easily watch the astronomy videos about the known universe (Organization). The required materials were available, as well as technical support. Various videos and software were prepared. Worksheets and other materials were ready for participants (Materials). The activity enhanced various goals mentioned in the curriculum, such as understanding the size, distance, and position in the universe, calculating in terms of powers of tens, and the connections between STEM and astronomy. Students wrote sticky notes with their questions about space and astronomy. These notes were posted visibly in the classroom (Learning objectives). Students were enabled to participate equally in all sub-activities. Questions were

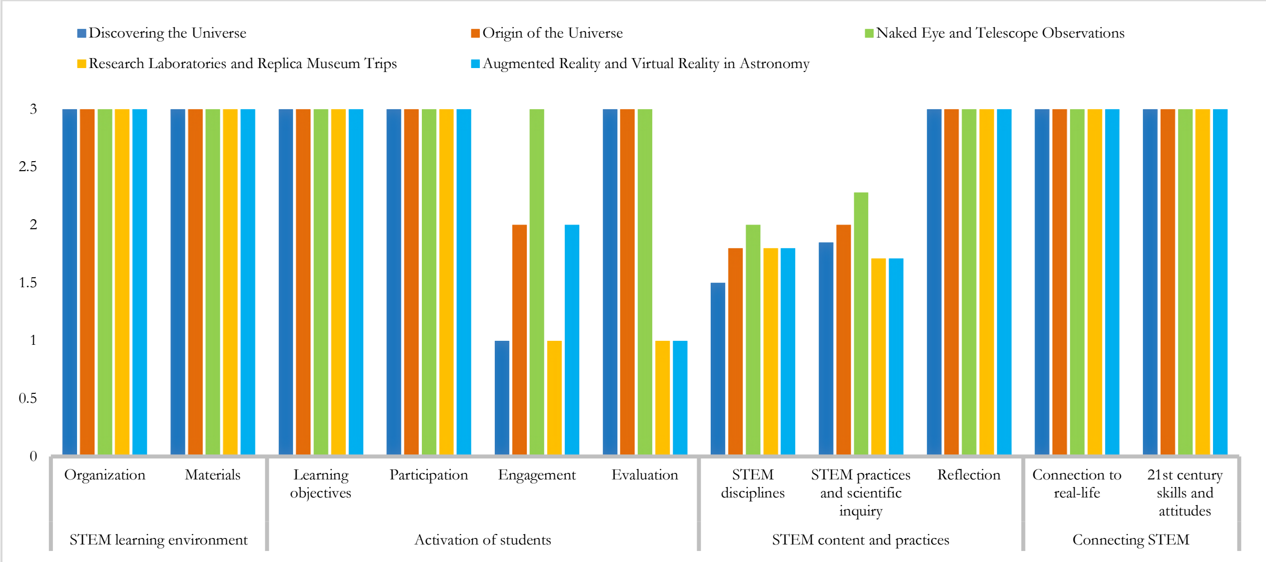

Figure 4. The results obtained for the five activities in the Curiosity Arousing module

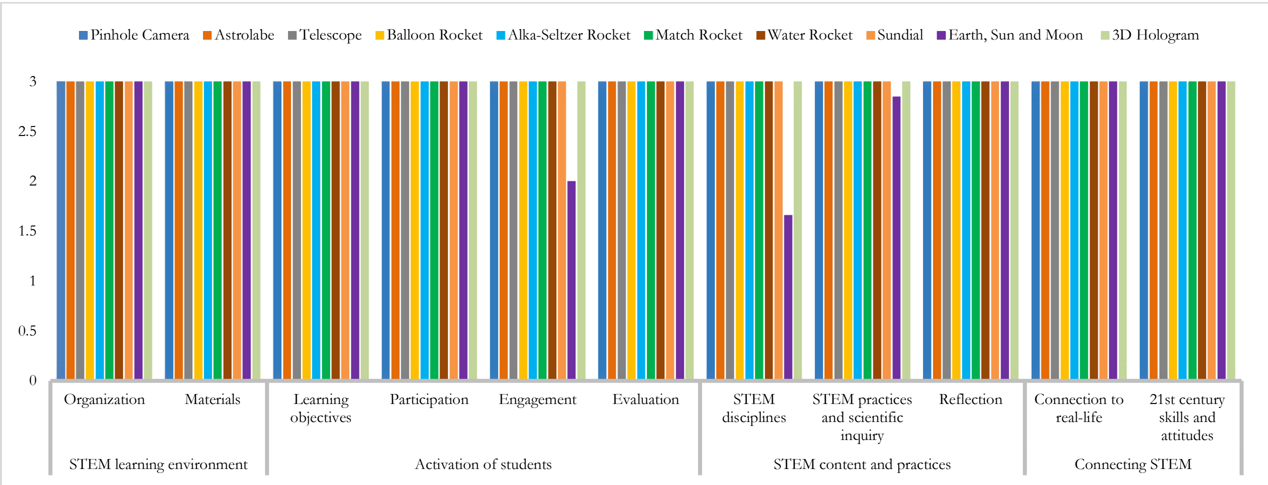

Figure 5. The results obtained for the ten activities in the Encouraging and Upskilling module

posed to all participants and all answers received attention (Participation). The activity did not involve hands-on activities. The emphasis was on answering questions and making inferences. Hence, the activity only engaged students' minds (Engagement). The activity includes process-oriented measurement and evaluation forms. Worksheets were used by participants to evaluate their own performance and learning (Evaluation). The activity did not involve an engineering design sub-activity nor did the participants have the opportunity to conduct their own research, so it received rather low scores for these items. This is not particularly worrying, since the activities in this module aim to foster curiosity, more than knowledge and skills (STEM disciplines). The participants did not have the opportunity to conduct their own research (STEM practices and scientific inquiry). The participants filled out worksheets and reflected on what they learned through writing and discussing. This was reinforced by questions posed by the teacher (Reflection). The participants were observed discussing how many days will it take to get to Mars, and whether life is possible outside Earth. A simulation of the power of ten used in this activity was directly related to daily life observations of the participants with respect to the limits of science (Connection to real-life). The activity highlighted the relation and importance of several 21st century skills to STEM, such as communication, reasoning, and critical thinking (21st century skills and attitudes).

Results for the Encouraging and Upskilling Activities

The results obtained for the ten activities in the Encouraging and Upskilling module are presented in Figure 5.

As can be seen in Figure 5, all activities except the Earth, Sun and Moon activity received the highest scores and thus encouraged students and helped them develop STEM skills. We illustrate this with observations from one of the activities in this module, on designing your own water rocket.

We observed that the duration (of four hours) was quite sufficient for defining the problem, sketching a design, creating a prototype, conducting experiments, collecting data, evaluating, and revising the prototype

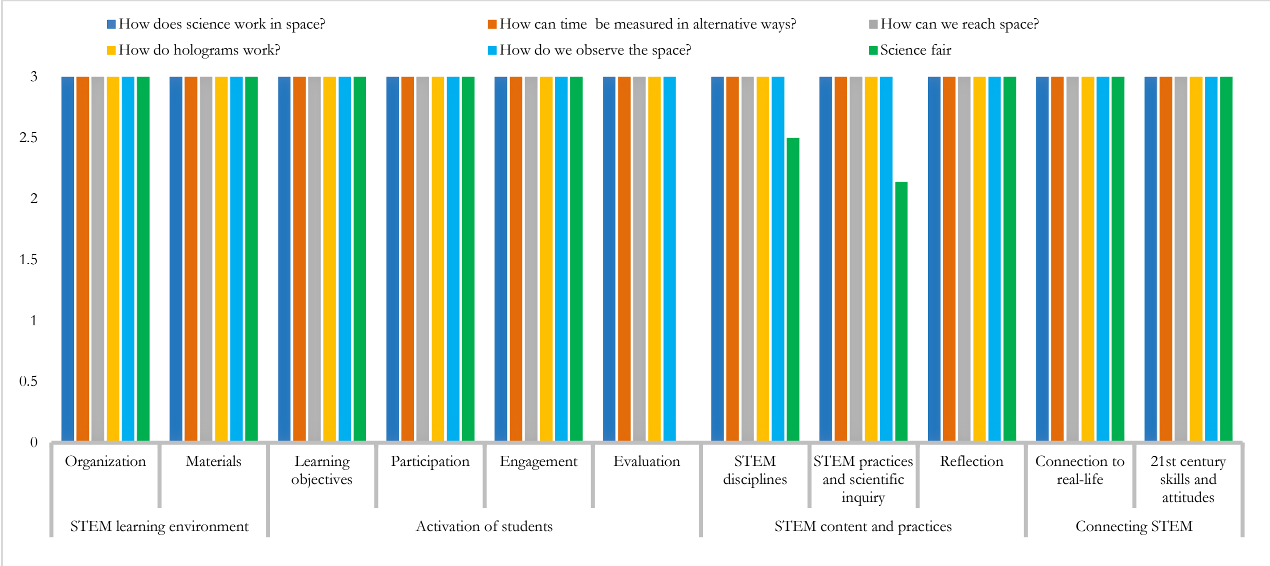

Figure 6. The results obtained for the five Research and Design Projects and the Science Fair

(Organization). The materials, also additional materials required by the students such as chalk and nylon rope were available or provided in a short time (Materials). The activity aimed at conceptual and skill-oriented achievements pertaining to energy transformations, thrust, air resistance, measurement, and the engineering design process (Learning objectives). Students were assigned to different design tasks, and they all participated in the sub-activities (Participation). The activity involved hands-on and minds-on activities. The participants expressed their ideas to complete the given task. They evaluated different ideas according to the evidence and realized their designs using their hands-on skills (Engagement). The worksheets used in the activity provided the teams to evaluate themselves and shape their learning (Evaluation). The participants had to convert a given bottle into a durable rocket using water and pressurized air. The rocket had to have a nose cone, fines, and a body. After launch, the rocket should move straight and reach the farthest distance. The participants performed all the steps of the engineering design process, such as defining the problem, revealing ideas for solutions, and choosing a solution. They spent considerable time to meet the durability criteria (STEM disciplines). They collected and recorded data in tables when testing the prototype. The teams analyzed and evaluated the results by comparing them with peers in the evaluation part (STEM practices and scientific inquiry). The teams verbally reflected on their understanding of relevant concepts, such as air resistance, pressure, and force. Questions on the worksheet on the primary variables for a rocket to reach space enabled participants to reflect on what they learned (Reflection). The activity connected phenomena that participants' experience and observe in real-life to scientific concepts such as kinetic energy, potential energy, air resistance, and the engineering design process (Connection to real-life). The participants constructed their artifacts using the engineering design process. Thus, the activity was particularly beneficial to support engineering interest (21st century skills and attitudes).

The Earth, Sun, and Moon activity did not receive high scores on all items. Analysis of qualitative observations confirmed this. The activity focused on astronomy simulations and animations. Hands-on activities were limited (Engagement), and there was no evidence of implementation of the engineering design process (STEM disciplines).

Results for the Research and Design Projects and the Science Fair

The results obtained for the five Research and Design Projects and the Science Fair are presented in Figure 6.

As can be seen, all research and design projects scored high on all sub-themes. We illustrate the scores for the research and design projects through the observations for the activity 'How can we reach space?' This activity was carried out in approximately two months. During this period, weekly workshops were organized for the participants. Each team designated their work plan, and had sufficient time to conduct the research and design tasks effectively (Organization). Often-used materials were ready at hand. When different or unique materials were required, these materials were provided to the participants (Materials). The objective was learning to solve an engineering problem. All sub-activities were related to the solution of the determined problem (Learning objectives). Three teams of four participants participated in the activity. All team members actively shared their scientific knowledge about the solution of the design problem. They gathered information from various sources and decided on a prototype through group discussions. The team distributed the tasks, such as obtaining materials and performing experiments and focused on the solution to the design problem (Participation). Initially, minds-on activities were prioritized by the teams because they had to decide via group discussions on solutions and constitute a design according to scientific evidence. Later, the teams predominantly were hands-on, constructing a prototype.

In the last steps, they were both hands-on and minds-on, engaged in testing, evaluating test results, and solving encountered design problems. For example, one of the teams designed a model rocket. In the test, the model failed because of flight instability. After evaluating data, the team found the problem: the center-of-gravity was not in front of the center-of-pressure. They improved the design and re-constructed the prototype (Engagement). The teams created a portfolio electronically or in written format. The portfolio included detailed sections on scientific concepts, principles, formulas, and sketching relevant for rocket science; the data obtained in the tests; and the features of the designs arranged according to results. The portfolio allowed participants to evaluate their progress (Evaluation). The activity was transdisciplinary. The participants applied a variety of knowledge and skills, especially from physics, chemistry, engineering, technology, and mathematics. For example, one of the team used computer simulations and mathematical calculations to determine the maximum altitude that the model rocket could reach (STEM disciplines). All teams executed the steps from the research and design process by themselves. For example, one of the team designed two different types of nose shapes for a model rocket. They tested the nose shapes and decided to use or give type nose shape (STEM practices and scientific inquiry). The teams used the portfolio to share and discuss what they had learned with respect to identifying and solving the engineering problem (Reflection). The challenge to reach space is a common theme and dream in daily life; participants see how STEM skills and knowledge are relevant for meeting such challenges (Connection to real-life). The activity involved solving a challenging problem through sustained teamwork. Thus, collaboration, effective communication, critical thinking, and creativity were supported (21st century skills and attitudes).

The STEM-based Science Fair also scored high on most characteristics, but it did not contain evaluation procedures, nor did it activate inquiry or design practices at the highest level. The learning environment of the fair was the showroom of a regional shopping mall. Here, workshops, exhibitions, and rocket tests were organized. The premises were large enough to perform the activities effectively (Organization). In the workshops, the teams showed rocket and hologram designs to the science fair participants. The fair used the materials and the artifacts designed by participants in previous modules, which were of course available (Materials). The fair aimed to raise self-confidence of the participants concerning STEM to show that they could reach large audiences via interactive presentations and workshops (Learning objectives). Choosing a shopping mall as an environment increased participation in the science fair. In this context, the participants met with children and shared their artifacts. While the participants were learners in the previous modules, they took the role of an implementer in this module. This encouraged them to feel and behave like a teacher. (Participation). The fair supported hands-on and minds-on activities. Design activities and demonstrations contributed to learning by doing for both participants and science fair participants (Engagement). However, no process-oriented measurement and evaluation techniques were applied (Evaluation). The engineering design process was limited in the fair. For example, only the design and testing steps were included in the water rocket designs (STEM disciplines). There was no evidence for inquiry concerning data collection, analysis, and interpretation (STEM practices and scientific inquiry). When sharing their knowledge, skills, and experiences with the public in workshops and interactive exhibitions, participants reflected on what they had learned in the previous modules (Reflection). By sharing their designs and their experiences with children, the participants, as prospective teachers, could connect to the real-life experiences of children (Connection to real-life). The activity concerned sharing STEM-focused artifacts with the public. Thus, participants' collaboration and communication skills were supported by the activity. Besides, the STEM-based science fair was beneficial for the participants to gain self-confidence (21st century skills and attitudes).

DISCUSSION AND CONCLUSION

This study aimed to develop and validate an activity evaluation form that is compatible with the nature of STEM education. The STEM Activity Evaluation Form we developed consisted of four categories: STEM learning environment, activation of students, STEM content and practices, and connecting STEM. It was tested and validated by evaluating all 21 STEM activities that occurred in an astronomy course for prospective science teachers. We found that we could use the form without inconsistencies. The majority of the activities scored high on all four themes of the form. Lower scores could be explained through analysis of the aims of the activity and of the observation data, confirming that the form applies well to a variety of activities with a bigger or lesser number of STEM characteristics. For example, activities meant to arouse curiosity such as excursions were not meant to develop specific engineering design practices, and as a consequence these activities scored lower on 'STEM disciplines.'

Only a limited number of studies in the literature investigated the evaluation of STEM activities. Hug and Eyerman (2018) concluded that the moving car activity in their case studies research significantly met the qualities of STEM education. Shah et al. (2018) developed an observation tool evaluating STEM program quality in out-of-school environments. They applied their Dimensions of Success tool to 340 activities. Their focus was limited to the engagement of students with STEM content and their development in STEM disciplines, which are comparable to the learning environment and activation themes in our form.

We applied our instrument to a course with four modules and 21 activities, with a sequential and complementary structure. This structure consists of raising curiosity and awakening interest, developing skills and gaining self-confidence in STEM disciplines, designing an artifact from the beginning to the end, and sharing the artifact with an audience through interactive presentations. Such a sequential and complementary pattern, we think, effectively reflects the nature of STEM education.

According to the results of the research, the following points for further discussion and research can be raised.

In STEM education, artifact construction should not be restricted to cookbook-type workshop assignments but should include inquiry and engineering design practices. In this manner, students acquire STEM content knowledge and skills through activities that are both motivating and valid.

STEM education activities should be evaluated from a holistic and goal-oriented perspective and foster interest, attitude, knowledge, skills, and understanding of STEM practices and their relations to real-life problems. Whether activities use fancy or costly equipment or materials such as robotics is less important. The use of simple and inexpensive materials that meet the essential elements of STEM education can equally well lead to high-quality STEM activities.

Activity-oriented observation tools are important to establish a correlation or causal relation between teaching and learning outcomes (Shavelson and Towne, 2002). These tools support teachers' content knowledge, teaching practices, and the learning of their students (Schultz and Pecheone, 2015). The STEM Activity Evaluation Form developed in this study is a useful measurement tool that can be used by (prospective) teachers to evaluate and improve STEM education practices.

The STEM Activity Evaluation Form developed in this study can be used to evaluate STEM activities based on various pedagogical approaches such as project-based learning, collaborative learning, problem-based learning, inquiry-based learning, and design-based learning. It may be less suitable to evaluate purely direct instruction and 'cook book' approaches.

In today's education, the diversification of challenges and information sources makes the teacher or the textbook not the only role model and authority to the student. Nowadays, the teacher and the student are in a position to continually renew themselves. To monitor the performance of a generation that can think creatively and critically, shows commitment and patience, is not afraid to make mistakes and can learn from mistakes, and collaborates with others, we need process-oriented evaluation tools and not just standardized assessment and evaluation tools.

There are some limitations to the current study. The observation-based evaluation form was validated on a limited number of STEM activities from only one, astronomy-based STEM course, which was taken by one specific group of students, namely prospective science teachers. There may be more STEM characteristics to STEM activities, to be discovered from applying the STEM Activity Evaluation Form to a larger variety of courses and students.

ACKNOWLEDGEMENTS

This study was prepared based on the doctoral dissertation titled as development and evaluation of astronomy activities within the scope of STEM education and funded by the Mugla Sıtkı Kocman University Scientific Research Project Office under grant number 16/171.

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APPENDIX A

The STEM Activity Evaluation Form

Theme	Sub-theme	Item	Score 0	Score 1	Score 2	Score 3	Observation, evidence, or example
STEM Learning environment	Organization	A proper learning environment for the activity is organized.					
		The duration of the activity is sufficient.					
		Transitions between the sub-activities occur systematically.					
	Material	Activity materials are proper for learning objectives.					
		Required materials are available for the activity.					
Activitation of students	Learning objectives	The activity is relevant to learning objectives.					
		Sufficient time is spent on achieving for learning objectives.					
	Participation	The activity enables students to participate equally in the sub-activities.					
		Students are encouraged to participate in the sub-activities.					
	Engagement	The activity involves hands-on and minds-on activities.					
	Evaluation	The activity includes process-oriented measurement and evaluation techniques.					
STEM content and practices	STEM disciplines	The activity emphasizes various STEM disciplines.					
		The activity includes STEM integration.					
		The activity includes the engineering design process.					
		The mistakes are essential parts of learning.					
		The activity allows students to provide evidence that they accurately understand scientific concepts.					
		The activity focuses on artifact construction.					
	STEM practices and scientific inquiry	The activity allows students to engage in scientific questions.					
		The activity supports students' evidence-based thinking skills.					
		The activity allows students to reveal their current ideas.					
		The activity allows students to do their research.					
		The activity enables students to use data collection, analysis, and interpretation.					
		The activity allows students to suggest different solutions for a problem.					
		The activity allows students to share their ideas or findings with their peers.					
	Reflection	The students are encouraged to reflect on what they have learned.					
		The activity allows students to reflect on what they have learned.					
Connecting STEM	Connection to real-life	The activity makes a connection between problems or subjects related to real-life and students' experiences.					
	21st century skills and attitudes	The activity supports students' interest in STEM disciplines.					
		The activity supports the development of students' 21st century skills.					

APPENDIX B

The Telescope: An example of an Encouraging and Upskilling Activity

Learning objectives

- To discover the working principles of lenses and refractor telescopes.
- To recognize that two thin-edged lenses optical system reverses the image
- To use basic mathematical calculations.
- To construct a prototype according to the given qualifications.
- To conduct an astronomical observation with a designed tool.
- To identify the problems and suggest alternative solutions for the problems.

Time required: 2 hours

Recommended materials: Two thin-edged lenses (preferably f = 15 cm and f = 5 cm) or two magnifiers with different focal length, 1 L bottle, tape, glue, aluminum foil, plastic ruler, scissors, flashlight, pencil, pencil, and activity worksheet

Recommended implementation procedures:
Preparation: Participants are divided into teams of two or three people. Two magnifiers and activity worksheets are given to each team.
Observation: Participants observe objects such as fingerprints and hairs using magnifiers. They discover how thin-edged lenses work.
Discussion: Participants discuss similar and different features of their observations using the naked eye and magnifiers.
Observation: Participants observe different objects in the environment by holding the two magnifiers in the same direction.
Inquiry: The following questions are posed to the participants to elaborate their observations: How is the sharpness of the formed image? How is the formed image inverted? and How is the formed image larger (or smaller) than the object?
Discussion: The teams discuss their observations with the other participants according to formed image features.
Inference: Participants are encouraged to make an inference that a system constructed with two thin-edged lenses may have the ability to magnify the formed image, and the sharpness of this image is relevant to the distance between the lenses.
Experiment: The implementer conducts a demonstration experiment. Light rays pass through the thin-edged lens with the help of a flashlight. The image is formed on the wall. The sharpness of the image arranges by moving the lens forward or backward. The distance between the formed image and the lens is measured by a ruler. This distance is recorded as the focal length. The same experiment is carried out with a second lens. The magnification is calculated according to the ratio of focal lengths.
Inference: Participants are encouraged to make an inference that the focal length of a lens can be found based on the refraction of the light.
Task: Each team is assigned the following task: You should design a telescope with the given magnifiers. This telescope should have lenses and a tube system. The magnification ratio should be calculated.
Experiment: Participants are encouraged to experiment to find the focal lengths required for telescope design.
Data recording: Participants record focal lengths in units.
Data analysis: Participants calculate the magnification ratio.
Identify the problem: Teams are allowed to explore the materials in the activity box. Participants are asked to fill the topics, research problem, and scientific information sections in the worksheet.
Decide a solution: Team members are encouraged to suggest alternative solutions to the problem. They decide the best solution based on materials, tasks, and variables.
Design: Participants draw their sketches on worksheets in detail and express essential features in their designs and how the design works. At this step, designs are evaluated by the implementer according to scientific concepts, how the design works, the proportionality of the sketches, and the essential ideas and materials. The implementer confirms the designs.
Prototyping: Participants construct prototypes.
Testing the prototype: Participants test their prototypes.
Redesign: Participants return to the design step and change their designs.
Re-prototyping: The participants reconstruct the prototype according to the redesign step.
Improving the design (If necessary): A new design task can be given to increase the magnification of the telescopes. Teams are supported to suggest their solutions.
Evaluation: Participants use their observation tools to make observations. They determine the image features and draw the image formation on the worksheets. Participants compare and discuss their designs with other teams based on magnification rates and tube systems. Participants are supported to make evidence-based conclusions about refraction and formed image features. After the given task is completed, the teams are asked to answer the questions on the worksheets, such as were there any parts of your design that do not work? If any, how did you fix them? And how would you improve your design? Responses are compared with group discussion.

EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 07
ISSN: 2468-4368

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Highlighting the Relevance of Mathematics to Secondary School Students – Why and How

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Citation: Fitzmaurice, O., O'Meara, N. and Johnson, P. (2021). Highlighting the Relevance of Mathematics to Secondary School Students – Why and How. *European Journal of STEM Education*, 6(1), 07. https://doi.org/10.20897/ejsteme/10895

Published: May 9, 2021

ABSTRACT

A lack of knowledge and appreciation of the prominence of mathematics in different careers can have a negative impact on a student's engagement with the subject. A perceived lack of relevance can result in disinterest, and even disengagement with mathematics entirely. This can lead to more serious consequences for the economy of a country who requires a consistent flow of well-educated science, technology, and mathematics graduates to ensure economic and social development. Research shows that the textbook is the most commonly used resource in Irish classrooms. Textbooks impact significantly on teaching and learning as they dictate what will be taught, in what order, and how. For this reason, this research commenced with an analysis of local textbooks to evaluate how well they highlight the relevance of mathematics within careers. This textbook analysis, in conjunction with interviews conducted with secondary school mathematics teachers, indicate a distinct lack of resources and support for teachers who want to highlight the relevance of mathematics within a range of careers as a means of enhancing student motivation and engagement with the subject. These findings motivated the conception of a pilot study designed to support secondary school mathematics teachers to fill this gap in teaching resources.

Keywords: mathematics education, STEM education, relevance of mathematics, careers education

INTRODUCTION

STEM is the acronym for the fields of science, technology, engineering, and mathematics. Policy makers and stakeholders understand that a consistent supply of well-educated STEM graduates is crucial to the success of a competitive economy and the health and welfare of all its constituents (Mujtaba, Reiss and Hodgson, 2014; Mujtaba, Reiss, Rodd and Simon, 2015; Reiss, 2004; Reiss and Mujtaba, 2017; Tripney et al., 2010). However, there is a concern in the UK and Ireland that the current number of STEM graduates is insufficient (Expert Group on Future Skills Needs, 2008; Reiss and Mujtaba, 2017) and, if not reversed, will have long-term devastating effects on the economy (Bennett, Braund and Sharpe, 2014).

Mathematics is recognised as the language that underpins all other STEM disciplines as well as the medical and social sciences, yet is accepted as a formidable discipline in its own right (Smith, 2004). The need for a country to increase the mathematical skills and proficiency of its students has been highlighted by many stakeholders (Hoyles, Wolf, Molyneux-Hodgson and Kent, 2002; Mujtaba et al., 2014) as it is the medium through which problems are solved in most areas including the physical sciences, computer science, engineering and medicine (Sheldrake, Mujtaba and Reiss, 2015). Mathematics widens the range of options available to young people, as it is a prerequisite for many university courses (Central Applications Office, 2020; Johnston, 1994). A school qualification in mathematics has been demonstrated to lead to more successful outcomes in relation to acceptance into choice of university, future career and increased salary (Mujtaba et al., 2014).

Mathematics pervades most occupations. It is often the case that mathematics exists implicitly in a variety of jobs and tasks, which are not explicitly mathematical (Hoyles et al., 2002; Keogh, Maguire and O'Donoghue, 2018). In 2002, an analysis of workplace mathematics conducted by Hoyles et al. (2002) found that the majority of employees surveyed, regardless of the level at which they were employed, required some level of mathematical proficiency. Today not only is mathematical proficiency still a prerequisite in most jobs (Hoyles et al., 2002; Keogh et al., 2018), there exists a strong relationship between the mathematical proficiency of many professionals and their competence in their field of expertise (Flegg, Mallet and Lupton, 2012). The mathematics skillsets demanded by employers are constantly changing and, frequently, employees are required to be proficient in a range of mathematics skills and competencies that would not have been needed by their predecessors. For this reason, mathematics education provision for young people needs to be appropriate and adapted regularly (Hoyles et al., 2002). It should bolster a person by providing them with a skillset that will be vital regardless of the profession they choose (Smith, 2004). However, there exists a distinct mismatch between skills acquired at school and those desired/required by the workplace (Smith, 2004; Tripney et al., 2010). In 2004, the Smith Report, a large-scale inquiry conducted into the state of mathematics education in the UK, stated that the curriculum was not addressing the needs of learners, employers, or higher education institutions. This has contributed to participation rates in STEM subjects, at the upper end of secondary school education, particularly at an advanced level, being cause for concern in the UK, Ireland and Australia for a number of years (Archer, Osborne, De Witt, Willis and Wong, 2013; Johnston, 1994; Mujtaba, Sheldrake, Reiss and Simon, 2018). To address this issue, this paper outlines a novel approach to support teachers in their attempts to engage secondary school students in STEM subjects by informing them about the importance and relevance of mathematics within a range of careers.

STUDENTS' PERCEPTIONS OF THE RELEVANCE AND UTILITY OF MATHEMATICS

The message that mathematics is useful and important is either not being heard or not believed by students (Brown, Brown and Bibby, 2008), with the result that too many young people make subject choices, when permitted to do so, that they later regret (Reiss and Mujtaba, 2017). High levels of disaffection with mathematics are common themes throughout the literature (Brown et al., 2008; Mujtaba et al., 2015; Reiss and Mujtaba, 2017). A study conducted by Hodgen and Askew (2007) of secondary school students demonstrated that mathematics is viewed less favourably than other subjects. Many students, both low and high attaining, perceive mathematics to be dull, boring, and irrelevant (Matthews and Pepper, 2006; Mujtaba et al., 2014; Smith, 2004). It is seen as too traditional and less useful than other subjects (Tebbutt, 1993). The Smith report (2004) indicated that GCSE (the General Certificate of Secondary Education, typically taken at the age of 15/16) mathematics appeared boring and irrelevant to students' lives and was not conducive to the further studying of mathematics. Similarly, Nardi and Steward's (2003) research concluded that for most students, mathematics was tedious and an "irrelevant body of isolated non-transferable skills, the learning of which offers little opportunity for activity" (Nardi and Steward, 2003, p. 361).

Many students therefore have the opinion that mathematics is neither needed nor useful to them, in school or in their future studies and careers (Brown et al., 2008). It is viewed as an isolated school subject that lacks connections to life and other subject areas (Nardi and Steward, 2003). Even within the cohort of students who do enjoy and manage to succeed at mathematics, a prevalent belief still exists that mathematics will never be useful, at any stage of their lives (Matthews and Pepper, 2006; Nardi and Steward, 2003). Matthews and Pepper (2005) and Kyriacou and Goulding (2006) found that students failed to see the relevance of either the GCSE or A-level (Advanced Level qualifications are the UK subject-based qualification for students aged 16 and above, usually studied over the course of two years) mathematics they studied at school, or how they would be of value in their futures.

Seeing the relevance of school lessons for students is important both for intrinsic motivation (Mujtaba et al., 2014; Mujtaba et al., 2018) and extrinsic motivation i.e., a perception of utility in life or in future studies and/or career (Mujtaba et al., 2018). In fact, the utility of a subject/extrinsic motivation has been found to have a bigger influence on some subject choices than intrinsic motivation (Sheldrake et al., 2015). Brown et al. (2008) found that the perception of mathematics not being useful for future careers was the main reason offered by students for why they discontinued studying it after the GCSE.

Making education relevant to students' lives (current and future) should result in increased learning and engagement (Hulleman and Harackiewicz, 2009). Students enjoy a subject more when they perceive the content to be relevant (Smart and Rahman, 2008). Increased emphasis on relevance helps students to identify better with a range of careers and thus increases the chances of students opting for STEM subject/career choices when permitted to do so (Hulleman and Harackiewicz, 2009). One evidenced based approach to introducing relevance into the mathematics curriculum is called Realistic Mathematics Education and is outlined next.

REALISTIC MATHEMATICS EDUCATION (RME)

Realistic Mathematics Education (RME) is an approach to teaching and learning to counter the boredom and difficulties which tend to occur as a result of traditional, abstract mathematics learning that lacks context (Laurens, Batlolona, Batlolona and Leasa, 2017). It was derived from the research of Hans Freudenthal who believed that abstraction was a great weakness, rather than a strength of mainstream mathematics, because '...it is wasted on individuals who are not able to avail themselves of this flexibility' (Hans Freudenthal, 1968, p. 5). He wrote that mathematics is primarily a human activity and therefore reality should be embedded in mathematics education (Gravemeijer and Terwel, 2000). RME endorses the notion that reality is the source of mathematics, not just where it is applied/utilised (Treffers, 1993). Devrim and Uyangor (2006, p. 1952) state that

> 'These real situations can include contextual problems or mathematically authentic contexts for learners where they experience the problem presented as relevant and real. Learners therefore learn mathematics by mathematising subject matter from real contexts and from their own mathematical activity'.

Reality thus leads to mathematical models and from here one may progress to more abstract mathematics. This represents a move from what is termed horizontal to vertical mathematising. Freudenthal (1991, pp. 41-42) distinguished between horizontal and vertical mathematisation as follows:

> 'Horizontal mathematisation leads from the world of *life* to the world of *symbols*. In the world of life one lives, acts (and suffers); in the other one symbols are shaped, reshaped, and manipulated, mechanically, comprehendingly, reflectingly; this is vertical mathematisation. The world of life is what is experienced as reality (in the sense I used the word before), as is symbol world with regard to its abstraction'.

This distinction makes it possible to characterise different types of mathematics teaching and learning. Freudenthal (1991, p. 133) classified mathematics curricula into 4 categories: mechanistic, empiricist, structuralist and realistic. The 'mechanistic' approach encompasses neither vertical nor horizontal mathematising. A course of this nature would encourage mathematics being learned and applied to routine step-by-step problems and lacks any real life or realistic contexts. 'Empiricist' mathematics education endorses horizontal mathematisation but lacks any vertical mathematisation. Here students learn mathematics from the world as they know it, however they are not required to schematise this knowledge or progress beyond this. A 'structuralist' approach to mathematics education includes vertical mathematisation, in the absence of horizontal mathematisation, thereby not including any content relating to the real world 'Realistic' mathematics education comprises both types of mathematising as defined by Freudenthal. In a curriculum like this, mathematical tasks originate in real life settings which is the basis of horizontal mathematising – putting real life into mathematical form. Mathematical skills are then required to solve these problems, which embodies vertical mathematising (Gill, 2006). The literature supports the view that a realistic mathematics curriculum, which encompasses both vertical and horizontal mathematising should be available to all students studying mathematics (Gravemeijer and Terwel, 2000; Vos, 2020). It provides the framework for the intervention described in this research.

CAREER GUIDANCE ACROSS STEM DISCIPLINES

School factors that influence uptake of various subjects include career advice provided to students (Bennett et al., 2014). It is believed that schools have a responsibility to inform students of the range of further study and career options when they finish (Reiss and Mujtaba, 2017). However, there is concern about the quality of the provision of careers education, and STEM careers education in particular (Archer et al., 2013; Reiss and Mujtaba, 2017). In the UK, shifts in government policy and funding have resulted in careers education being unsatisfactory and not being given the priority it warrants (Reiss and Mujtaba, 2017). Similar reports emerged from Ireland in 2018, stating that careers guidance at school is under resourced and ineffective and therefore not meeting the needs of learners (Irish Business and Employers Confederation, 2018). Part of the reason for this ineffective delivery of STEM careers education/guidance, is that careers teachers rarely have a background in STEM and there is a danger that the education they provide about STEM subjects can be out of date or stereotyped (Reiss and Mujtaba, 2017). Bennett et al. (2014) found that schools where there were high levels of GCSE participation in science had careers advice actively facilitated by science teachers and staff.

The need for the provision of better careers education has been highlighted in previous research (Bennett et al., 2014). Smith (2004) flagged a lack of useful careers advice in schools about mathematics and the study of mathematics and stated that it was an area that needed to be addressed as a high priority. Recent research papers state that it has not improved much in the decade since the Smith report. Archer et al. (2013) found that one quarter of secondary school students surveyed said that school did influence their choice of career but less than 0.5% were influenced in any way by the careers education provided in their school.

Opportunities for students to engage with the world of work, through the use of role models in the local community, i.e., STEM Ambassadors, is one vehicle for educating students on the possibilities the study of STEM disciplines can lead to (Bennett et al., 2014). It has been shown that the introduction of STEM Ambassadors at school has benefits for all: students, teachers and schools (Reiss and Mujtaba, 2017). Bennett et al. (2014) reported on a project in the USA which was designed to raise interest in STEM subjects by assigning to each female student a STEM mentor. The project resulted in a significant number of girls planning to pursue a career in mathematics (Bennett et al., 2014). In science the use of ambassadors facilitating career talks and giving advice and demonstrations within schools has been shown to result in increased levels of interest in the subject, and heightened ambitions towards careers in science (Straw and Macleod, 2015). These findings are supported by the work of Mujtaba et al. (2015) who showed that simply emphasising the relevance and utility of science and explaining the type of work that scientists do has helped to increase students' interest and attainment in science. There is a dearth in the literature on the use of STEM Ambassadors in mathematics education, which this study aims to address.

This paper reports on a study conducted in Ireland to investigate the extent to which the relevance and utility of mathematics within careers are promoted by teachers and how well they are supported to do so, in terms of the resources that are available to them. There are many factors that could potentially influence how students perceive a subject such as parental or peer influence, cultural background, teacher influence etc. This manuscript argues that the use of real-life / applied mathematics, that is particularly focused on actual careers, is a powerful motivational tool that could be used to support and encourage students within mathematics. This study began by exploring the occurrence of career information in the textbook, as the textbook is the resource most commonly used by teachers within Irish classrooms (O'Sullivan, 2017). We endeavoured to investigate if, and how well, the most commonly used mathematics textbooks succeed in exemplifying the key role that mathematics plays in a variety of careers. This analysis demonstrated a clear paucity of career references in the textbooks examined. These findings motivated further inquiry. We wanted to investigate if teachers use the relevance and utility of mathematics as motivation for their students and, in the absence of an abundance of textbook examples, what resources they use as a supplement. Interviews conducted with a panel of seven teachers provided evidence that teachers are very much lacking in training and resources in this area, with the result being that the relevance and utility of mathematics in a range of careers is rarely highlighted. What resulted from these findings was the creation and dissemination of a teaching and learning package to fill this gap in resources and support secondary school mathematics teachers without adding to their workload. The package was designed to support teachers in convincing students that a knowledge of mathematics is crucial for the pursuit and execution of all careers, and to highlight that the mathematics they are studying at school *is* relevant to their futures.

MATHEMATICS EDUCATION IN IRELAND

In Ireland after eight years of primary school, students proceed to five or six years of secondary school. The Junior Cycle encompasses the first three years, culminating in the Junior Certificate examination (taken at approximately 16 years of age). This is followed by a two- or three-year senior cycle (many, but not all, students participate in an additional, non-academic year in the fourth year, called Transition Year) which concludes with the Leaving Certificate examination. Students typically study seven subjects for the Leaving Certificate and almost all students study mathematics. A fail in mathematics in the Leaving Certificate, means exclusion from many university degree programmes for those who intend on progressing directly there (there are alternative entry routes for adult learners returning to education after the age of 23). Mathematics can be taken at either Foundation, Ordinary or Higher level, the latter being the most demanding in terms of content quantity and rigour. Up until 2011 there was a steady decline in the numbers taking higher level mathematics at Leaving Certificate. At this time only 15.8% of the school-leaving cohort chose to study mathematics at this level (State Examinations Commission, 2015). By 2019 participation rates had doubled to 32.9%, mainly because of a bonus points incentive[1] (Treacy, Prendergast

[1] The best six grades in the Leaving Certificate examination are counted towards a student's 'points'. A student's points score dictates entry to degree programmes at university. The maximum points a student can be awarded is 625 points, if they attain six H1 grades at higher level (6 x 100 points) plus an additional 25 'bonus points' if they achieve upwards of 40% in the higher-level mathematics examination. Bonus points are not awarded for any other subject.

and O'Meara, 2019). While the increase in participation at Leaving Certificate higher level mathematics is welcomed, there is still a large cohort of students, 50% of those who take higher level mathematics in the Junior Certificate examination, who do not continue to study mathematics at higher level for senior cycle and opt to take ordinary level mathematics instead. Given the association between perceived relevance and uptake of advanced mathematics discussed earlier, we felt an initiative focussing on enhancing students' appreciation of mathematics might reduce this figure of 50%.

State examinations that take place at the end of both the Junior and Senior Cycle place substantial pressure on both students and teachers with many teachers believing that the time allocated to mathematics during both cycles is insufficient (O'Meara and Prendergast, 2019; Prendergast and O'Meara, 2017). As such, any innovative intervention which researchers wish to pilot with post-primary students tends to take place in the optional year, Transition Year (also known as TY or 4th year). The philosophy of this non-academic 'gap' year is to promote students' social and personal development and it is recommended that schools and teachers should focus on increasing student engagement with mathematics and building confidence in students' mathematical abilities during TY (Clerkin, 2012). Furthermore, during this year mathematics teachers should introduce students to how mathematics pervades careers and inform them about the mathematics requirements and content of a variety of third-level courses (Moran, Perkins, Cosgrove and Shiels, 2013).

METHODOLOGY

Overview

This study was conducted in three phases. Phase one was an exploratory phase to quantify the extent to which textbooks in Ireland demonstrate the relevance and utility of mathematics across a range of careers. Phase two was a follow-on investigation to explore the extent to which teachers educate their students on the relevance and utility of mathematics and the resources they use in this effort, in the absence of supportive textbooks. This was done via semi-structured interviews with a panel of experienced mathematics teachers. Phase three was the development of an authentic, useful and novel suite of resources which is called Career Mathways, to fill the gaps previously identified in Phases one and two of the study. Phases one and two are detailed in the following sections.

Phase One - Textbook analysis

The predominant classroom aid used at secondary level in Ireland is the textbook (National Council for Curriculum and Assessment, 2005; O'Sullivan, 2017). Research shows that it has a significant influence on the teaching and learning that occurs in a classroom (Nathan, Long and Alibali, 2002). School mathematics textbook analysis is driven usually by concerns about the quality, suitability, presentation and inclusion (or lack thereof) of content (Petersson, Sayers, Rosenqvist and Andrews, 2020). Sometimes textbook analysis is a systematic comparison of local textbooks with texts from countries that are viewed as superior in terms of educational accomplishments (Petersson et al., 2020). As part of this study an analysis of the three most popular textbook series used in Transition Year and Senior Cycle in Ireland was conducted to see how frequently these textbooks highlighted the use of mathematics in careers. Our method of textbook analysis was a more rudimentary method of that used by Borba and Silva (2013) and Ding (2016). Borba and Silva (2013) analysed 48 textbooks in use in Brazil, to investigate how well they include and promote the use of calculators. They did this by identifying the instances of calculator usage and activities with calculators within the textbooks. Four distinct categories of activities were established, and all activities were subsequently categorised accordingly by independent researchers. The frequency and distribution of the activities were then recorded. Ding (2016) used a similar method in a study conducted on Chinese and US textbooks. Instances of addition and multiplication were coded, recorded and counted for each textbook analysed. Similarly, this method of textbook analysis was further supported by the work of Brating, Madej and Hemmi (2019) who analysed algebraic development in textbooks in Sweden, by counting the total number of pages devoted to the topic. Petersson et al. (2020, p. 209) state:

> "Methodologically, much textbook-related research has employed some form of qualitative description, typically aligned with some form of analytical framework that may be supplemented by frequency analyses, whereby the number of occurrences of particular forms of task is counted and compared".

Our textbook analysis categorised two types of reference to careers: *type (a),* where a career is mentioned in the absence of any mathematical context e.g., 'a hairdresser goes on holiday to Spain every year', and *type (b)*, where a career is mentioned within a mathematical context e.g., 'an accountant forecasts the projections for sales over a six-month period'. In order to carry out this analysis the research team first met and reviewed one chapter from one of the textbook series as a team in order to clarify the two different reference types and to determine how they would record the references. Each member of the team was then assigned one of the three most popular textbook series used in Senior Cycle in Ireland and they were required to identify all references to careers (type (a) and type (b) references) in the text, in the worked examples and in the problems posed for students. Upon completion of this task, and in order to ensure reliability, each of the researchers analysed a chapter from a different textbook series and compared their findings with those of the original reviewer. The results from this process indicated a very strong correlation between the two sets of analysis across all textbook series.

Phase Two - Teacher Interviews

Upon completion of the textbook analysis schools were randomly selected for participation in Phase 2. Initially six schools expressed an interest in participating thus guaranteeing a good geographical spread. Once schools were finalised semi-structured interviews were conducted with seven teachers from the different schools to ascertain the extent to which they demonstrate the relevance of mathematics within careers to their students and the resources/training available to support this endeavour. The questions contained in the interview broached teachers' perceptions of their own levels of knowledge in relation to the usefulness and applicability of mathematics. The interviews also sought to determine if teachers taught the relevance and utility of mathematics within careers to motivate their students in mathematics class, how they felt the textbooks supported them in this quest, what other resources were available and used by them and if they felt they have had adequate training to prepare them to deliver this level of information. Grounded theory was the method of analysis deemed most appropriate given the qualitative data collected in this phase of the study. What emerged from the analysis of textbooks and interview data is described next.

RESULTS

Phase 1

The results of the textbook analysis are summarised in **Table 1**.

Table 1. References to careers in three Irish textbook series

	Books in Series	Descriptive Text	Worked Examples	Exercises
Series A	4	567.85 pages 6 references to careers (4 *type (a)*, 2 *type (b)*)	N = 1586 44 (2.77%) references (25 *type (a)*, 19 *type (b)*)	N = 3114 103 (3.31%) references (40 *type (a)*, 63 *type (b)*)
Series B	3	279.35 pages 100 references to careers (49 *type (a)*, 51 *type (b)*)	N = 874 25 (2.86%) references (12 *type (a)*, 13 *type (b)*)	N = 4884 155 (3.17%) references (80 *type (a)*, 75 *type (b)*)
Series C	3	374.12 pages 10 references to careers (2 *type (a)*, 8 *type (b)*)	N = 685 9 (1.31%) references (1 *type (a)*, 8 *type (b)*)	N = 5103 77 (1.51%) references (25 *type (a)*, 52 *type (b)*)

From **Table 1** we can see that out of a total of 3,145 worked examples across the three series of books, only 1.28% utilised a career focus (type (b)) in a mathematics context in the examples. 1.2% of the examples mentioned careers in the absence of any mathematics context (type (a) references). There were 13,101 exercises across the three series of textbooks and only 190 (1.45%) of these used a career within a mathematics context as motivation within the question. 1.11% of the exercises had a type (a) reference. The three textbook series collectively contained approximately 1221.32 pages of descriptive text (we gauged incomplete pages of text to be $\frac{1}{3}, \frac{1}{4}, \frac{1}{5}$ etc. full of text, then summed them). Within these pages, we found a total of 116 references to careers, but only 61 of these were instances where the career was mentioned in a mathematics context.

It is worth noting that we are not suggesting that relevance is solely an issue within mathematics, nor are we implying that it is worse in mathematics textbooks than in other subjects. Teppo and Rannikmäe (2003) and Sjøberg and Schreiner (2015) have highlighted relevance as an issue within science education. Sjøberg and Schreiner (2015) in particular criticized textbooks in Norway for their lack of emphasis on relevance but a textbook analysis to identify percentage cover was not conducted. Osborne and Collins (2001) reported on the issues of relevance in chemistry education, where secondary school students failed to see how it related to their everyday lives or their futures. The study was conducted with a large number of focus groups consisting of secondary school students. It did not refer to how well relevance was addressed within chemistry textbooks, however. So, while relevance is also clearly an issue for other STEM subjects, the reality is that mathematics has more applications across other subject areas than other STEM disciplines so applications based on realistic scenarios should form a core part of any mathematics education (Ubuz, Gravemeijer, Stephan and Capraro).

Phase 2

One of the main findings from the interviews conducted with teachers for this study was that the majority of secondary school students do not see the relevance of mathematics. As part of the second phase of this study the teachers were asked if their students appreciate the usefulness of mathematics in their lives. Two teachers stated that students acknowledge its importance because of its core status on the syllabus and its role as a gatekeeper into university. Teacher 1 said

> "I don't know if they appreciate how much they will use it, but I think they, it's more that they know they have to have it".

Teacher 7 said that students have an awareness it is an important subject because their parents tell them it is,

> "Some of them do [appreciate how important mathematics is]. It's definitely emphasized at home".

However, six of the seven teachers stated that students have a negative view of mathematics and do not see its relevance to real life. As Teacher 2 stated,

> "If you're teaching algebra there is always a lot of 'when am I going to use this in real life?'… I think in general there is such a negative vibe around it [mathematics]"

Teachers 4 and 1 stated that the negative perception stems from the fact that they are not informed about the relevance of the mathematics they study at school.

> T4: '..and some of them kind of don't really understand that you do need it in everyday life. And maybe that's to do with the syllabus. The syllabus is a bit detached from, em, everyday life'.

> T1: "I think a lot of the time it's probably difficult for them to see where they'd use probability or where they'd use algebra, or where they'd use trigonometry or anything like that so it's probably that they just don't really see where it is applicable in their later on life".

In the process of the interview, teachers were also asked to provide their opinions in relation to how useful they believed the textbook was in highlighting the relevance and applicability of mathematics. They informed us that while the textbooks available make an attempt to introduce applications of concepts, they do not highlight the relevance of mathematics within careers. All seven teachers stated that the textbooks they use are inadequate for this purpose. When asked if the textbooks they use demonstrate the importance of mathematics in the real world, Teacher 1 told us

> "Probably not very well to be honest. [The textbook is] more geared towards the exam really...I think myself they're not really imparting how useful [mathematics] is".

Teacher 7 was more forceful in his reply saying the textbooks are *'horrific'* for this purpose.

When asked if there were resources available to help them convey how important mathematics is within a range of careers, six out of the seven teachers stated that there is a distinct lack of resources available to help them educate students in this area. Teacher 5 highlighted how in their search for resources they have

> "..never come across anything talking about careers. The odd things, very basic stuff, but nothing in any way in detail or really informative."

These sentiments were reiterated by the other teachers, including Teacher 2, who felt that there was a dearth of resources available regarding the role of mathematics in careers and that this hindered their ability to communicate the pervasiveness of mathematics within careers to their students, *"Definitely not [a lot of resources] I would say. I would say there is very, very little".*

Four of the seven teachers said there are resources available on the internet, but it is very time-consuming searching for something appropriate. Teacher 7 said that *"There's incredible stuff out there more than ever. Em, the problem nowadays is there's too much".* Teacher 1 echoed these sentiments that there are resources available, but it can take quite some time to find what you need,

> "There's loads of stuff in kind of TED [Technology, Entertainment, Design] and those kind of things but again you could spend an hour trying to find something".

Two teachers said however, that some resources do not always translate easily for use in an Irish context. Teachers 2 gives a good example of this:

> "I came across a thing and it was actually really good and it was American and it was just kinda like how, it was kinda like maths for everyday life and there was a unit on measurement and converting, like there was a picture of weighing scales and those kinda things, and it was really basic and there was an example of how you had to budget for your holiday and those kind of things, but again all the units were off because it was American and it didn't really translate."

Typically, teachers do not use careers to motivate students in mathematics. Five of the seven teachers said they never use careers as a way of motivating students in mathematics class. Teacher 5 said *'I use different resources to engage them with maths but not in relation to careers.*" One teacher said she tried to but only '*the obvious'* jobs where mathematics plays a key role. Another said she informs students they will need mathematics in their futures whatever path they choose but does not give specific mathematical examples of this.

> T1: "Probably not as much as I should. I feel comfortable doing the maths that we're doing if you know what I mean but probably imparting, em, where they would see where it would be useful to them in their later life is something that I, I'd like to improve in my teaching because at the minute it's just, it's a matter of can you do that and then move onto the next thing".

The teachers were asked if they felt that they had had sufficient preparation or support thus far in their careers to educate their students about the utility of mathematics within careers. What emerged was that, in general, these teachers feel they have not been adequately educated or supported to do so either in their teacher education or via CPD events. Five out of the seven teachers interviewed in this study said that training in this has area for them had been limited and left them feeling underprepared to teach specific examples of the relevance of mathematics in a range of careers. Only two teachers said they felt adequately prepared to integrate this into their teaching. One who has 23 years of teaching experience said it is up to individuals themselves if they wish to upskill. The remaining teacher interviewed had worked in a career in finance before training as a teacher and had witnessed the importance of mathematics first-hand and was able to relay this to their students when needed. Teachers 3 and 4 stated respectively; *"No. I think the training is … I suppose lacking",* and *"[Training has] been limited".* Teacher 5 said she feels *'extremely inadequate'* in the knowledge required to teach the relevance of mathematics within a range of careers.

The final finding to emerge from these interviews with the teachers was the heavy emphasis on examinations in Ireland. This was mentioned by six of the seven teachers as being detrimental to teaching anything off-syllabus. Teachers of examination groups are reluctant to spend time on something that is unlikely to be formally examined.

The analysis conducted on the most commonly used local textbooks in Ireland provided evidence that the relevance and utility of mathematics within most occupations is all but absent in the text and exercises that students and teachers work with on a daily basis. Interviews with experienced teachers confirmed these findings, and further informed us that resources that demonstrate the relevance of mathematics are difficult and time-consuming to find and training in this area for mathematics teachers is inadequate. The cumulative results of this work confirm suspicions that issues of relevance in mathematics apparent in other countries as outlined in the literature earlier are prevalent in Ireland too. These research findings inspired an intervention entitled Career Mathways, a medium through which teachers can inform students about the relevance and utility of mathematics in a range of career pathways that are not explicitly mathematical.

Phase 3 - The Inception of Career Mathways

To address the shortcomings highlighted in the textbook analysis, and the feedback from the teachers, the research team conceptualised an initiative entitled 'Career Mathways'. This initiative involved collaboration with several high-profile Irish personalities and professionals by inviting them to become STEM Ambassadors, with the overall aim of helping to make STEM, and mathematics in particular, more visible and relevant to students. A variety of professionals were approached: a chef, a florist, a farmer, a garda (Irish police officer) vehicle collision expert, a hairdresser, a veterinary nurse, a doctor, a dentist, a sports scientist, a photographer, a lawyer, a radio presenter, a sports presenter, and a meteorologist. More typical mathematics intensive careers, for example those in engineering or science, were avoided and instead careers where the relevance and need for mathematics was not so explicit were chosen. Fourteen professionals agreed to act as STEM Ambassadors and consented to be interviewed and video recorded by the research team.

When the interviews with the STEM Ambassadors were completed, we developed a teaching and learning package based on the mathematical content contained in the interviews. This package consisted of: 12 six-minute professionally produced video clips of the STEM Ambassadors detailing their careers and the mathematics that underpins them, a series of 12 posters that contained still images of the STEM Ambassadors and a quote of theirs

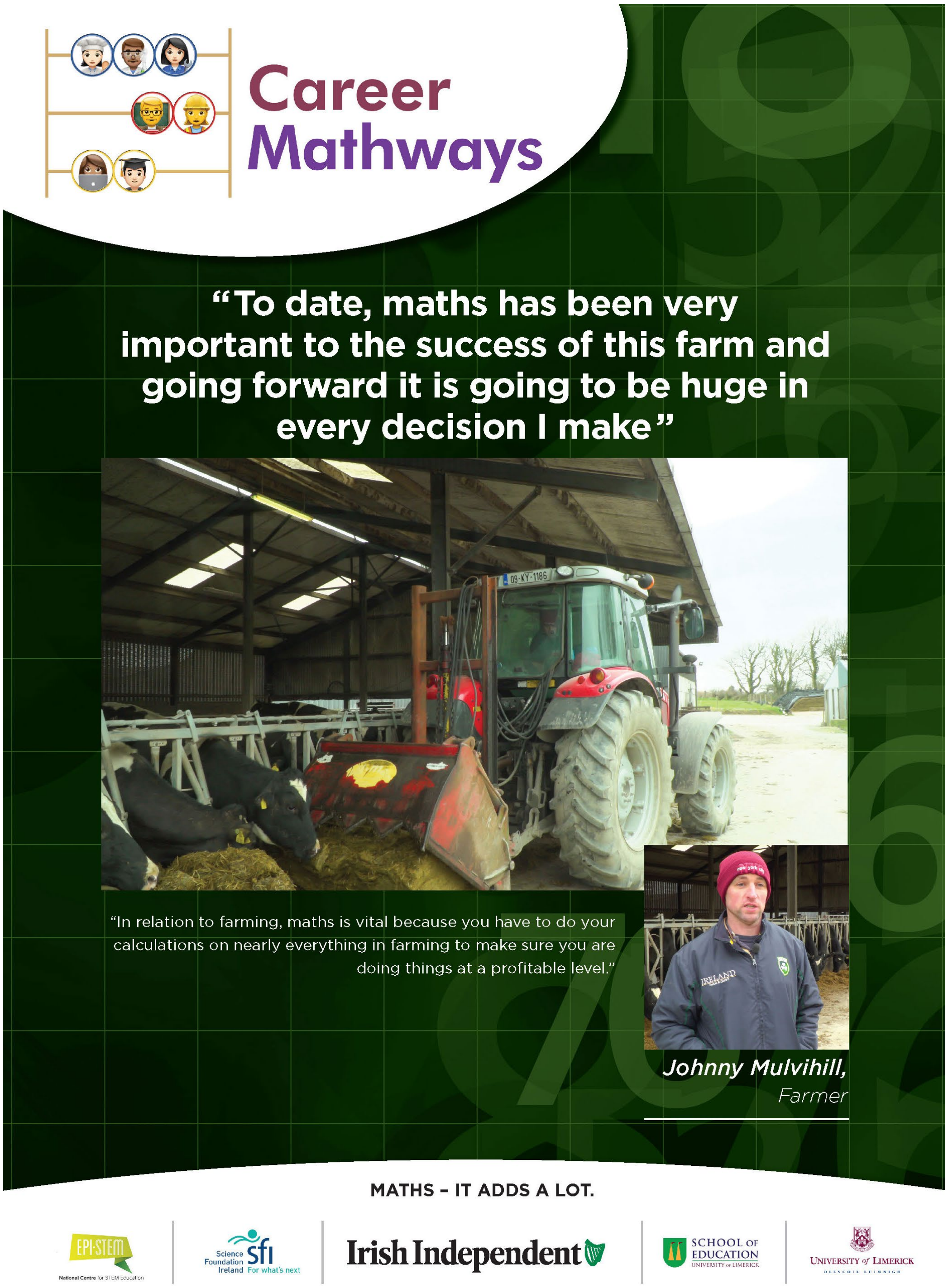

Figure 1. Poster from Farmer Interview

emphasising how mathematics plays a key role in their careers (see **Figure 1**) and a teacher handbook comprising 36 teaching and learning guides/plans (3 based on each occupation) with accompanying PowerPoint presentations for each lesson. A student handbook that comprised 36 worksheets, which aligned with the teaching and learning guides, was also created.

In a bid to ensure authenticity of content, all material contained in the teaching and learning resources were based on real and/or realistic tasks undertaken by the STEM Ambassadors in their daily lives and careers that require a level of mathematical skills and knowledge. For example, the farmer discussed grass growth on his farm and this example was used to teach students about arithmetic sequences (see **Figure 2**). We also outlined explicitly where the content in each teaching and learning guide was aligned with content in the school curriculum to demonstrate to students how relevant the content was to the real world and careers they might potentially consider when they finish school. We acknowledge that the real/realistic applications used to create these resources may not be relevant to students' lives at present, but their purpose is to illustrate that whatever career they ultimately choose, the need for a good foundation in mathematics is crucial.

Farmer – Lesson 2

Activity 1

Johnny is preparing a field for grazing. On the beginning of day 1 the grass is 2cm high. Due to a spell of good weather, the grass is expected to grow at a rate of 0.5cm a day.

a) Complete the table below to show the height of the grass at the beginning of each day of the coming week.

Day	1	2	3	4	5	6	7
Height							

b) Use the grid below to represent the growth of grass from part (a) graphically.

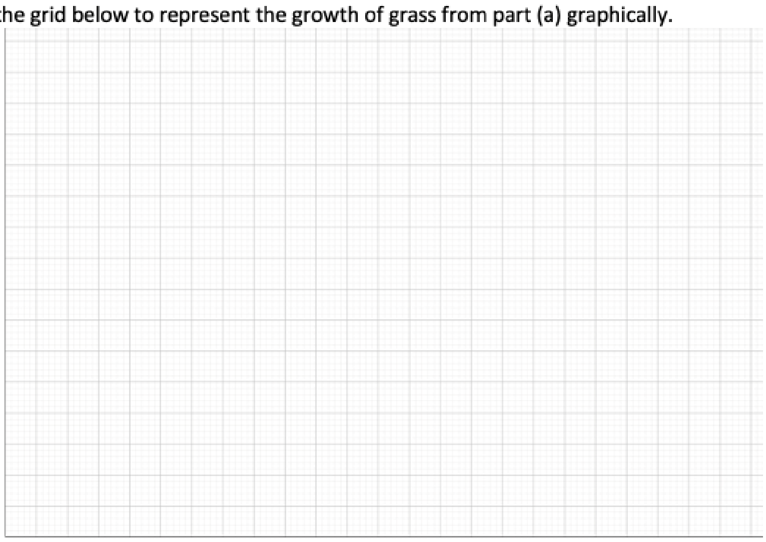

Figure 2. Excerpt from a student worksheet based on the farming interview which formed the basis for the teaching of arithmetic sequences

Initially, eight schools were approached, and their TY teachers were invited to take part in the Career Mathways initiative, but ultimately only five secondary schools (184 students) participated in this pilot study. The teachers were invited to attend an induction evening in the researchers' university where they were provided with all the resources created for the Career Mathways initiative. They were given 12 weeks to implement the initiative with their TY classes. There was enough flexibility within the project to allow teachers to select which careers or mathematical topics they wanted to focus on. The research team remained in regular contact with the participating teachers throughout its implementation. The focus of this stage of the project was not on professional development, but on piloting the initiative and seeing how the teachers and students implemented the teaching and learning package. There was, however, a two-hour induction to introduce the range of resources to the teachers and discuss the possible ways in which it could be utilised in the classroom. The intervention itself and its evaluation will be detailed in another paper.

CONCLUSIONS AND RECOMMENDATIONS

The capacity of secondary school students to appreciate the relevance and utility of mathematics in future study and careers is a problematic issue in mathematics education. One of the key factors that influences a student's subject choice is their perception of how useful the subject will be for further study and for career purposes (Bennett et al., 2014; Johnston, 1994; Jones, 1988; Matthews and Pepper, 2006; Mujtaba et al., 2018; Sheldrake et al., 2015; Tripney et al., 2010). Research shows however that students do not see the relevance of the mathematics they study at school to their future (Brown et al., 2008; Kyriacou and Goulding, 2006) or the real world (Quilter and Harper, 1988). The teachers interviewed in this study also confirmed this to be the case in Ireland.

Brown et al. (2008) recommend that the usefulness of mathematics be communicated through the curriculum in the classroom. Freudenthal believed that mathematics education should be designed and delivered in a way that will facilitate the solving of problems in everyday-life situations, as that is the capacity in which the majority of those who study mathematics will require it (Gravemeijer and Terwel, 2000). Embedding real-world contexts within mathematics has the potential to highlight its relevance to both students and teachers, and can act as a vehicle to boost motivation, interest and achievement (Honey, Pearson and Schweingruber, 2014; Hoogland, de Koning, Bakker, Pepin and Gravemeijer, 2018; Laurens et al., 2017). Furthermore, the move from real-life to the abstract (horizontal and vertical mathematising), as emphasised in RME, is critical for students to progress in the discourse of mathematics, and thus was selected as the framework for the intervention described in this study.

Careers education needs to help broaden students' awareness of the value of mathematics qualifications and the wide range of further study and career opportunities they open up (Archer et al., 2013). Archer et al. (2013) endorse embedded models of careers education, where teaching and learning is purposefully linked to various careers as much as possible. Embedded STEM careers education entails teachers of STEM using materials and pedagogic practices to communicate how STEM subjects are used in the world of work (Reiss and Mujtaba, 2017). It has been shown that interventions of this nature are effective in nurturing engagement. Effective careers education provision must incorporate the creation of a range of teaching and learning resources, alongside appropriate Continuing Professional Development (CPD) (Bennett et al., 2014). However, successful implementation of effective careers education into the curriculum of schools will not happen without appropriate support for teachers in place (Archer et al., 2013). It is difficult for teachers of any subject to combine enrichment activities with their teaching duties in an already crowded curriculum (Smart and Rahman, 2008). The teachers interviewed in this study stated the textbooks used in their classrooms do not fulfil this purpose and while there may be resources available on the internet, it can be very time-consuming to find ones appropriate for their students. Career Mathways is a suite of teaching and learning resources that offers a potential solution to issues of relevance and embedded careers education where teachers are already overburdened as it marries careers education with mathematics content on the school syllabus. It is one way of addressing the issue of the relevance of mathematics alongside the limited resources, and time, available to secondary school teachers to impart this in a realistic and effective way. In addition to CPD for inservice teachers, careers education for preservice teachers in Initial Teacher Education is also worth exploring. The researchers in this study who are all mathematics teacher educators have already started to embed the relevance of mathematics in careers within mathematics pedagogy modules in their institution. In this way, future teachers of mathematics are informed on this topic before they even qualify.

In this paper we provide an explanatory account of the exigency and design of an educational intervention to improve the knowledge of secondary school teachers and students of the relevance and utility of mathematics within a range of careers. In developing this intervention, we drew on a range of evidence including: literature from other countries where relevance has been an issue in mathematics education, an analysis of textbooks in Ireland, and interviews with experienced teachers. We conclude the description of this pilot study with three main recommendations for the future of Career Mathways. Firstly, we recognise the need for a comprehensive evaluation of the programme. The development of a valid research instrument to measure the impact of Career Mathways on student knowledge and engagement with mathematics needs to be created and administered, to provide empirical evidence that the intervention is a success. Secondly, arising from the evidence attained from the teachers interviewed in this study the creation of a professional development programme to prepare and support teachers who wish to embed the Career Mathways initiative (or any similar initiative) in their classrooms is necessary. This will ensure the programme is implemented appropriately in a manner that informs and supports the enhancement of students' knowledge regarding the relevance and utility of mathematics. Finally, research indicates that issues of relevance and utility are not solely the concern of mathematics and are contributing factors to poor participation rates in other STEM subjects (Archer et al., 2013). It has been shown that many young people and their families have a very superficial understanding of how STEM plays a part in scientific and non-scientific careers (Bennett et al., 2014). We believe that Career Mathways is an initiative that can easily be extended to these disciplines, where engagement and participation levels need enrichment.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 08
ISSN: 2468-4368

Tech Lunar Toilet: A STEM Project with High School Students

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Citation: Bustamante, D. G., Perez, A. M., Calderon-Cerquera, K., Orozco-Donneys, C., Orozco, A. M. and Giron-Sedas, J. A., Perea, J. D. (2021). Tech Lunar Toilet: A STEM Project with High School Students. *European Journal of STEM Education*, 6(1), 08. https://doi.org/10.20897/ejsteme/11322

Published: November 5, 2021

ABSTRACT

We performed an innovative STEM outreach project. High school students from the Colombian robotics' designed a prototype of a Lunar Loo named Tech Lunar Toilet (TLT) that was part of the international HeroX-NASA Challenge. These experiences were possible thanks to a wonderful network of collaboration. As a result of this program, the students that participated were able to cultivate their curiosity, strengthen their scientific skills and increase their interest in pursuing careers in STEM fields. Simultaneously, they were able to contrast visual and instrumental data obtained from the robotics and new technologies that can be performed in the microgravity environments for future space explorations. The efficient TLT suction system will guarantee proper operation in both microgravity and lunar gravity. Most of the structure can be built in a 3D printer using PLA as a raw material. This polymer made from renewable resources with mechanical properties comparable to the petroleum-based ones will allow reducing the weight of the structure. We recognized that our project-based education is a powerful engine for development. We share our methodology for the construction of our TLT that can be used in microgravity. We also show the progression and impact of this innovative project of scientific dissemination.

Keywords: democratization of outer space, STEM education, science, outreach, education, democratization of science, social-scientific, lunar toilet, robotics

INTRODUCTION

Increased community participation and understanding of the importance of contributions from science, technology, engineering, and mathematics (STEM) are social change drivers (Kendall-Taylor, 2017). Because STEM education has the potential to strengthen a country's economy, educational programs with an emphasis on science, mathematics, technology, and engineering have become a global priority (Quigley and Herro, 2016; Kelley and Knowles, 2016). Several countries have been implementing strategies in the teaching of STEM careers, generating technologically advanced societies. Such is the case of South Korea, Germany, Singapore, among others. Since the provision of educational services and programs aimed at the democratization and appropriation of scientific knowledge requires large investments for implementing STEM educational strategies at the national level, the integration of such strategies into the educational systems of low- and middle-income countries has proven to be very difficult. While the challenges of implementing STEM education strategies vary from country to country, lack of resources, resistance to curriculum change, and social inequality are prevalent issues in countries with high poverty rates and poor infrastructure (Savage, 2018).

The conditions of outer space require appropriate technology and tools to deal with the consequences of microgravity, reduced water supply and restricted diet, among others, on the human body during medium and long term space missions. The development of human metabolic debris collection for spacecraft presents some important challenges in microgravity conditions. The capture and separation of feces and urine from crew members and the reduction of water use are examples of things to consider in this technology. In this context, we present the *Tech Lunar Loo*, which is a pre-treatment and treatment system for the use and final disposal of organic waste under zero and microgravity conditions. In this case, the safe, reliable and economic way of integrating the Environmental Control and Life Support System (EC-LSS) and the systems used in the International Space Station (ISS), allows us to have a novel configuration in addition to new elements to the systems designed previously, since it implements the principle of modularity and does not compromise the operation of other components, optimizing the process at a low cost. Our system is composed of three stages for the management of organic liquid, solid and solid/liquid waste. In addition, it has physical and chemical treatment phases (filtration, disinfection, dehydration, and stabilization). Typically, there are different methods to treat urine, feces, vomit, diarrhea and menstruation both on Earth and in outer space. Traditional methods of separating liquid and solid waste are proposed in this article.

WHY COLOMBIA?

Throughout history, Colombia has suffered from a diverse range of socio-economic issues that arise from widespread corruption, drug trafficking, and an ongoing internal conflict that has severely affected rural communities for more than six decades. However, the Colombian government signed a peace agreement with one of the many armed groups that participated in the armed conflict (LeGrand et al., 2017). Other armed groups continue to make a war that affects farmers, rural communities and are also causing many deaths of social leaders throughout the country. Research reveals that increased community participation and understanding of the importance of STEM fields' contributions are drivers of social change (Kendall-Taylor, 2017). Yet, the scientific advancement in countries like Colombia requires large investments in infrastructure and a diverse offer of educational services and programs aimed at the democratization and appropriation of scientific knowledge. In this sense, the articulation between different economic and academic sectors with international cooperation is fundamental for the country's scientific advancement.

As scientists and Colombian citizens, our group is committed to strengthening STEM education in Colombia. To achieve this goal, we collaborated with public and private entities to work with one of the population groups with the most significant social transformation potential: middle and high school students. To do so, we brought together highly recognized international scientific actors to collaborate in an *avant-garde* scientific experience, and at the same time, gain a better understanding of the wide diversity of social contexts in the country.

OUR METHODOLOGICAL APPROACH

The latest technology developments have become space investigation, a milestone that was only available and sponsored by the wealthiest governments. It is expanding, and now, it is an initiative funded by private organizations (Smith et al. 2012; Bugga and Brandon, 2020; Ackerman, 2020). The new generations should equally have access and encourage them to enjoy STEM fields worldwide. For that, it is compulsory to promote STEM initiatives. Educational efforts to spread STEM education, such as Cubes in Space, drive initiatives to encourage STEM projects for underrepresented and low-income groups that originally these scientific contributions due to the lack of infrastructure and mechanisms have not been relevant. In our project with MyRoboTech S.A.S, we considered these restraints and set up the development of this plan. MyRoboTech S.A.S is an educational institution that supports students in science, electronics, mechatronics, and robotics drives in enhancing self-thinking, manual skills, creativity, and management in solving problems combining science and innovation.

In our project, the students are given a space where they have a greater approach to the development of technology, being a doer and not just a consumer, with the purpose of making them inventors, creators, innovators and entrepreneurs. The ideation phase of the project begins with the proposal by HeroX-NASA. The ideation consisted of presenting a prototype of a toilet that adapts to lunar gravity and microgravity conditions. Through Newtonian mechanics and robotics classes, the main bases were given to understand the effects of microgravity. The aspects that would involve using liquids and other essential factors to take into account in space were investigated through videos of astronauts' experiences developed in the International Space Station (ISS). After

Figure 1. Flow chart of the methodological process

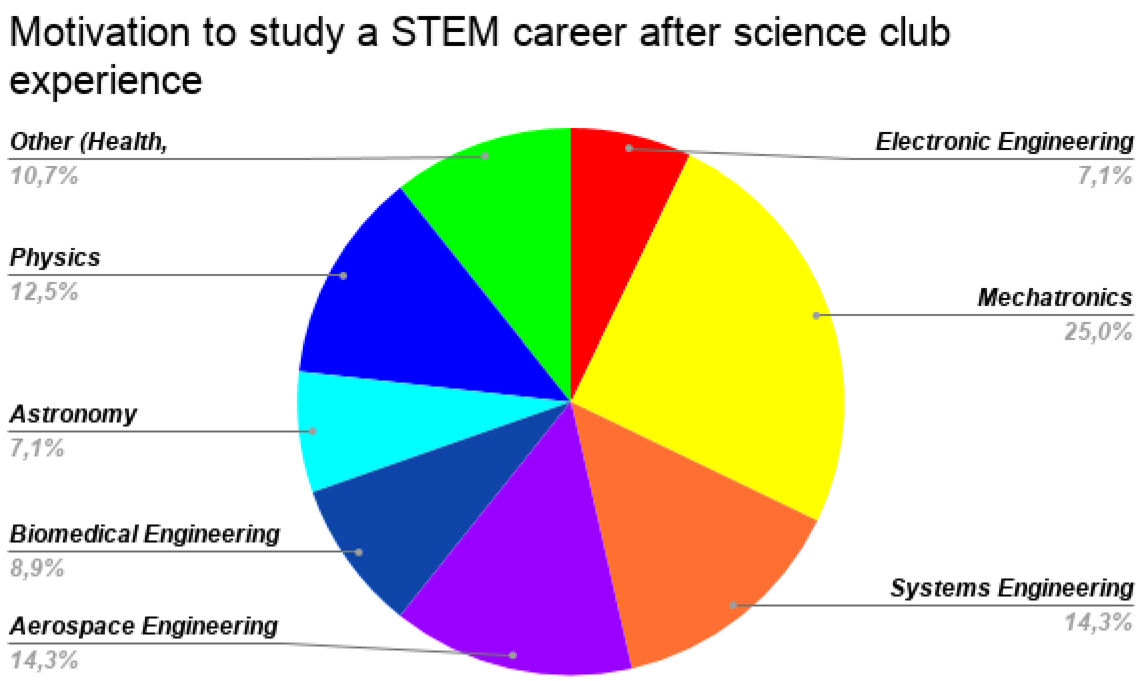

Figure 2. Pie chart of the future STEM careers of MyRoboTech's children choice

understanding the essential characteristics, a brainstorming session was developed. The children made the respective presentations to our working group, which was resolved to question how they could develop the best toilet on the moon? We took the best ideas with a group of scientists and mentioned them to implement a preliminary design. Here, we divided the working group of children into three teams. According to their expertise in mechanical, electrical/electronic, and programming. Each of them had the feedback according to the process to reach a design with modular features, mechanical development easy to use and low weight, so it was finally raised in the mechanical design development in 3D with PLA filament, easy installation. All measures were acceptable for the project and programming to implement the Internet of Things (IoT). Finally, each of the design proposals was integrated and adapted to the final design. **Figure 1** shows a flow chart to illustrate the process.

Finally, we wanted to know about the motivation and future application in STEM careers, given the fact that 100% of MyRoboTech students will intend to study STEM careers. In this case, we wanted to know to which careers they would apply and how these projects oriented them to decide on which topic. It is worth noting that there is an extension of these results in Supporting Information, also giving a close look at the percentage of girls in STEM. **Figure 2** shows a percentage of the STEM careers that MyRoboTech students will apply when they finish their school studies.

MAKING THE TECH LUNAR LOO

At this toilet design (**Figure 3**), the astronaut ergonomy is considered. The best position of his body during the toilet usage, considering both men and women. Once the astronaut takes a seat, the device turns on.

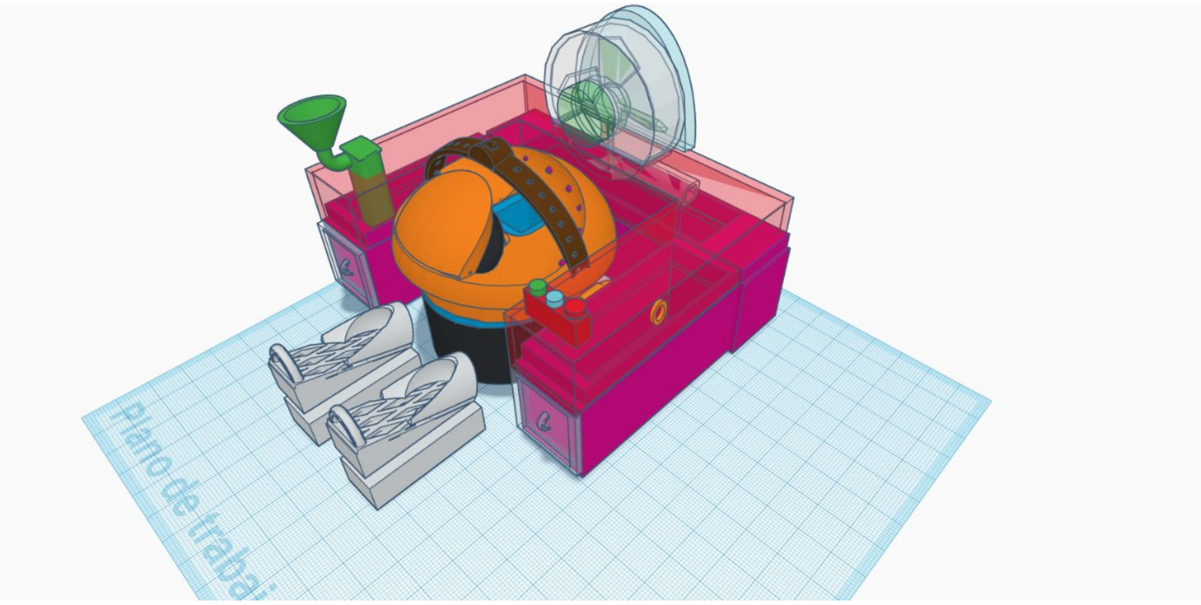

Figure 3. Final mechanical design of the Tech Lunar Loo

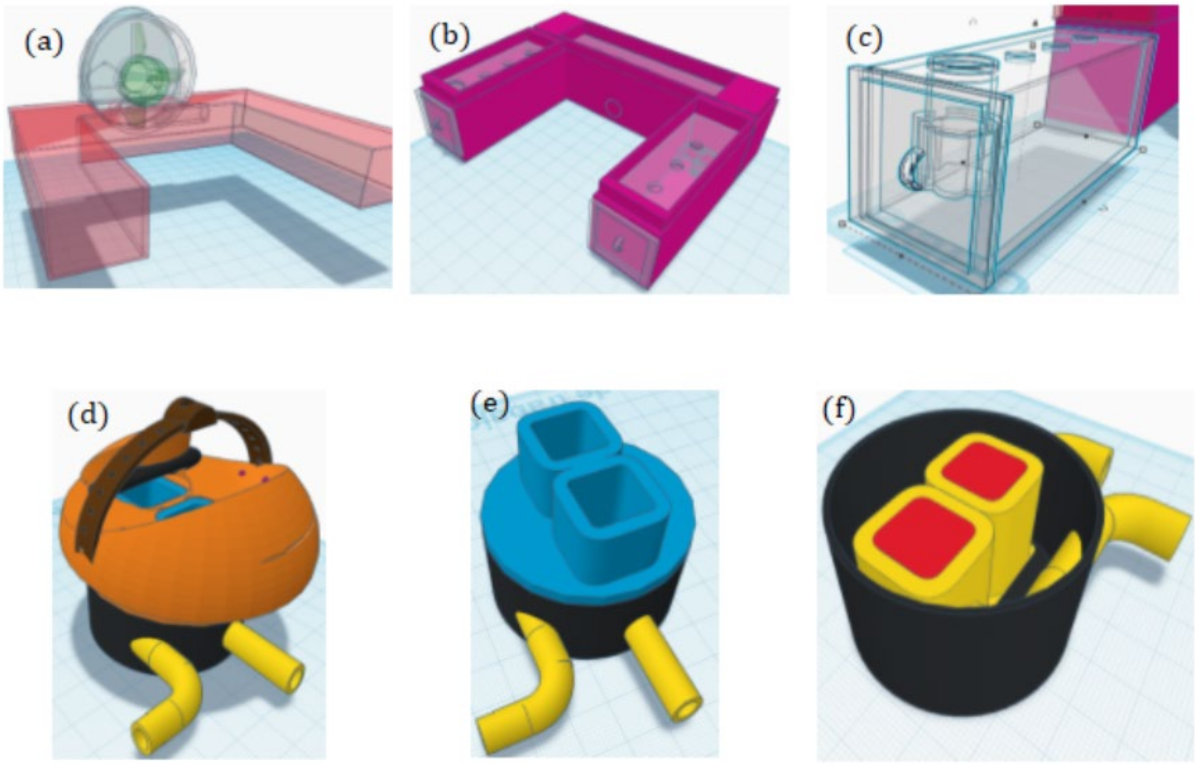

Figure 4. Tech Lunar Loo with easy to install modular system: (a) upper vacuum module, (b) lower vacuum module, (c) storage compartment, (d) chair with strap and genital locking system, (e) valve connection duct, and (f) liquid and solid valve system

The suction system is then activated when the lower sluice detects a pressure differential in any of the two cavities and allows the passage of the waste to the bag subdued into negative pressurization. This system avoids unpleasant odors in the toilet cabin. The negatively pressurized cabin is easily disassembled to fix any damage. Inside it is sealed with a material covering the 3D impression's porosity until 10 PSI, using a plastic band on the lower part; this improves the equipment sealing. The toilet bowl has an inclination of 15° for the better ergonomic position of the astronaut. The system is sealed and perfectly aligned, which makes the piece replacement. According to the change of pressure on any of the three entry cavities, the suction system has two servomotors to open or close the cavity gate. In the case of a positive pressure change, the gate is open. As the gate is closed in the case of negative pressure change, the waste is carried to the respective bag. Something important to highlight in this toilet design was the ease given to the crew to assemble and disassemble the complete assembly (**Figure 4**).

On the other hand, we considered that each part is manufactured on a 3D printer with polylactic acid (PLA). PLA is a biodegradable thermoplastic made from renewable resources such as corn starch or sugar cane. Making easy disposal and returning to the natural life cycle.

The toilet has a UVC ray-based disinfection process, which is performed when the toilet is not in use, and it requires at least 15 minutes for cleaning. The astronauts can activate manually the suction system located to the right side for throwing up. Once used, the astronaut must change the deposit funnel and throw it in the fecal matter hole. On the left side, the astronaut can find wet towels to clean any part of their body. Security is essential for the crew. Thus, the Tech Lunar loo has a Bluetooth system of communication and a Door Color Lights Code, which activates the emergency system if anyone in the toilet is at risk and controls the temperature-humidity in the bath. The electronic system (Supporting Information) was designed with the HeroX contest's specifications and the students' ideas with the bases provided by MyRoboTech S.A.S Academy. Our ideas included the internet of things (IoT) bases for real-time communications between the main cabin's electronic systems with the toilet, which included the voltage regulation system (a future work would include principles of self-driving labs as (Langner et al., 2020)). We also included humidity sensors, temperature in circuits and cabin, passive infrared presence sensors (PIR), external, internal lighting system, differential pressure sensor in the two ducts and proportional valve closure by servomotors, button panel for manual-automatic use, vacuum system with the blower motor, servomotors with mechanical pressure sensor for closure system in genitals and continuous disinfection system by UVC rays, all controlled by an Arduino UNO which will help us with the control strategy and sending data via Bluetooth.

CONCLUSIONS

Our results show that cutting-edge research can motivate young people in society and produce extraordinary results. By carefully preparing the experiments, we have proven that our toilet named Tech Lunar Loo that we proposed employed robotics, programmation.

Our team has been supported by several active academics interested in science and outer space democratization as an engine for social and scientific change. Our project gained momentum thanks to their contribution and allowed the participation of new actors who intensified our methodology's replication and continuous implementation. Thus, our project arises from a cooperative approach that develops science, technology, and mathematics education in a small city in Colombia, and contributes to the strengthening of scientific culture. We hope that shortly, the students who benefited from this type of program can help increase our planet's sustainable development.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 09
ISSN: 2468-4368

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Promoting Geometric Reasoning through Artistic Constructions

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Citation: Courtney, S. A. and Armstrong, B. (2021). Promoting Geometric Reasoning through Artistic Constructions. *European Journal of STEM Education*, 6(1), 09. https://doi.org/10.20897/ejsteme/11332

Published: November 9, 2021

ABSTRACT

In order to promote geometric understanding, teachers frequently use hands-on activities. Such activities can be used to expound upon the declarative statements and theorems of geometry. Using a compass, straightedge, and protractor, students are able to actively build conceptions involving bisectors, midpoints, and perpendicular lines. Additionally, activities that require students to problem-solve and formulate problems, using their construction knowledge and skills, can reinforce and strengthen that which they have learned. This article describes STEAM instruction with high school geometry students designed to productively integrate geometric constructions, digital technology, elements of art, and principles of design to enhance students' geometric reasoning.

Keywords: geometric reasoning, geometric constructions, art

INTRODUCTION

Geometry and spatial sense provide students with understandings and ways of thinking that can be applied in a variety of contexts. In addition, geometric reasoning offers ways to interpret, describe, and reflect on our physical environment and can serve as a tool for study in other areas of mathematics, the sciences, and various real-world situations (National Council for Teachers of Mathematics, 2000, p. 41). In the United States, Geometry not only frequently represents a high school student's first formal introduction to abstract reasoning, but the Common Core's Geometry conceptual category also places "new emphasis on geometry proof and construction (*prove geometric theorems, make geometric constructions*)" (Harel, 2014, p. 25)—concepts well established as one of the most difficult for students and their teachers (e.g., Battista and Clements, 1992; Chavula and Nkhata, 2019; Erduran and Yesildere, 2010; Harel and Sowder, 2007; Hart, 1994; Yackel and Hanna, 2003).

Prior research has examined instruction designed to promote students' mathematical reasoning, particularly as it relates to proof, through a focus on increasing teachers' awareness of students' cognitive skills, attitudes, and misconceptions (Mistretta, 2000), students' intellectual need (Harel, 2013; 2014), technology (e.g., Battista, 1998, Hollebrands, 2007), and the organization of students' knowledge (Lawson and Chinnappan, 2000). In this article, we describe a high school Geometry teacher's attempts to promote a STEAM environment by providing her students with opportunities to use geometric constructions, and mathematically challenging and aesthetically pleasing geometric figures in mathematical proofs; specifically, the report addresses the following research question: How can a high school Geometry class integrate geometric constructions, digital technology, elements of art, and principles of design to enhance students' geometric reasoning?

GEOMETRIC PROOFS AND CONSTRUCTIONS

In Geometry, proof can take on different forms, such as: two-column, informal, indirect, and paragraph proofs. Geometric constructions are valuable to proof because of the hands-on way that students are motivated to visualize theorems as they "come to life" with compass and straightedge. According to Sanders (1998), "Geometric constructions can enrich students' visualization and comprehension of geometry, lay a foundation for analysis and deductive proof, provide opportunities for teachers to address multiple intelligences, and allow students to apply their creativity to mathematics" (p. 554). Integrating hands-on activities and proof through geometric constructions, not only promotes greater student interest, but also provides students with more meaningful learning experiences.

Research by Middleton (1995) indicates that hands-on activities are considered to be motivational by both teachers and students. Furthermore, Bergin (1999) describes hands-on activities to be one of the situational factors that positively influences classroom (i.e., student) interest. According to Bergin (1999), "People seem to be interested in hands-on activities, activities in which they manipulate materials, move around, and engage learning in a physical way" (p. 92). In her own classroom, the second author engages students in such activities that include straightedge and compass constructions. Furthermore, the second author regularly takes a practical approach to STEAM education through arts integration, which Liao (2019) asserts is often "discussed at the level of instructional approach and lessons, although its larger goal is also 'integration,' which can be implemented in a variety of ways" (p. 41).

STEAM EDUCATION

Goldsmith et al. (2016) suggest the "development of visual-spatial thinking through the visual arts could support geometry learning for students who are not succeeding in mathematics classes" (p. 56). In addition to providing much-needed motivation, an important value of explicitly connecting mathematics and art is that it "can illuminate pupils' understanding[s] of some of its purpose" (Hickman and Huckstep, 2003, p. 2). The mathematics community often talks about beautiful or aesthetically pleasing theorems or theorem proofs in much the same way the art community talks about beauty (Malkevitch, 2003, Introduction section, para. 4). For Hickman and Huckstep (2003) there is "an undeniably aesthetic dimension to mathematics . . . [that] is not simply confined to the notion of an 'elegant solution' to a problem" (p. 4). Rather, mathematics itself has "aesthetic properties and . . . one can have an aesthetic experience through mathematics, while acknowledging that aesthetics is not confined to artistic activities" (Hickman and Huckstep, 2003, p. 4).

STEAM education has been described as "intentionally integrating the concepts and practices articulated with 21st-century skills in curriculum, instruction, assessment, and enrichment, while purposefully integrating science, technology, engineering, arts (including but not limited to the visual and performing arts), and mathematics" (Gettings, 2016, p. 10). The activities described here incorporate STEAM concepts to promote creativity, digital technology (i.e., dynamic geometry software), and Thuneberg et al.'s (2018) assertion that the "aesthetic elements of . . . art promote understanding of mathematical concepts by exposing students to concrete space and shape experiences" (p. 153). In the following sections, we describe the second author's implementation of a sequence of high school mathematics activities designed to provide students with opportunities to engage in geometric reasoning and develop meaningful understandings involving geometry and proof through artistic compass and straightedge constructions and digital technology. Taking note of Gettings' (2016) warning regarding the danger of superficially including art in STEM projects, the sequence of activities utilize art to enhance students' geometric reasoning.

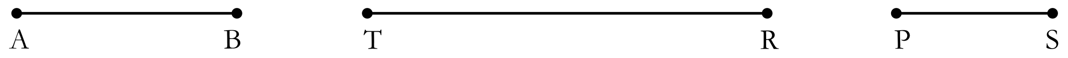
METHODS

The activities described below are utilized by the second author as part of her Geometry curriculum at a small private suburban high school in the midwestern United States. Although the school is a private, college-preparatory institution, 40% of the student population receive financial aid, and 25% of students come from minority populations (below the state average of 30.4%). Furthermore, the average class size of 19 students is smaller than the state average of 20.7 students.

Data is comprised of class handouts (e.g., activity sheets); student work (written and using GeoGebra); the second author's recollections of her students' questions, discussions, assertions, and reactions to the activities; and video recordings of discussions between both authors regarding the rationale for each activity and their sequencing, anticipated and actual student responses, and potential lesson modifications.

Table 1. Common Core Content Standard Addressed by Lesson (NGA Center & CCSSO, 2010, p. 76)

Conceptual Category	**Geometry (G)**
Domain	Congruence (CO)
Cluster	D. Make geometric constructions
Standard	12. Make formal geometric constructions with a variety of tools and methods (compass and straightedge, string, reflective devices, paper folding, dynamic geometric software, etc.). *Copying a segment; copying an angle; bisecting a segment; bisecting an angle; constructing perpendicular lines, including the perpendicular bisector of a line segment; and constructing a line parallel to a given line through a point not on the line.*



1. Construct $\overline{XY}$ congruent to $\overline{AB}$.
2. Construct $\overline{VW}$ so that $\overline{VW} \cong 2\overline{AB}$.
3. Construct $\overline{DE}$ so that $\overline{DE} \cong \overline{TR} + \overline{PS}$.
4. Construct $\overline{QJ}$ so that $\overline{QJ} \cong \overline{TR} - \overline{PS}$.
5. Construct $\overline{XL}$ congruent to $\overline{AB}$.
   Construct the perpendicular bisector of $\overline{XL}$.
6. Construct $\overline{MN}$ congruent to $\overline{TR}$.
   Construct the perpendicular bisector of $\overline{MN}$.

Figure 1. Line Segment Constructions

Standards Addressed by Activities

Throughout the sequence of activities, the second author and her students investigate (as a class) segment and angle constructions, and angle and segment congruence. The first half of the four-day lesson (comprised of four 45-minute class periods) culminates with students individually constructing a perpendicular bisector to a given line segment. The Common Core content standard addressed in these activities are illustrated in **Table 1**.

Proof as an interactive, class activity, requires that students create logical arguments by employing meanings and reasoning, explicating their own thinking, and critiquing the reasoning of others. As such, the activities provide students with opportunities to engage in several of the Common Core Standards for Mathematical Practice (frequently identified as MPs). In particular, students engage in MP3 (Construct viable arguments and critique the reasoning of others) by making conjectures and building a logical progression of statements to explore the truth of their conjectures, by justifying their conclusions, communicating them to others, and responding to the arguments of their classmates and teacher (NGA Center & CCSSO, 2010, pp. 6-7). In addition, students will need to attend to precision (MP6), by examining claims and making explicit use of definitions (NGA Center & CCSSO, 2010, p. 7), and use appropriate tools strategically (MP5) by becoming familiar with and utilizing tools (i.e., compass and straightedge) to "explore and deepen their understanding of concepts" (NGA Center & CCSSO, 2010, p. 7). Along with the mathematical content and practice standards described above, the activities also address two state high school visual arts standards (Ohio Department of Education, 2020, p. 4): "Integrate selected elements of art and principles of design to construct works of art" and "Increase relevant vocabulary to describe and analyze components related to visual art." Finally, we employ a definition for geometric reasoning as provided in NCTM's (2000) geometry standard, as to: "analyze characteristics and properties of two- and three- dimensional geometric shapes and develop mathematical arguments about geometric relationships; apply transformations and use symmetry to analyze mathematical situations; and use visualization, spatial reasoning, and geometric modeling to solve problems" (p. 41).

ACTIVITY HIGHLIGHTS

In order to support students in using their compass and straightedge, the second author projects her sample constructions directly to a SMART Board. The class completes most of the requested constructions together, but students are occasionally asked to solve problems on their own so they can internally develop the construction using their geometric tools. By using this more moderate pace throughout the activities, the second author provides time for students to create their own relational system for constructions (van Hiele, 1959/1985; van Hiele and van Hiele-Geldof, 1958).

Some of the constructions involving line segments that students are requested to complete are displayed in **Figure 1**. Note that students' constructions are completed on a separate sheet of paper and completion of these constructions conclude the first 45-minute class period.

Throughout the line segment construction portion of the lesson, students are motivated to share their thinking and reasoning both in pairs and as a whole class. When necessary, students are prompted to use appropriate

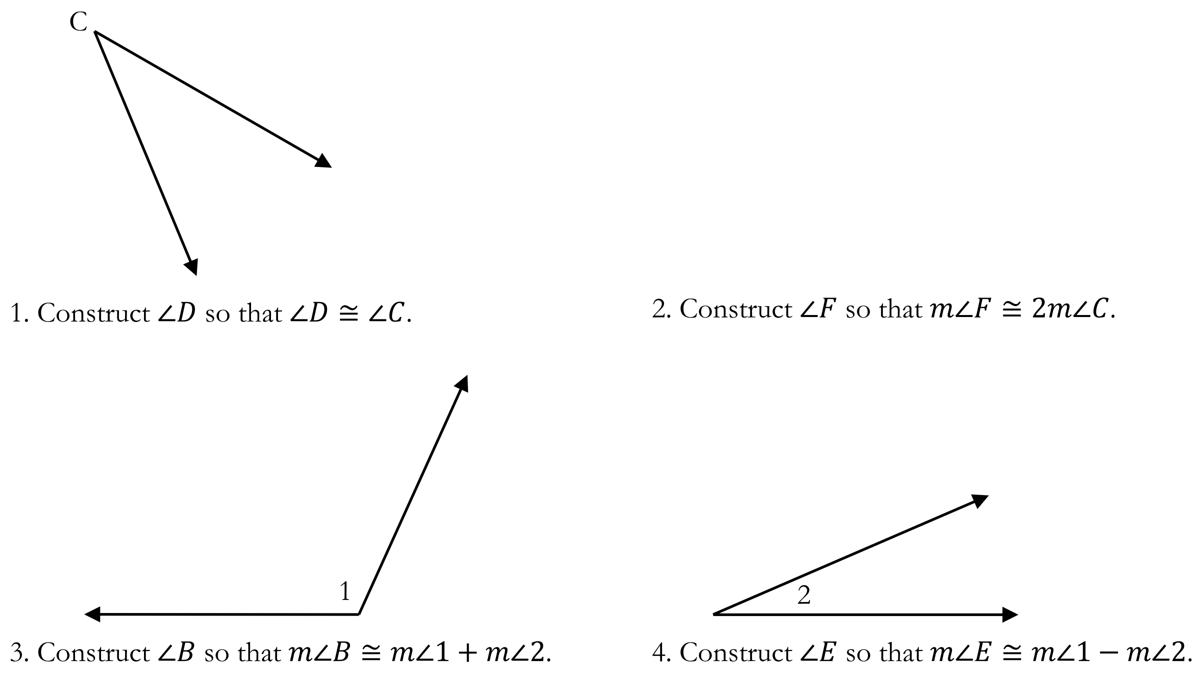


Figure 2. Angle Constructions

terminology (e.g., congruent). According to the second author, students typically extend the activity by asking one another questions such as:

- "Describe how to construct a perpendicular bisector of segment TR that is congruent to segment AB"; that is, describe how to construct a perpendicular bisector of $\overline{TR}$ that is congruent to $\overline{AB}$.
- "Describe how to construct a perpendicular bisector of segment AB that is congruent to twice the length of segment PS"; that is, describe how to construct a perpendicular bisector of $\overline{AB}$ that is congruent to $2\overline{PS}$.
- "Describe how to construct a perpendicular bisector of a segment with length equal to the sum of PS and TR that is congruent to 3 times the length of segment AB"; that is, describe how to construct a perpendicular bisector of $\overline{PS} + \overline{TR}$ that is congruent to $3\overline{AB}$.

These examples show students coordinating their understandings for congruence and perpendicular bisector and visualizing geometric constructions to formulate problems. A long line of research has shown the potential for problem posing to benefit student learning in mathematics (e.g., Cai et al., 2013; English, 1998; Yuan and Sriraman, 2011). The second author always allows time for students to complete some of these student-formulated problems.

Students also frequently question—either themselves, one another, or their teacher (i.e., second author)—whether attempts to construct $\overline{PS} - \overline{AB}$ could support their understanding of what it means for the "subtraction of a larger number from a smaller number to yield a negative result." As with students' other extension questions, the second author provides students with time to address this question prior to moving on to angle constructions. The second author asserts she must handle such instances with care and focus students' attention on the definition of the length of a line segment as "the distance between its endpoints" and that, as a distance, this length cannot be negative. Therefore, the line segment $\overline{PS} - \overline{AB}$ does not exist and the second author promotes (to her students) an understanding that the "difference of two line segments" is not the same as arithmetic subtraction.

Discussions between the two authors have included adding the question: "Describe how to construct $\overline{FG}$ so that $4\overline{FG} \cong \overline{TR}$ (or $\overline{FG} \cong \frac{1}{4}\overline{TR}$)." We concluded that in future classes, the second author would ask half of her students (working in pairs) to construct $\overline{FG}$ so that $4\overline{FG} \cong \overline{TR}$ and the other half of students (also working in pairs) to construct $\overline{FG}$ so that $\overline{FG} \cong \frac{1}{4}\overline{TR}$. Once these constructions are completed, the whole class would be asked to compare these two constructions in terms of their "ease of construction" and similarity of results.

Some of the angle constructions that students are requested to complete are illustrated in **Figure 2**. Note again that students' constructions are completed on a separate sheet of paper and these constructions comprise part of the second 45-minute class period.

As with the line segment constructions, students are prompted to share their thinking and reasoning, critique the thinking of others (including the teacher's), and use appropriate terminology throughout the angle constructions. Students again typically extend the activity by formulating their own problems for one another such as:

- "Describe how to construct an angle H so that the measure of angle H is congruent to the difference of the measure of angle 1 and the measure of angle C"; that is, describe how to construct $\angle H$ so that $m\angle H \cong m\angle 1 - m\angle C$.
- "Describe how to construct an angle G so that the sum of the measure of angle G and the measure of angle C is congruent to the measure of angle 1"; that is, describe the construction of $\angle G$ so that $m\angle G + m\angle C \cong m\angle 1$.

As with the student-formulated line segment construction questions, the second author always allows time for students to complete some of these angle construction extension questions. Furthermore, as with the difference of line segments problem—where the second line segment (subtrahend) is longer than the first line segment (minuend)—students frequently question whether the construction $m\angle 2 - m\angle 1$ is possible. The second author provides students with time to address this question and promotes the idea that the difference is given by $|m\angle 2 - m\angle 1|$ (Larson and Boswell, 2019a, p. 39). However, the second author also asserts (to her students) that although the definition of angle measurement does not support the concept of a negative angle, it is frequently useful (e.g., Trigonometry) to impose a convention so that the measure of an "angles is positive when the rotation of its terminal side is counterclockwise and negative when the rotation is clockwise" (Larson and Boswell, 2019b, p. 470).

One of the last constructions that students are asked to create during the second 45-minute class period states:

> Construct the perpendicular bisector of $\overline{XY}$ [a given segment]. Then bisect one of the right angles. Measure it with your protractor to check that it is a 45° angle and that your point of intersection divides $\overline{XY}$ into two congruent segments.

This problem requires that students incorporate two major concepts of construction: perpendicular and angle bisector. Class discussions related to congruent segments and 45° angles reinforces the definitions of midpoints, angle and segment bisectors, and perpendicular bisectors. Such engagement using hands-on tools and reflective discourse promotes student development of key understandings in geometry and supports geometric reasoning. After completing this last problem, the second author returns to the angle construction activity (**Figure 2**), where she poses the following questions:

- "Describe how the construction of $\angle F$ so that m$\angle F \cong 2m\angle C$ is related to showing $\angle C$ is the angle bisector of $\angle F$."
- "Determine n so that $n \cdot m\angle C \cong m\angle 1$."

This last question involves students making conjectures and attempting to determine n using straightedge and compass via trial and error and inductive reasoning, where, by inductive reasoning, we mean reasoning which places "emphasis on discovering patterns, interpreting information to make generalisations, and making analyses by finding similarities, differences and relations between the attributes" (Misrom et al., 2020, p. 159). This last question further provides students with out-of-class work, as the second author requests that students attempt to solve the problem in pairs or in groups of three.

CULMINATING CONSTRUCTION ACTIVITY

When finished with the first two 45-minute class periods (i.e., the first two activities), the second author gives her students an assignment that requires them to figure out how to replicate given constructions, such as an eight-petaled rose (based on an octagon) and a 12-pointed flower. Students are required to make their constructions larger than the given diagrams, making it impossible to simply copy the originals. Students use their straightedge and compass along with the understandings and skills they developed in prior lessons and the current sequence of activities to create these new objects. Finally, students are encouraged to color their constructions to enhance their aesthetic beauty.

There are no instructions provided for how to make their construction; rather, students are asked to problem solve and use inductive reasoning in order to create aesthetically pleasing constructions as illustrated in **Figure 3**. To determine whether an object or item is "aesthetically pleasing," students are asked to focus on critical features that contribute to aesthetic pleasure, such as "symmetry, balance, proportion, complexity, and so on" (Blijlevens et al., 2014, p. 101). Sample student work is shown in **Figure 3**.

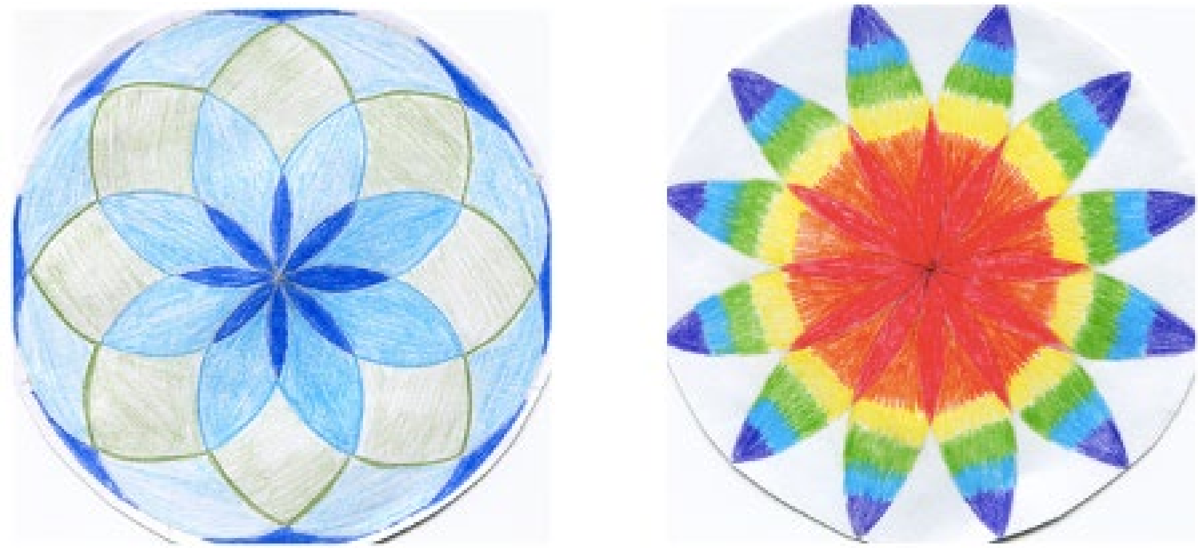


Figure 3. Eight-Petaled Rose (left image) and 12-Pointed Flower (right image) Constructions

Figure 4. Geometric Artwork

The eight-petaled rose is created by first constructing an octagon with straightedge and compass. Once students construct the eight points of the octagon, they use inductive reasoning to adjust their compass setting to obtain the small, medium, and large eight-petaled roses. For the 12-petaled flower construction, students first construct the six-petaled flower using their compass and the radius of a circle to create six evenly spaced arcs and points around the circle. Next, students continue using their compass and the same radius to construct six additional evenly spaced arcs and points around the circle. This results in the 12-petaled flower.

Near the end of the third day, the second author takes pictures of each construction and uploads these images to her students' Chromebooks. Once each student has the image of their construction uploaded to their Chromebook, students use their constructions to decorate the classroom with beautiful artwork (see **Figure 4**).

Hereafter, this artwork serves as a focus of discourse during parent-teacher conferences and subsequent classes.

ENHANCING STUDENTS' GEOMETRIC REASONING

During the fourth and last day of the lesson, the second author integrates GeoGebra's geometry application into the lesson. GeoGebra is a free interactive geometry, algebra, statistics and calculus application, available on multiple platforms and in over 25 languages, and a tool the second author's students regularly utilize throughout the school year. Once students have inserted their image into GeoGebra's interactive geometry environment using GeoGebra's image tool, the second author discusses selected elements of art, principles of design, and relevant vocabulary to help her students describe and analyze their constructions. Specifically, students are asked to think about line, shape, form, and color, and examine balance (i.e., symmetrical, asymmetrical, radial), pattern, and proportion in their constructions. As described by Esaak (2020), artists may signify a pattern using color, by

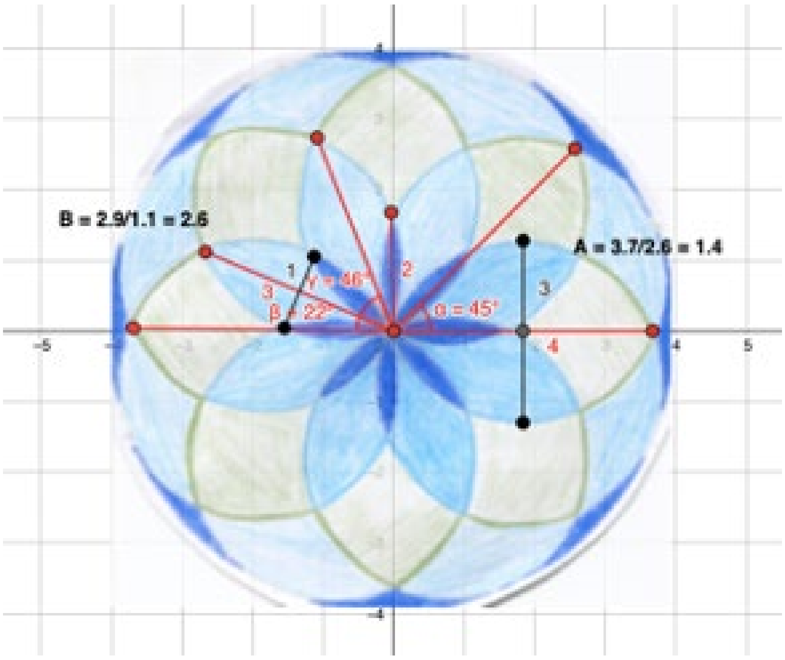


Figure 5. Examining the Geometric-Artistic Constructions in GeoGebra

"repeating a single or select palette of colors throughout a work" (para. 6), or by using lines, shapes, tones, textures and forms (MacTaggert, n.d.). Symmetry (or symmetrical balance) means that "the work of art is the same on one side as the other, a mirror image of itself, on both sides of a center line" (Issaquah Schools Foundation, 2021, para. 2). Conversely, asymmetry (or asymmetrical balance) means that "the two halves of the work of art are different, however . . . there will be elements that interact in a way that makes each side equally important" (Issaquah Schools Foundation, 2021, para. 3). Finally, radial symmetry means "the weight of the image or form radiates from a center point" (Issaquah Schools Foundation, 2021, para. 3).

The final activity involves students developing and analyzing hypotheses regarding their individual constructions, the constructions of two of their classmates, and sharing and discussing their results. Such actions support the integration of geometric constructions, digital technology, elements of art, and principles of design to enhance students' geometric reasoning. For example, one of the student's constructions, illustrated in **Figure 5**, is analyzed using several GeoGebra tools (e.g., point, segment, perpendicular line, and angle measure).

The seven elements of art (i.e., color, form, line, shape, space, texture, and value) are the "building blocks used by artists to create a work of art" (J. Paul Getty Museum, 2011a, p. 1). According to the second author, students typically describe and discuss the lines in their own and their classmates' constructions by focusing on the existence and placement of vertical, horizontal, diagonal, straight, and curved lines. Students also discuss form and whether an object has width. Finally, students typically focus on each object's colors including the name of the color used (i.e., hue), and how light or dark the colors are (i.e., value). Sample student responses include:

- "The contrast between the light and dark blues and the grey really make the smallest eight-petaled flower pop out in the drawing" (image on left in **Figure 3**).
- "I really like how the width of the grey overlapping petals is larger than the width of the light blue petals, which, in turn, is larger than the width of the dark blue petals" (image on left in **Figure 3**).
- "I wish the contrast between the red flower and the orange circle was greater, because it was challenging for me to see the inner flower" (image on right in **Figure 3**).

According to the J. Paul Getty Museum (2011b), the principles of design "describe the ways that artists use the elements of art in a work of art" (p. 2) and are comprised of balance, emphasis, movement, pattern, repetition, proportion, rhythm, unity, and variety. According to the second author, students typically discuss ideas of balance, including whether an object has symmetry or radial symmetry. Sample student responses include:

- "The color contrast between the red, orange, and yellow really makes the figure radiate outward from the center of the drawing" (image on right in **Figure 3**).
- "I think the repeating dark blue-light blue-green-yellow pattern the figure displays on each outer petal is very calming" (image on right in **Figure 3**).
- "I really thought the proportion of petal length to petal width between the grey petals and the light blue petals was going to be a whole number, like the light blue petal [i.e., petal length to width = 2.9/1.1 = 2.6] proportion was going to be twice as large as the grey petal [i.e., petal length to width = 3.7/2.6 = 1.4] proportion" (**Figure 5**).

- "Although GeoGebra's measurement tool indicated the small, dark blue petals occurred every 45°, which is what I expected, the light blue petals did not follow the same pattern, occurring every 44° or 46°. I must have been off somewhere in my construction" (**Figure 5**).

Though challenging, students find this sequence of activities to be very interesting and enjoyable. Through their engagement in the sequence of activities, students develop a sense of satisfaction and an understanding of the connections between geometry and art.

DISCUSSION AND CONCLUSION

The work that students do with geometric tools (such as compass and straightedge) helps them develop an understanding of significant geometric connections. Such connections, in turn, supports students' capacities to prove and problem solve. When students learn a geometric concept that is not coherent, that is, connected to nothing but a theorem in a book, sentences in their notes, or statements made by their teacher, they are not able to provide meaning to that theorem. In the preceding sections, we described a sequence of activities that integrated geometric constructions, digital technology, elements of art, and principles of design to enhance students' geometric reasoning. More specifically, we demonstrated how students analyzed characteristics and properties of two-dimensional geometric shapes, developed mathematical arguments about geometric relationships, used symmetry to analyze mathematical situations, and used visualization to solve problems.

Several authors have developed and utilized such tools or rubrics (e.g., Isaacson, 2012; Loong et al., 2018; Pegg et al., 1998) and these existing rubrics served as a starting point in our discussions for determining how best to capture and measure these notions. Ayuningtyas et al. (2019) developed assessment criteria for geometric reasoning based on five indicators (p. 4): observe pattern or regularity; formulate generalization and conjecture related with regularity observed; assess/test the conjecture; construct and assess mathematical argument; and describe/validate logical conclusion about some ideas and its relatedness. Burger (2013) developed a series of rubrics for use as part of a project in college-level Geometry that focuses on five criteria: accuracy, neatness, creativity, effort, and meeting deadlines/fallowing directions. Finally, Rajdl (2014) designed a five-point art rubric that incorporates the elements of art and principles of design. We are currently working to integrate these three rubrics into one instrument that would allow teachers to practicably capture and assess students' capacity to reason in geometry, accurately construction objects with straightedge and compass, and understand and incorporate elements of art and principles of design.

In addition to the lack of an instrument to measure students' understandings and skills, study limitations also included the small student sample, and the lack of video recordings or transcriptions of classroom discussions. The National Council for Teachers of Mathematics has long encouraged math teachers to "develop multiple representations and connections, and construct meanings from new situations" (NCTM, 1989, p. 125). The sequence of activities described in this article, implemented through a STEAM approach that focuses on the benefits of integrated learning (Liao, 2019), provide students with opportunities to develop such meanings and connections in the context of creating artistic geometric constructions.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 10
ISSN: 2468-4368

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The Process of Designing Integrated STEM Learning Materials: Case Study towards an Evidence-based Model

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Citation: De Meester, J., De Cock, M., Langie, G. and Dehaene, W. (2021). The Process of Designing Integrated STEM Learning Materials: Case Study towards an Evidence-based Model. *European Journal of STEM Education*, 6(1), 10. https://doi.org/10.20897/ejsteme/11341

Published: November 11, 2021

ABSTRACT

This study models the process of designing learning materials for integrated STEM (iSTEM) in secondary education, as gone through by four multidisciplinary teams of STEM teachers in Flanders (Belgium). In order to identify the crucial, counterproductive, and missing activities in the observed design processes, the learning materials developed by each team were assessed with respect to the key principles of iSTEM education. Crucial activities in the observed design processes appeared to be the formation of a multidisciplinary design team, a brainstorm on themes, the identification and linking of STEM contents, and the exploration of a feasible, engaging student challenge with interrelated subproblems. The observed processes lacked a specification of the targeted learning goals and the inclusion of research-based instructional strategies aiming at these goals. The evidence-based model of the iSTEM design process resulting from this study can fuel teacher training programs and empower pre- and in-service teachers to create high-quality integrated STEM education.

Keywords: integrated STEM, secondary education, teacher design teams

INTRODUCTION

An integrated, problem-centered approach to secondary STEM education is believed to be the key to piquing students' interest and at the same time fostering their robust understanding of STEM subjects (Kennedy et al., 2014). STEM teachers have a key role in establishing such integrated STEM (iSTEM) education, but are not trained nor supported to do so (Shernoff et al., 2017; Dare et al., 2018). The research literature on educational innovation (Voogt et al., 2011; Parke et al., 1997) suggests that teachers will be better prepared for implementing iSTEM education when they are at the driver's seat not only of its implementation, but of its design as well.

With these aspirations for secondary STEM education, the 4-year research project STEM@school was launched in Flanders (Belgium) in 2014 (De Meester et al., 2020). STEM@school engaged 30 teams of STEM teachers to implement iSTEM learning materials in their classroom, 10 of which were also involved as teacher design teams (TDTs) in the design of these learning materials. At the start of STEM@school, no concept for effective iSTEM education or learning materials tailored to the Flemish education system were available. In the scope of STEM@school, the study presented in this article investigated the activities teachers undertake to integrate learning contents from separate STEM subjects into the curricula of grades 9 to 12.

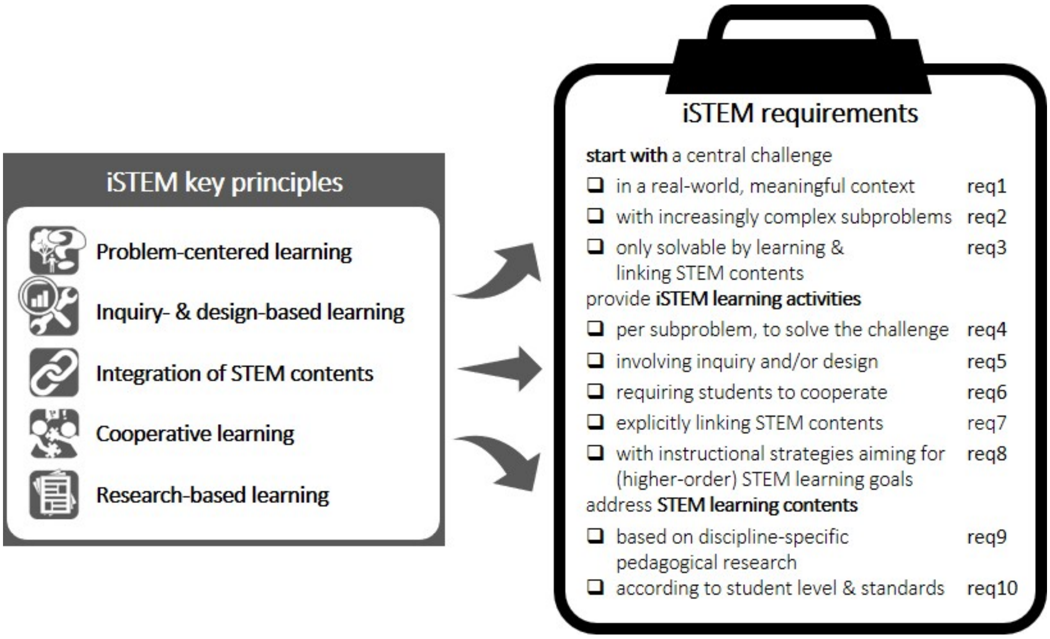


Figure 1. Key principles and requirements for high-quality integrated STEM education

THEORETICAL FRAMEWORK

iSTEM Key Principles and Requirements

From a comprehensive review of literature on integrated STEM, Thibaut et al. (2018) extracted four key principles that constitute effective iSTEM education: (1) problem-centered learning, (2) inquiry- and design-based learning, (3) integration of STEM learning contents, and (4) cooperative learning. To endorse the value of long-lasting (educational) research in each of the different STEM disciplines (NRC, 2012), we add the extra principle of research-based learning. As a result, we advocate the five key principles for establishing high-quality iSTEM education in secondary school classrooms shown at the left of **Figure 1** (De Meester et al., 2020). Based on the research literature on instructional design for integrated STEM education (NAE et al., 2014; Felder et al., 2016), we translated these five key principles into 10 requirements for high-quality iSTEM education, shown at the right of **Figure 1**.

iSTEM Curriculum Design

An effective way to prepare teachers for implementing a new instructional approach is to immerse them in the key principles underpinning this new approach (Loucks-Horsley et al., 2009). This particular strategy of active teacher involvement fosters their self-efficacy (Ingvarson et al., 2005), their beliefs (Girvan et al., 2016), and their classroom practices (Jeanpierre et al., 2005) in favor of the targeted principles. Involving teachers in *curriculum design* results in findings that are in line with these effects (Voogt et al., 2011; Mooney Simmie, 2007). Design can be considered a form of complex problem solving, involving interdisciplinary thinking, handling of multiple decisions and unanticipated problems, inquiry, collaboration in multidisciplinary teams, and a scientific basis to start from (de Vries, 2020; Jonassen et al., 2006; Stanovich et al., 2003). Teachers will thus experience the key principles of iSTEM education (**Figure 1**) firsthand when they participate in cooperative, interdisciplinary design of iSTEM learning materials, which, in turn, will prepare them to implement these principles in their classrooms.

The role of TDTs in curricular innovation has gained much interest in educational research, often in the context of professional development (Handelzalts, 2019; Coenders et al., 2015; Huizinga et al., 2014). However, there is little in-depth research on teacher endeavors to design *iSTEM* learning materials. Some studies report on teachers' experiences and struggles while designing integrated or context-based STEM materials (James et al., 2000; Stolk et al., 2016). Guzey et al. (2016), who examined 20 teacher-designed iSTEM learning units, concluded from their study:

> [I]ntegrated or interdisciplinary science curriculum is not a new concept; however, designing instructional materials for integrated STEM education is new for many teachers. Put simply, there are few resources available for teachers to help them develop integrated STEM curriculum materials and designing curriculum materials is a complex process. (Guzey et al., 2016: 14)

Little research has focused on the teachers' process itself when they are designing iSTEM learning materials. McFadden et al. (2017) observed two TDTs' design processes and visualized these processes via flowcharts. These flowcharts contain dilemmas and design decisions that reflect the particular group dynamics in the TDTs, but do not seem to be meant as general guideline for iSTEM curriculum design. Better generalizable are the design activities mentioned in the study of Satchwell et al. (2002). In their study, a team of nine competent middle-school teachers and researchers from different STEM disciplines engaged in (1) choosing a shared theme based on the national math and science standards and key STEM concepts, (2) developing a series of discipline-oriented objectives aligned with the national standards, (3) creating an introductory challenge to raise students' interest, (4) designing learning materials and authentic assessments to have students explore, study, and apply the new key concepts. The designed learning units were reviewed on content by STEM experts, and feedback from field-tests and classroom visits was incorporated afterwards. Satchwell et al. state that "[t]he development of a standards-based, integrated mathematics, science, and technology curriculum is a challenging task" (p. 16) and indicate that the development of a framework, field testing, collection of feedback, reflection, and revision are important parts of the design process.

These studies suggest that secondary STEM education would considerably benefit from more in-depth research on the specific *activities* constituting TDTs' actual iSTEM design process and on how these activities affect the designed learning materials. In this study, we translated the research literature's calls for guidance regarding the iSTEM design process into two research questions:

RQ1: How can we model the process teacher teams go through when they are designing integrated STEM learning materials from scratch? Which activities can we identify in their design process?

RQ2: Based on the learning materials designed by the teacher teams and the requirements for high-quality integrated STEM education, which crucial, profitable, detrimental, and missing activities can we distinguish in the design process we found in RQ1?

An evidence-based model and assessment of such activities could support school organization, teacher education, and professional development programs to better prepare and support STEM teachers to establish high-quality integrated STEM education (Guzey et al., 2016; Shernoff et al., 2017). It could facilitate teachers' design process, empower them to work in a systematic and organized way, and to communicate with a common language (Woods, 2000).

Outset of This Study

Regarding this study, the following initial conditions should be taken into account: (1) the participating teacher teams were not guided by the iSTEM key principles shown in **Figure 1**, since these were established during the successive research cycles of STEM@school; (2) the teacher teams were not guided by any design or problem solving framework. They were only guided by the aspiration of deepening students' understanding and stimulating their interest in STEM subjects by meaningfully integrating STEM learning contents. Given these conditions, we looked open-mindedly at how the teacher teams approached the design of iSTEM learning materials, and the design activities they engaged in. The iSTEM requirements in **Figure 1** are the criteria against which we evaluated the iSTEM learning materials designed by the TDTs, to assess the effect of each of the TDTs' design activities on the designed learning materials.

METHODS

An inductive, data-driven approach was applied to build a model describing teachers' process of designing iSTEM learning materials. We chose case study as research method because of the real-world and incontrollable character of the context in which this study would take place (Kitchenham et al., 1995; Yin, 2003). Each project year of STEM@school, a TDT was selected for the case study by means of purposive sampling (Mortelmans, 2007) until we obtained theoretical saturation (Eisenhardt, 1989). In total, four cases (C1, C2, C3, and C4) were studied, each involving a TDT engaged in the process of designing iSTEM learning materials from scratch. In order to construct a valid model of this process, we gathered and triangulated data from multiple sources of evidence (Yin, 2003), as shown in **Figure 2** and elaborated below.

Construction of the Case-based Model of the TDTs' iSTEM Design Process (RQ1)

Model construction via within- and cross-case process analysis (step 1.1) – Each case was first analyzed separately, in order to be able to identify unique patterns before generalizing them across cases (Eisenhardt, 1989). Therefore, the main researcher (first author) kept field notes and reports on the TDTs' design meetings, and memos on team dynamics. These data were supplemented by secondary data, such as e-mails sent among TDT members and coaches, annual planning schemes, materials, prototypes and presentations produced by the TDTs, as shown in **Figure 2**. First, open coding was used to label excerpts of meeting notes as particular actions, by means of direct interpretation

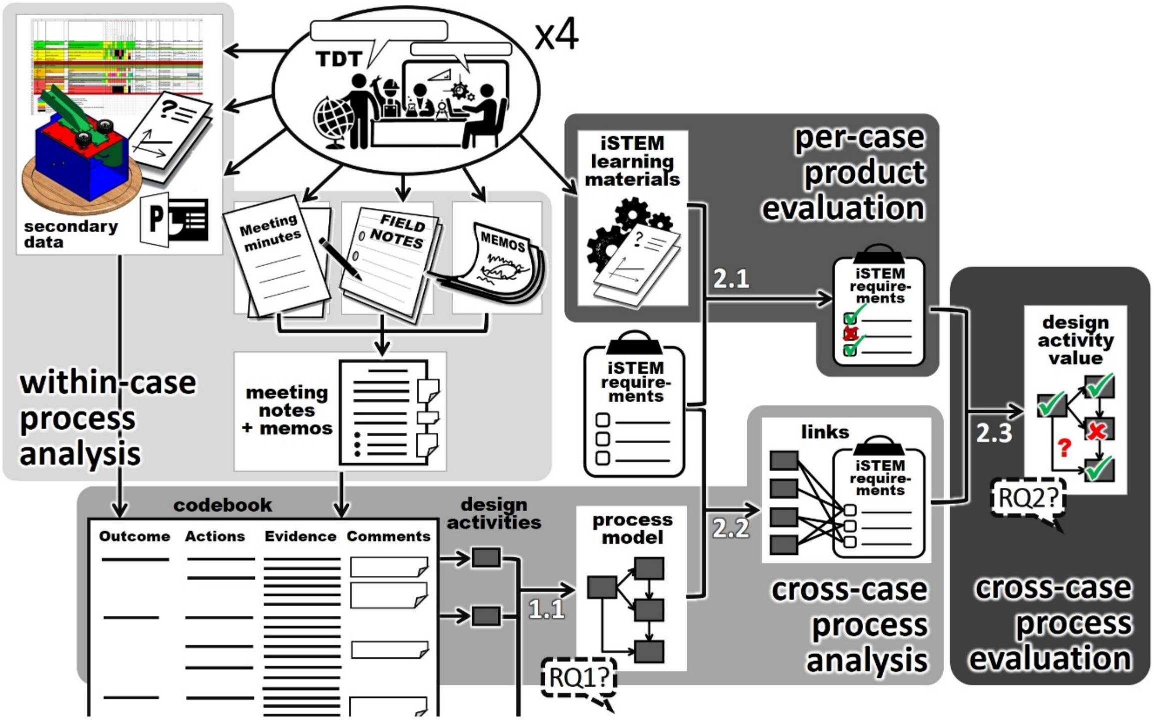


Figure 2. Data collection and analysis of this study

(Stake, 1995). The main researcher then engaged in axial coding (Charmaz, 2006; Stake, 1995): by means of a codebook, she interrelated codes that seemed to lead to one and the same outcome. Such outcomes were, e.g., a target group, an inventory of prescribed STEM curriculum standards, and a list of constraints for the central student task. Actions leading up to one outcome were classified under one category, i.e., a *design activity*. These categories were refined based on the secondary data. From C2 on, the main researcher performed a cross-case analysis (Eisenhardt, 1989) after the design process of a case had come to an end (see **Figure 2**): via constant comparison (Charmaz, 2006), she checked the data collected and codes generated in the different cases to see whether and which actions could be classified under design activities identified in the previous cases. On a weekly basis, the researcher discussed the data and her interpretations with other STEM@school researchers. They shared their perspectives until a consensus on the categorization was reached. **Appendix 3** shows the identified categories with their major actions (clustered codes) and outcomes.

Model validation (step 2.2) – To verify the veracity (or representativity) of the constructed model (Van Driel et al., 1999), we asked a teacher who had participated in three of the cases to draft a model based on his own impression of the iSTEM design process. He was asked to send it per e-mail. We compared his digital model to our case-based model to look for discrepancies.

Evaluation of the Design Activities Constituting the Case-based Model (RQ2)

To determine the crucial, detrimental, and missing activities in the observed design processes (RQ2), we triangulated data from multiple sources:

- the learning materials designed by the TDTs of each case,
- the iSTEM requirements shown at the right of **Figure 1**,
- the design activities constituting the case-based model resulting from RQ1.

Per-case product evaluation (step 2.1) – Three STEM@school researchers (among whom the first and last author of this paper) collectively evaluated the products of the studied design processes (i.e., the learning materials designed by the TDTs in cases C1, C2, C3, and C4) against the iSTEM requirements (see **Figure 1**).

Cross-case linking of the design activities to the iSTEM requirements (step 2.2) – Based on a concise list of their constituting actions, each of the design activities of the process modeled in step 1.1 was linked to one or multiple iSTEM requirements. Therefore, the main researcher and an external researcher (not associated with STEM@school and therefore unbiased by the events) individually assessed per design activity whether or not its actions (as shown in **Appendix 3**) could affect the fulfillment or failing of each iSTEM requirement. Afterwards, they compared and discussed the resulting associations until they reached a consensus.

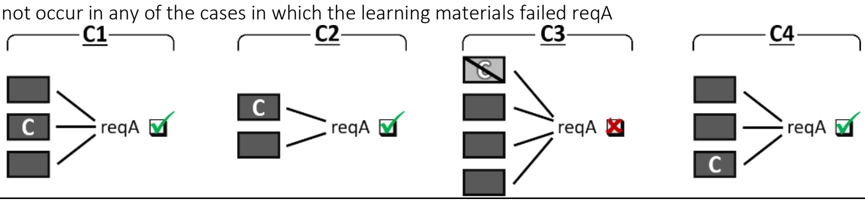
Cross-case process evaluation (step 2.3) – We interconnected the result of step 2.1 (i.e., the evaluation of the materials designed in each case against the iSTEM requirements), the result of step 2.2 (i.e., the links between the iSTEM requirements and the design activities of the case-based model), and the result of step 1.1 (i.e., the case-based

Table 1. Determination of the crucial, profitable, detrimental, and missing design activities

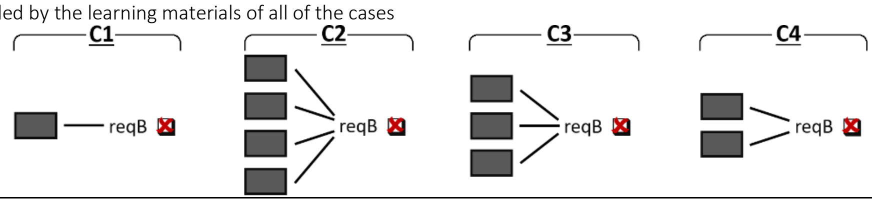
Meaning of the symbols			
A	= activity A was observed in this case	~~A~~	= activity A was not detected in this case
—	= link between activity and requirement	reqX	= iSTEM requirement (see right of Figure 1)
✓	= this requirement was fulfilled by the learning materials designed in this case	✗	= this requirement was failed by the learning materials designed in this case

Determination of the different types of activities

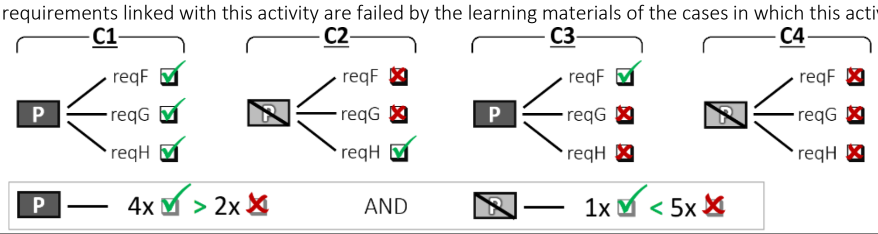
A design activity C is assumed to be **crucial** for reqA if
activity C is linked with reqA
AND activity C occurred in all of the cases of which the learning materials fulfilled reqA
AND activity C did not occur in any of the cases in which the learning materials failed reqA



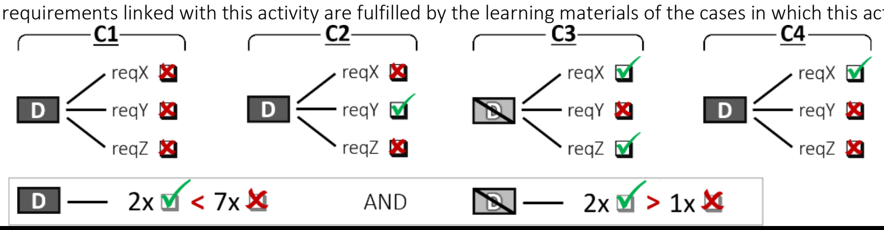
A non-observed design activity M is assumed to be **missing** for requirement B if
reqB was failed by the learning materials of all of the cases



A design activity P is assumed to be **profitable** if
most of the requirements linked with this activity are fulfilled by the learning materials of the cases in which this activity occurred
AND most of the requirements linked with this activity are failed by the learning materials of the cases in which this activity did not occur.



A design activity D is assumed to be **detrimental** if
most of the requirements linked with this activity are failed by the learning materials of the cases in which this activity occurred
AND most of the requirements linked with this activity are fulfilled by the learning materials of the cases in which this activity did not occur.



model with the occurrence or absence of the design activities in each case). Through this interconnection, the quality of the product of a design process was traced back to the occurrence or absence of certain design activities in the modeled process, using determination **Table 1**.

Context and Selected Cases

In autumn 2013, the STEM@school project team launched an open call among Flemish schools to sign up for trying out a new, integrated approach to STEM in their secondary education. The schools had to indicate whether they also wanted to participate in the design of this approach and associated learning materials. Thirty schools signed up to pilot the new iSTEM approach. The STEM@school team initially selected 10 schools to delegate a teacher team for the iSTEM curriculum design, based on whether their motivation favored interest and enthusiasm over political agenda (such as using the new approach merely as a pretext for student recruitment). The selection held a balanced mix between schools providing education with a science focus (S), and schools providing education with a technical focus (T). Each of these schools delegated one team of two to five teachers for the iSTEM curriculum design. From this 'big group' of teacher teams, each project year, the STEM@school team composed several multidisciplinary, cross-school TDTs based on considerations prevalent at that time (see **Table 2**). Out of these TDTs, we selected one team per project year for our case study by means of purposive sampling. The school team of C1 had presented itself to the STEM@school staff before the project was actually launched and was therefore included as an exploratory case. The context of the selected cases is shown in **Table 2** and **Table 3**.

Table 2. Participation and selection of TDTs

Year	Stage in STEM@school	Big group of teacher teams [a]		Basis for TDT composition	Selection for the case study [a,b]	Case
'13 – '14	Exploratory phase	1 school S: 1	4 TDTs	multidisciplinarity + within-school dynamics	1 TDT S: 1 (A_S)	C1
'14 – '15	First project year	10 schools S: 5 T: 5	4 TDTs	multidisciplinarity + geographical proximity	1 TDT S: 2 (A_S, C_S) T: 1 (B_T)	C2
'15 – '16	Second project year	8 schools S: 3 T: 5	2 TDTs	multidisciplinarity + fruitful previous cooperation + shared ideas for topics	1 TDT S: 2 (A_S, C_S) T: 3 (B_T, D_T, E_T)	C3
'16 – '17	Third project year	4 schools S: 2 T: 2	2 TDTs	multidisciplinarity + fruitful previous cooperation + shared ideas for topics	1 TDT S: 2 (A_S, F_S) T: 1 (G_T)	C4

[a] 'S' represents the number of teacher teams from schools providing science-focused secondary education,
'T' represents the number of teacher teams from schools providing technology-focused secondary education
[b] school codes (see **Table 3**) withing brackets

Table 3. Selected cases

Case	Learning materials		TDT members	
	Target group	Chosen theme	School [a]	Teachers [b,c]
C1	Grade 7	Biking ⇉ Motion in 1D	A_S	C1_Math, C123_Phys; C123_Coach
C2	Grade 9	Kinematics 1D ⇉ Automatic car through green wave	A_S B_T C_S	C123_Phys; C23_TA, C23_Elec1, C23_Elec2, C23_Math; C2_Math-Phys, C23_Phys, C23_Math, C23_Principle; C123_Coach
C3	Grade 10	Kinematics 2D + motor control ⇉ Ball launcher & stepper motor car	A_S B_T C_S D_T E_T	C123_Phys; C23_TA, C23_Elec1, C23_Elec2, C23_Math, C3_Elec; C23_Phys, C23_Math, C23_Principle, C3_Phys; C3_Mech1, C3_Mech2; C3_Elec, C3_Mech; C123_Coach
C4	Grade 11	Water treatment ⇉ Algae	A_S F_S G_T	C4_Chem; C4_Phys, C4_Bio-Chem1, C4_Bio-Chem2, C4_Math1, C4_Math2; C4_Phys-Chem, C4_Bio, C4_Elec; C4_Coach

[a] school code $_{\text{focus of education}}$, in which 'S' means science focus, and 'T' means technology focus
[b] pseudonym of participating teacher: case(s) in which s/he participated _ subject(s) s/he taught
[c] for background information on the participating teachers: see **Appendix 1**

For our purposive sampling, we implemented the following criteria (Mortelmans, 2007):

– *informational contribution and convenience* – TDTs who did not manage to get started properly in the iSTEM design were excluded from the case study. C1, C2, and C3 were selected because their TDTs were coached by the main researcher, which gave her plenty of opportunities to gather data on the iSTEM design process.
– *homogeneity* – To identify the influence of commonalities and to explore evolution in time on the identified pattern of design activities, we selected C3 based on its correspondence with C2 in terms of team composition, learning contents to cover, and team coach.
– *heterogeneity* – In order to identify commonalities in the design processes of TDTs *despite* variation, C4 was selected because its TDT composition differed completely from the TDT composition of C3 (different TDT members and coach). Furthermore, the stage of the TDT of each case in the project varied from zero years of design experience (C1) to three years of design experience (C4).

Apart from schools B_T and C_S (see **Table 3**), all participating schools agreed to the following terms proposed by the STEM@school team:

- The learning materials designed in year *i* would be implemented in the pilot classrooms in school year *i*+1.
- A new subject 'iSTEM' would be incorporated into the students' weekly timetable (see **Table 4**), especially designated for activities concerning STEM integration, inquiry, and design.
- Truly integrated learning materials cover contents from different STEM subjects. Therefore, not only the new 'iSTEM' subject but all of the involved STEM classes and their teachers would have to be engaged with the implementation of the materials.

Table 4. Traditional and adjusted weekly timetable of the study options in which the iSTEM learning materials were to be implemented

Subject	S schools		T schools	
	Sciences	Sciences-iSTEM	Industrial Sciences	Industrial Sciences-iSTEM
	hours [a]	hours [a]	hours [a]	hours [a]
Physics	2	2	1 or 2	1 or 2
Chemistry	2	2	1 or 2	1 or 2
Biology	2	2	-	-
Geography	1	1	1	1
Applied sciences & Engineering	-	-	9	7
Mathematics	5	5	5	5
Non-STEM subjects	19	17	14	14
iSTEM	-	2	-	2

[a] one 'hour' represents one class period of 50 minutes

- To consistently and profoundly expose students to integrated STEM activities, two to four large learning units were to be implemented per school year, each unit covering several weeks to up to a whole semester. Each TDT would design iSTEM learning materials for one unit.
- In the timetables of the teachers participating in the iSTEM design, Tuesday afternoons would be reserved for weekly within-school design meetings and monthly cross-school TDT meetings.
- The design process would be limited to the period from September until April each project year.
- Each TDT would be coached by a researcher from the STEM@school project team. These coaches would take the lead in the TDT composition, planning of TDT meetings, writing of a script for the learning materials, and finally bundling the materials developed by the different school teams in the TDT.

RESULTS

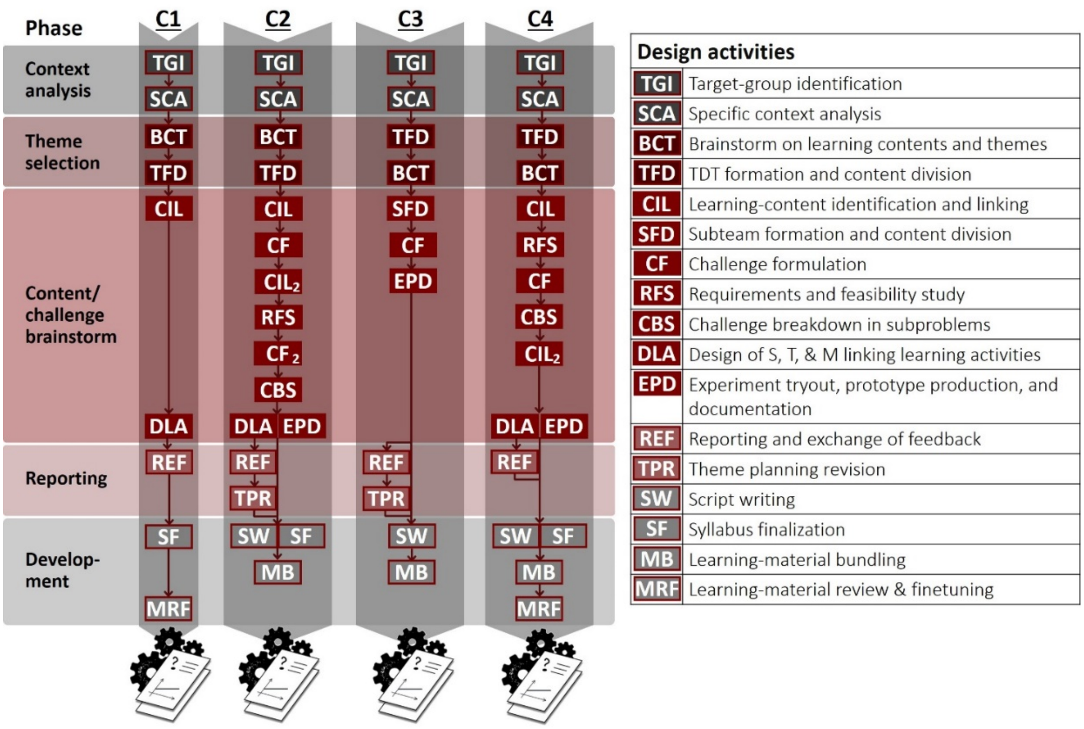


Figure 3. Model of the phases and activities (indicated by acronyms) identified in the design processes studied in cases C1, C2, C3, and C4

Construction of the Case-based Model of the TDTs' iSTEM Design Process (RQ1)

Figure 3 shows the model of the design processes of the four studied cases. In these processes, we distinguished five phases, each consisting of several design activities, which we briefly discuss below. **Appendix 2** gives a detailed overview and illustrates the design activities we identified in each case.

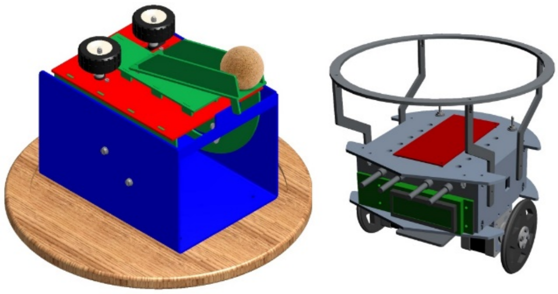


Figure 4. Result of design activity EPD in C3 (theme ball launcher and car)

In the *Context analysis phase*, the teachers defined the target group of students for whom they would design the iSTEM learning materials (TGI) and analyzed the context, i.e., scanned the national curricula of the different STEM subjects of this target group to look for learning contents that could be integrated (SCA).

In the *Theme selection phase*, based on the learning contents extracted from the STEM subject curricula, the TDTs discussed possible themes for the learning units and a sequence in which these units should be implemented in the target group's school year (BCT). Based on the conditions shown in **Table 2**, the STEM@school team then composed the TDTs and divided the themes among them (TFD).

In the *Content/challenge brainstorm phase*, the TDT members discussed the learning contents relevant for the theme that was assigned to them (CIL), as exemplified by the following excerpt of a meeting in C4 (theme algae):

> We made the exercise: which learning contents can be addressed from (…) the curriculum of [grades 11 and 12]? In biology, it's indeed more about microscopy, mitosis: what is that? Eh, the connection with the growth charts, but that is the math. Photosynthesis came up (…) And then, the biochemistry of what plants and algae consist of. The link with lipids, proteins, and which nutrients do we need to [grow] them. And then we get to the link with growth medium. (…) Then, within chemistry, we [distinguished] determination of concentration and dilution, possibly, in preparing the media. (…) And also, if we are working with acidity, if we are measuring that in our medium, eh... we could develop some learning materials on that as well. And eh... then, of course, also the separation and extraction techniques, if we want to go into... how to isolate the lipids. *(C4_Bio/Chem2)*

> What we would like to develop is, eh... about spectrophotometry: specifically what it is; what the relationship is between the [algae] concentration and the [light spectrum]. Eh, we also want to develop learning materials on LDRs and phototransistors: what the relationship is between the light intensity and the electric current. *(C4_Phys)*

Based on the listed contents, they formulated a student challenge that would raise the need to learn and link these contents (CF). In C2 and C4, the TDTs iterated these activities to better match the challenge with the learning contents. These TDTs also studied the feasibility and open-endedness of the challenge (RFS) and broke it down into smaller subproblems (CBS). The TDTs then conceived learning activities that would lead students of the target group to learn and link the targeted contents in order to solve the challenge (DLA). **Figure 5** illustrates this phase for C2. The TDTs also carried out experiments and built example prototypes of their students' future products (EPD). The result of this activity in C3 (theme ball launcher and car) is shown in **Figure 4**. The TDT of C3 started this phase by forming monodisciplinary subteams who further developed discipline-specific materials regarding the targeted learning contents (SFD).

The *Reporting phase* took place in one plenary meeting within the big group of TDTs, organized by the STEM@school team in order for the TDTs to present their preliminary designed materials and exchange feedback (REF). In C2 and C3, the TDTs also discussed the rescheduling of the learning unit implementation within the students' school year (TPR).

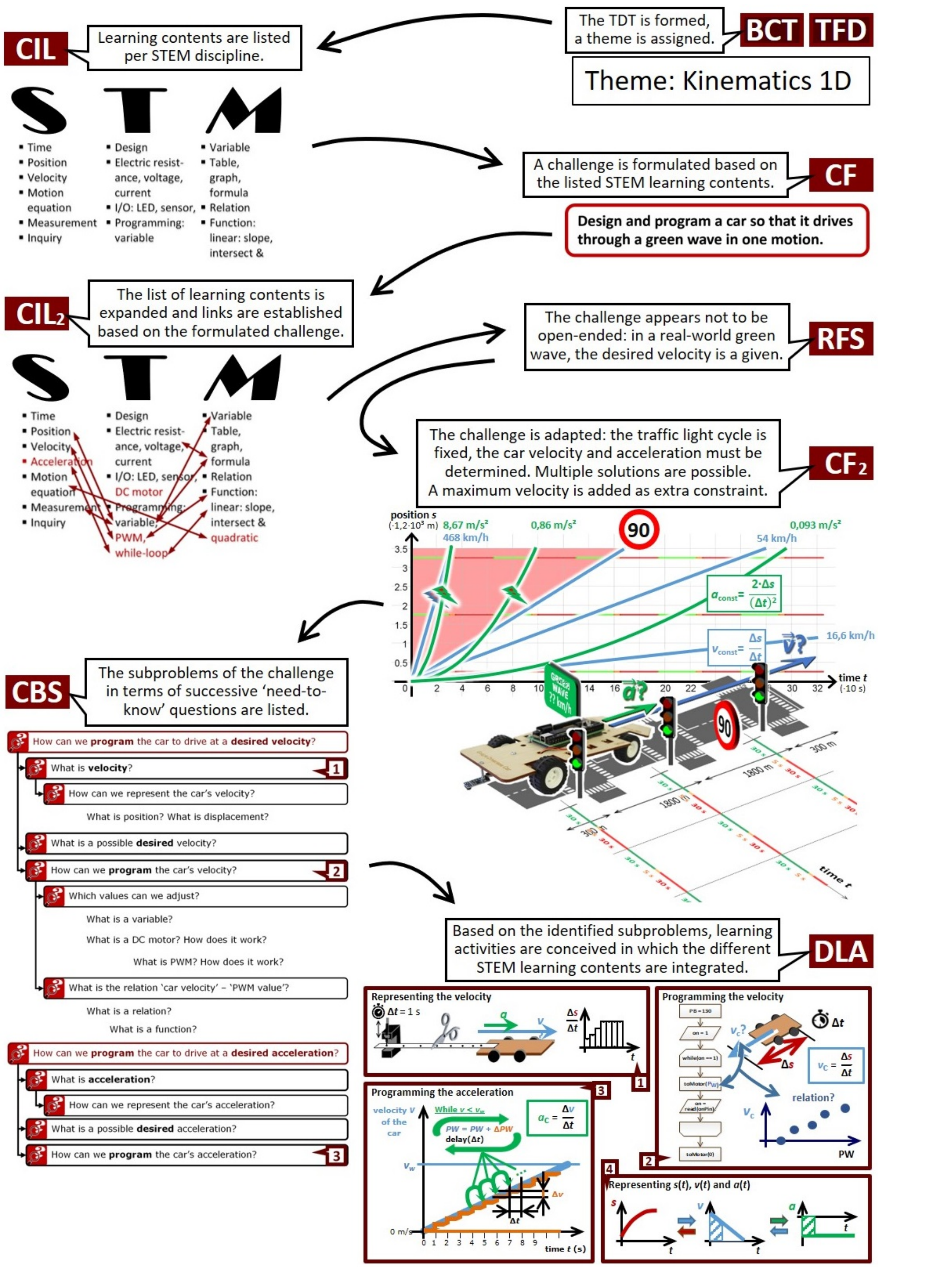


Figure 5. Overview of the results of some important activities in C2

In the *Development phase*, the TDT coaches wrote a script (or learning-unit scenario) to interconnect the student challenge and the learning activities that had been conceived by the different school teams constituting the TDT (SW). Meanwhile, the TDT members refined their syllabi (SF), elaborating the learning activities and instructions for the target group. These materials were bundled by the TDT coach (MB) and revised and fine-tuned a last time by the TDT members (MRF).

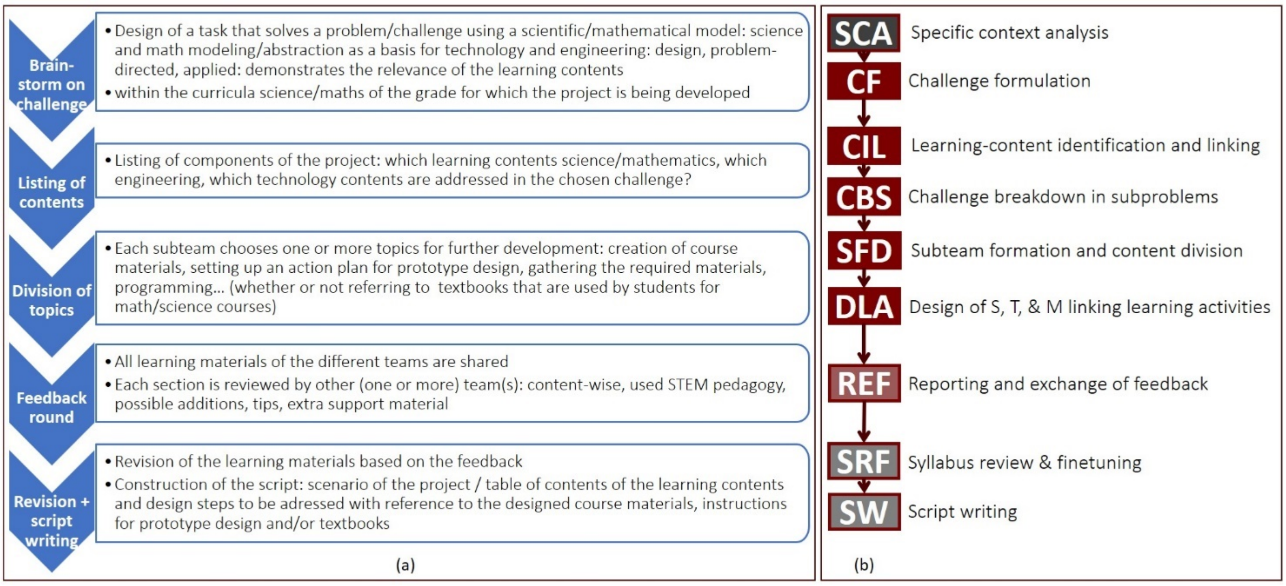


Figure 6. Participant A_S_C123_ Phys's model of the design process activities (a) and matching activities identified in our case study (b)

The revision of the learning materials, based on the feedback from the teachers who implemented them in the pilot classrooms, fell out of the scope of this study, as it was merely conducted by the STEM@school staff. The final learning materials can be found on the project webpage (STEM@school, 2017).

The left of **Figure 6** shows the digital model made by one of the case-study participants (translated to English) upon our request in order to validate our model (step 1.2 of our study design). On the right, we depict the activities of our case-based model, of which the labels and descriptions strongly match the descriptions in the participant's model. Comparison suggests that our case analysis produced a representative and more fine-grained abstraction of the design process, and that we did not overlook any activity.

Evaluation of the Design Activities Constituting the Case-based Model (RQ2)

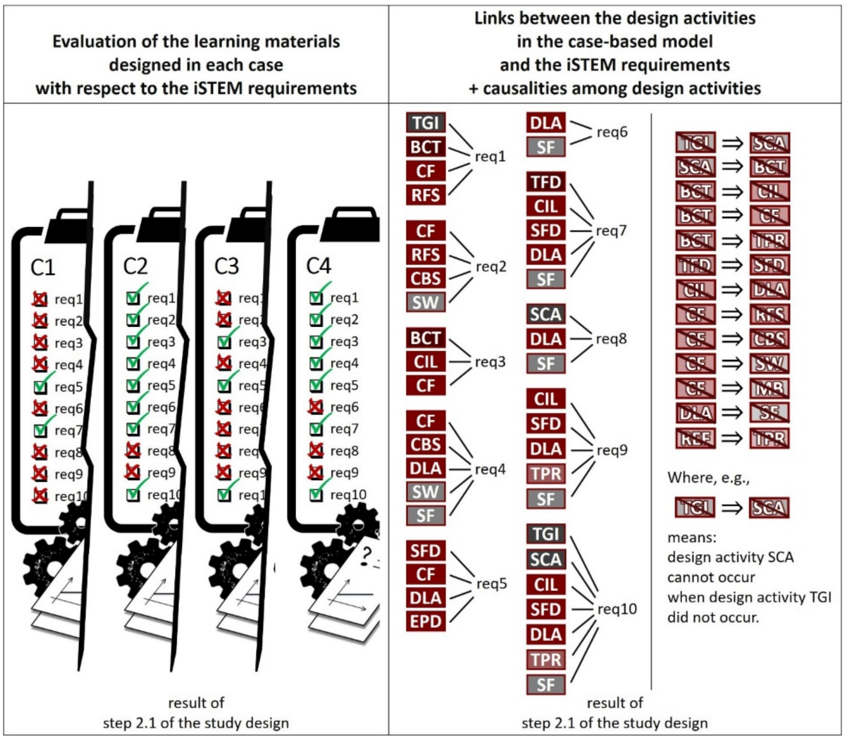


Figure 7. Results of the per-case product evaluation (step 2.1) and the cross-case linking of the design activities to the iSTEM requirements (step 2.2 of the study design)

To identify the crucial, detrimental, and missing activities in our case-based model (**Figure 3**), we utilized the list of iSTEM requirements shown at the right of **Figure 1**. The left side of **Figure 7** shows how the learning

Table 5. Fulfillment of each iSTEM requirement per case (see step 2.1), together with the occurrence or absence in each case (see step 1.1) of the design activities linked to each requirement (see step 2.2)

	C1	C2	C3	C4
req1	✗ TGI BCT ~~CF~~ ~~RFS~~	✓ TGI BCT CF RFS	✗ TGI BCT CF ~~RFS~~	✓ TGI BCT CF RFS
req2	✗ ~~CF~~ ~~RFS~~ ~~CBS~~ ~~SW~~	✓ CF RFS CBS SW	✗ CF ~~RFS~~ ~~CBS~~ SW	✓ CF RFS CBS SW
req3	✗ BCT CIL ~~CF~~	✓ BCT CIL CF	✓ BCT ~~CIL~~ CF	✓ BCT CIL CF
req4	✗ ~~CF~~ ~~CBS~~ DLA ~~SW~~ SF	✓ CF CBS DLA SW SF	✗ CF ~~CBS~~ ~~DLA~~ SW ~~SF~~	✓ CF CBS DLA SW SF
req5	✓ ~~SFD~~ ~~CF~~ DLA ~~EPD~~	✓ ~~SFD~~ CF DLA EPD	✓ SFD CF ~~DLA~~ EPD	✓ ~~SFD~~ CF DLA EPD
req6	✗ DLA SF	✓ DLA SF	✗ ~~DLA~~ ~~SF~~	✗ DLA SF
req7	✓ TFD CIL ~~SFD~~ DLA SF	✓ TFD CIL ~~SFD~~ DLA SF	✗ TFD ~~CIL~~ SFD ~~DLA~~ ~~SF~~	✓ TFD CIL ~~SFD~~ DLA SF
req8	✗ SCA DLA SF	✗ SCA DLA SF	✗ SCA ~~DLA~~ ~~SF~~	✗ SCA DLA SF
req9	✗ CIL ~~SFD~~ DLA ~~TPR~~ SF	✗ CIL ~~SFD~~ DLA TPR SF	✗ ~~CIL~~ SFD ~~DLA~~ TPR ~~SF~~	✗ CIL ~~SFD~~ DLA ~~TPR~~ SF
req10	✗ TGI SCA CIL ~~SFD~~ DLA ~~TPR~~ SF	✓ TGI SCA CIL ~~SFD~~ DLA TPR SF	✓ TGI SCA ~~CIL~~ SFD ~~DLA~~ TPR ~~SF~~	✓ TGI SCA CIL ~~SFD~~ DLA ~~TPR~~ SF

where, e.g., SCA means: design activity SCA, which was linked to reqX, occurred in case Cy
and ~~SCA~~ means: design activity SCA, which was linked to reqX, did not occur in case Cy

Table 6. Cross-case determination of the activities crucial for each iSTEM requirement to be fulfilled, derived from **Table 5**

	(a) Minimal combination of design activities sufficient for reqX to be fulfilled	(b) Maximal combination of design activities insufficient for reqX to be fulfilled	(c) Design activities crucial for reqX to be fulfilled
req1	TGI BCT CF RFS (C2,C4)	TGI BCT CF (C3)	RFS
req2	CF RFS CBS SW (C2,C4)	CF SW (C3)	RFS and/or CBS
req3	BCT CF (C3)	BCT CIL (C1)	CF
req4	CF CBS DLA SW SF (C2,C4)	DLA SF (C1) CF SW (C3)	CBS
req5	DLA (C1) SFD CF EPD (C3)		DLA or (SFD and/or CF and/or EPD) or –
req6	DLA SF (C2)	DLA SF (C1,C4)	?
req7	TFD CIL DLA SF (C1,C2,C4)	TFD SFD (C3)	CIL and/or DLA and/or SF
req8		SCA DLA SF (C1,C2,C4)	?
req9		CIL DLA TPR SF (C2) SFD TPR (C3)	?
req10	TGI SCA CIL DLA SF (C4) TGI SCA SFD TPR (C3)	TGI SCA CIL DLA SF (C1)	SFD and/or TPR

materials designed in each case were evaluated with respect to each of the iSTEM requirements (step 2.1 of our study design). The right side of **Figure 7** shows the links between the design activities identified in our case study and each of the iSTEM requirements (step 2.2 of our study design).

The combination of the results shown in **Figure 7** and the case-based model in **Figure 3**, which shows the occurrence or absence of the design activities in each case, is shown in **Table 5**. This table formed the basis to further analyze the effect of each design activity on the learning materials designed in each case (step 2.3 of our study design). We note that, in these analyses, we did not take into account other, unidentified activities or factors that might have played a role in the design processes.

In order to determine the *crucial and missing design activities* in the modeled design processes, we performed a cross-case analysis per iSTEM requirement based on **Table 5**. For each requirement, we determined (a) the minimal combination of design activities linked to this requirement that sufficed to fulfill (✓) the requirement in at least one case, and (b) the maximal combination of design activities linked to the requirement that had not sufficed to fulfill the requirement and had thus resulted in its failing (✗) (see **Table 6**).

By subtracting the insufficient combination of activities from the sufficient combination (i.e., (a) – (b) in **Table 6**) and taking into account the causalities between activities (see at the right of **Figure 7**), we can conclude for certain that the following activities are *crucial* to fulfill some of the requirements for high-quality iSTEM education:

- CIL (learning-content identification and linking), since CIL is also an important precondition for DLA (design of STEM linking learning activities), which is in turn an important precondition for SF (syllabus finalization),
- CF (challenge formulation),
- as important preconditions for CIL and CF:
    - BCT (brainstorm on learning contents and themes), and therefore:
        - SCA (specific-context analysis), and therefore:
            - TGI (target-group identification),

Table 7. Cross-case number of fulfilled versus failed iSTEM requirements linked to each design activity, derived from **Table 5** and the causalities in **Figure 7**

	(a)		(b)		(c)		(d)		(a)		(b)		(c)		(d)
	#✓		#✗		#✓		#✗		#✓		#✗		#✓		#✗
TGI	8	>	3	~~TGI~~	-	=	-	CBS	4	>	-	~~CBS~~	-	<	4
SCA	8	>	5	~~SCA~~	-	=	-	DLA	19	>	10	~~DLA~~	2	<	10
BCT	26	>	3	~~BCT~~	-	=	-	EPD	3	>	-	~~EPD~~	1	>	-
TFD	5	>	1	~~TFD~~	-	=	-	REF	2	>	-	~~REF~~	-	=	-
CIL	18	>	5	~~CIL~~	2	<	7	TPR	2	=	2	~~TPR~~	1	<	3
SFD	2	=	2	~~SFD~~	8	>	4	SW	4	>	2	~~SW~~	-	<	2
CF	24	>	3	~~CF~~	1	<	14	SF	8	<	10	~~SF~~	-	=	-
RFS	4	>	-	~~RFS~~	-	<	4								

where, e.g., SCA means: across all cases in which design activity SCA occurred
and ~~SCA~~ means: across all cases in which design activity SCA did not occur

- CBS (challenge breakdown into subproblems), and
- RFS (requirements and feasibility study).

Furthermore, the learning materials of none of the cases met requirements 8 and 9, and **Table 6** is not conclusive about the activities necessary to fulfill requirement 6. These findings suggest that one or a few design activities are *missing* in order for requirements 6, 8, and 9 to be fulfilled. More precisely, actions should have been taken in the design processes to ensure:

- student cooperation (~req6);
- goal-oriented strategies (~req8); and
- integration of know-how from discipline-specific educational research (~req9).

In order to determine the *profitable and detrimental design activities* in the modeled design processes, we performed a cross-case analysis per design activity based on **Table 5**. For each design activity, we counted the total number of iSTEM requirements linked to this activity: (a) those that were fulfilled (✓) across all cases in which this activity had occurred, and (b) those that were failed (✗) across all cases in which this activity had occurred. We did the same for all cases in which this design activity had *not* occurred. Taking into account the causalities between activities (see at the right of **Figure 7**), this resulted in **Table 7**.

Using determination **Table 1**, **Table 7** suggests that most activities were *(rather) profitable*, having a moderate to very positive effect on the fulfillment of the requirements for high-quality iSTEM education. Design activities SFD (subteam formation and content division) and SF (syllabus finalization) appear to be *rather detrimental*.

Interpretation of the Findings

In this section we relate the most significant results on the assessment of each design activity to our observations during the case study. The identification and cross-disciplinary linking of STEM learning contents (CIL) and the formulation of a student challenge (CF) are shown to be crucial activities for the designed materials to fulfill the iSTEM requirements. Particularly in C2 and C4, we saw how iteration of these two activities played a pivotal role in the TDTs' design processes. This finding is remarkable, given the fact that the TDTs of these two cases had no team member or coach in common. This iteration manifested itself in lively cross-disciplinary discussions during TDT meetings, which reflected the iSTEM key principles *problem-centered learning, integration* and *cooperative learning* among the participating teachers: The teachers were trying to find a common ground, for which they had to understand each other, and therefore, they had to learn from each other across STEM disciplines. This resulted in a clever alignment of an engaging student challenge and the targeted learning contents from different STEM subjects. In C1, no challenge was formulated. As a result, the learning activities in the designed materials of C1 contained an incoherent set of cross-disciplinary but unrelated experiments and exercises (De Meester et al., 2015). In the other cases, we found the formulated challenge to be the main focus and motivator for the TDTs. In C3, no actual learning activities were designed (no activity DLA), probably because the specific learning contents to be addressed, had not been articulated or discussed (i.e., activity CIL was not found in C3).

The requirements and feasibility study (RFS) appeared to be a crucial design activity as well. This activity had manifested itself in two different ways. In C2, this activity was carried out to ensure that the challenge would be open-ended (i.e., allow for different possible solutions). In C4, the TDT undertook company visits to assess the feasibility of different algae applications, such as waste water treatment, biofuel production, and nutritional supplements. In this design activity, as well as in the investigation of learning contents, we saw teachers engaging in the iSTEM key principle of *inquiry-based learning.*

The challenge breakdown into subproblems (CBS) seemed to help the TDTs of C2 and C4 to identify the sequence in which to address the targeted learning contents throughout the learning unit, which, in turn, guided the design of the learning activities (DLA). The outcome of this activity formed the basis of the script writing

(SW), in which the scenario of the learning activities was outlined (except from C3, in which the TDT coach had to build the script from scratch).

We attribute the absence of activities CIL, RFS, CBS, and DLA in C3 to the fact that the TDT split up into smaller, monodisciplinary subteams, who independently developed materials for the separate STEM classes (SFD). These materials contained no links across STEM disciplines and did not contribute to solving the challenge. This could explain why activity SFD came out of the analysis as a 'rather detrimental' activity. Also the syllabus finalization (SF) came out of our analysis as rather detrimental, but no observations in our case study could corroborate this finding.

In C2, C3, and C4, the TDTs devoted a lot of design time to a tryout of the experiments or the design of a prototype (activity EPD). In C2 and C4, this activity fed into the design of the learning activities (DLA), as the pedagogical approach of the learning activities relied on the process and results of the experimentation and prototyping. In C3, the majority of the design process was absorbed by this activity. The intermediary reports of the subteams of C3 and the discussions during the TDT meetings were dominated by the teachers' efforts to produce working prototypes (see **Figure 4**) and test their accuracy. This resulted in many technical documents which lacked a pedagogical approach. The final designs were so complex that the students, in order to get working prototypes, would have to follow a cookbook plan.

We believe that the composition of multidisciplinary TDTs (activity TFD) has strongly facilitated the cross-disciplinary brainstorming that took place in activities CIL, CF, and the design of cross-disciplinary learning activities (DLA) in C2 and C4. Activity REF (the review and exchange of feedback) was much appreciated by several teachers, as evidenced by their reflections:

> Actually, I find it quite important: explaining what we want to do, and that [other teams] can say: "yeah, that is maybe a bit odd," or "that can be done better like this," or "I would put more emphasis on that." So that we can take this into account *before* we [proceed], 'cause... yeah, if we would already have developed everything, and *then* they [would come up with] a lot of comments, that [would be] quite annoying. *(C4_Phys)*

In none of the observed cases, and nowhere in the design processes did the TDTs take the time to construct a clear and comprehensive list of learning goals they wanted their students to achieve. We believe that this missing though important design activity, explains the fact that certain requirements for high-quality iSTEM education were failed by all designed materials. Although the teachers' main drive was to address the learning contents mentioned in the national curriculum standards, they never discussed what they considered to be important competences with regard to these contents. Furthermore, none of the TDTs consulted scientific articles on students' difficulties with regard to these learning contents. Consequently, the iSTEM key principle of research-based learning was missing in the TDTs' design practices.

DISCUSSION

We conducted a case study to model the design processes of four TDTs involved in the development of integrated STEM learning materials. Assessing the learning materials designed by each of these TDTs against the requirements for high-quality iSTEM education and linking the modeled design activities to these requirements, allowed us to distinguish the crucial, detrimental, and missing activities in the design processes. In sum, our study shows evidence that a successful iSTEM design process is constituted by (1) the multidisciplinary TDT formation (activity TFD), and (2) the alignment of (a) the identification and linking of STEM learning contents and (b) the formulation of a real-world student challenge (activities CIL and CF). We found that, via these activities, STEM teachers engage in constructive, cross-disciplinary conversations. In turn, these conversations lead to engaging student challenges and activities that do not only address learning contents from different STEM disciplines but also add meaning to students' learning in the light of solving these challenges. On the other hand, our study also revealed that, in order to fulfill all requirements for high-quality iSTEM education, TDTs should explicitly be encouraged to discuss and create learning opportunities that ensure (1) students' achievement of important learning goals associated with (higher-order) STEM competences, (2) student cooperation, and (3) the use of research-based strategies. In this discussion we first situate our findings in the broader research field on interdisciplinary curriculum design and in its national educational context. We then elaborate the limitations of our study. We conclude with suggestions for future research and opportunities entailed by our findings.

Table 8. Emergence of our identified design activities across different studies

High-school TDTs' design of integrated STEM materials	**Theory on design of inter-disciplinary learning units**	**High-school TDTs' design of integrated STEM units**	**Primary school TDTs' design of integrated STEM materials**	**Model of learning-goals-driven design for project-based science materials**
Our case study	Jacobs (1989)	Satchwell et al. (2002)	McFadden et al. (2017)	Krajcik et al. (2008)
Target-group identification (TGI), and specific context analysis (SCA)				
Multidisciplinary TDT formation and theme division (TFD)		Rigorous selection of a few S, T, and M teachers to form one TDT		Physical science TDT formation (mix elementary teachers and expert)
Brainstorm on learning contents and themes (BCT)	'Brainstorming associations'	Identification of a shared theme based on the national math and science standards	Choosing a phenomenon as a central topic for the curriculum	
Learning-content identification and linking (CIL)	Generating ideas for interesting topics	Determination of key concepts and working hard to find opportunities for integration		Unpacking national science standards, create maps of clusters of interrelated contents and misconceptions
?		Development of a series of discipline-oriented objectives		Articulation of learning performances
Challenge formulation (CF)		Creation of an introductory challenge to pique students' interest	Formulation of an engineering design challenge	Contextualization via a driving real-world problem question
Subteam formation and content division (SFD)				
Requirements and feasibility study of the challenge (RFS)			Discussion about keeping the challenge as simplistic as possible	
Challenge breakdown in subproblems (CBS)	'Establishing guiding questions as a scope and sequence'		Compartmentalization into modules	Creating a coherent instructional sequence of the science concepts to help build student understanding and answer the driving question
Design of S, T, E & M linking learning activities (DLA)	'Writing activities for implementation'	Design of learning activities in which the students explore, study and apply new concepts	Assembling series of activities related to the central topic	Creating instructional tasks to help students develop mastery of learning goals
?		Development of authentic assessment instruments		Development of assessment items in alignment with the learning performances
Experiment tryout, prototype production, and documentation (EPD)				
Reporting and exchange of feedback (REF)		Collection of feedback from content experts		
Theme planning revision (TPR)				
Script writing (SW),				
Syllabus finalization (SF)				
Material bundling (MB), and review and finetuning (MRF)				

This study presents a first explicit model of the particular activities constituting the design of integrated STEM learning materials as carried out spontaneously by teams of in-service high-school STEM teachers. Table 8 shows the design activities we identified via our inductive approach and compares them to actions and activities we could detect via deeper analysis of other research on interdisciplinary curriculum design, using our case-based model as a lens. A testing stage did not fall within the scope of this study. Table 8 shows that our model portrays a comprehensive account of the activities comprised by the design of interdisciplinary materials for STEM. The endeavors of the teams in Satchwell et al.'s (2002) study show the biggest overlap with the design activities carried out by the TDTs in our study. Satchwell et al. and the theoretical model of Krajcik et al. (2008) mention the development of student learning objectives and assessments. This activity was lacking in McFadden et al.'s (2017) as well as in our study. Teachers enthusiastically dive into the design of a fun challenge (Guzey et al., 2016) and the inherent hands-on design (see activity EPD in our case study), without setting their objectives first. Furthermore, since teachers do not easily find their way to research literature (See et al., 2016), they do not tend to use evidence-based instructional strategies in their design. Much like in McFadden et al.'s (2017) study, the design discussions in our cases often "remained geared around what types of experiences students should be engaged in and not how students learn best during integrated learning experiences" (p. 13). Unlike the teams of McFadden et al., however, the TDTs in our case study did not seem reluctant to explore the multitude of learning opportunities encompassed by open-ended challenges (see activity RFS). We believe this courage stems from the fact that the TDTs in our study were composed by teachers from different STEM disciplines, from different grade levels and from different schools (see activity TFD). Each TDT thus held a lot of expertise in diverse areas for the TDT members to rely upon.

As the findings we present result from a case study, they should be situated in the specific context in which the study was carried out. Before STEM@school, the subject of 'how to teach integrated STEM' did not make part of STEM teacher education programs in Flanders (Belgium). The high-school teachers participating in this study have been schooled in teaching one or two STEM subjects (e.g., physics, biology, mathematics) in a monodisciplinary way. They were, therefore, used to adhering to subject-specific national curricula and handbooks, and to consulting with colleagues teaching the same STEM subject(s). This traditional way of teaching STEM subjects did, however, not require them (and, therefore, they were not used) to consider viewpoints and curricula from colleagues teaching other STEM subjects. The consequential tendency to resort to monodisciplinary teaching is reflected in activity SFD (monodisciplinary subteam formation) which occurred in C3 and was found to be harmful to the design of high-quality integrated STEM materials. Furthermore, before the start of STEM@school, the concept of 'integrated STEM' at school had been promoted in Flanders via short-term projects or events, such as a STEM day, workshop, or company visit. Such activities did address learning contents from different STEM subjects, but often in a 'fun' and not necessarily integrated or instructive (i.e., standards-based or competence-oriented) way. This idea may have played a role in the fact that the high-school teachers in this study (1) have not considered articulating meaningful learning objectives and assessments around the contents they extracted from their subject-specific curricula, and (2) sometimes prioritized the development of fun, hands-on activities addressing these contents over the design of minds-on learning activities aiming at meaningful STEM competences related to these contents. We believe that guidelines based on our evidence-based model can favor teachers, teacher educators, and schools in any educational context that shows characteristics similar to those of the Flemish context described here.

This study has some constraints. As in other case study research, certain features, such as team dynamics, the participants' knowledge and beliefs, and the role of the team coach could not be clearly distinguished from the process under study. As a result, we cannot indicate which variables might have influenced the occurrence and quality of the design activities and how. In order to construct a valid model, we implemented several literature-based methods such as purposeful sampling and theoretical saturation, and recursive cycling through and triangulation of different data sources (Creswell et al., 2000; Eisenhardt, 1989). However, the research was mainly conducted from an insider's view by the STEM@school project staff, and some bias can thus not be ruled out. On the other hand, complete immersion in the process enabled the researchers to experience the endeavors of iSTEM design first-hand, and to interpret the observed activities in their specific context, which they got to know from inside out (Mortelmans, 2007). Another limitation of the study is that we cannot claim that certain design activities re-emerged in the different cases by coincidence, since some learning effect might have set in among the TDTs during the course of STEM@school. However, taking into account these limitations, the combination of observation-based modeling, criterium-based product assessment, linking, and logical deduction, provides a useful new approach to evaluating curriculum design processes.

Future research could advance the case-based model presented in this work. Firstly, the classroom implementation and corresponding revision of the designed materials could be examined and included (e.g., as extra phases) in the model (Satchwell et al., 2002; Berland, 2013). Additionally, further research among pre- and in-service STEM teachers could examine the extent to which the case-based model and findings of this study support other TDTs' endeavors to design integrated STEM education. Our observations showed indications that participants in our TDTs were being immersed in some of the key principles of high-quality iSTEM education. In order to further inform teacher training programs, future research could focus on (1) teachers' immersion in these principles when being involved in iSTEM curriculum design that is guided by our findings, and (2) the effect on their knowledge and self-efficacy and those of their students (van Keulen et al., 2015).

With the notion of its crucial, detrimental, and missing activities, the evidence-based model constructed from our case study can inform (student) teachers and teacher educators who want to transform high-school STEM education into high-quality integrated STEM education. Since the model reflects a path towards iSTEM learning materials that was fully conceptualized by in-service teacher teams during this study, in- and pre-service teachers will naturally relate to these findings. Currently, this particular model together with the good practices and pitfalls found in the case study already form the basis of pre- and in-service teacher training for integrated STEM in several higher education and professional development programs in Flanders. The model and implications of this study provide (student) teachers with a common language and encourage them to engage in cross-disciplinary discourse, to search for ways to create competence-oriented, meaningful, and thus motivating STEM learning opportunities for their students.

LIST OF ABBREVIATIONS

iSTEM	integrated Science, Technology, Engineering, and Mathematics
S	secondary education with a focus on science
T	secondary education with a focus on technology
Bio	biology
Chem	chemistry
Elec	electricity-electronics
Math	mathematics
Mech	mechanics
Phys	physics
Eng	engineering

ACKNOWLEDGEMENTS

This study was carried out in the scope of the research project STEM@school, which was funded by the Agency for Innovation through Science and Technology (IWT) of the Flemish government (Belgium). We want to thank all teachers who participated in this study, and who worked tirelessly to design engaging and relevant STEM education for their students. We also want to thank Leen Goovaerts and Anthony Coyette for the important contribution they made to this study and for their invaluable support. Finally, we want to thank Marie-Paule Buyse, Stijn Ceuppens, Jan De Lange, Hanne Deprez, Yves Vanbilsen, and fellow teacher educators for promoting and advancing the results of this work.

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APPENDIX 1 - BACKGROUND INFORMATION TDT MEMBERS

Case[a]				TDT member		Gender		Age				Education[c]									Years of teaching experience[c]			
												diploma					discipline							
C1	C2	C3	C4	School	Teacher code[b]	F	M	≤30	≤40	≤50	≤60	5B	BEd	BSc	MSc	Eng	S	T	E	M	≤10	≤20	≤30	≤40
■				A_S	C1_Math	■			■				■							M		■		
■	■	■		A_S	C123_Phys		■		■						■		S				■			
			■	A_S	C4_Chem	■				■					■		S					■		
	■	■		B_T	C23_Eng		■			■					■	■		T	E					
	■	■		B_T	C23_Elec1	■			■									T						
	■	■		B_T	C23_ Elec2	■			■									T						
	■	■		B_T	C23_Math	■				■										M				
		■		B_T	C3_Elec	■			■									T						
	■			C_S	C2_Math-Phys		■	■					■					T		M	■			
	■	■		C_S	C23_Phys		■			■					■	■		T	E		■			
	■	■		C_S	C23_Math	■			■						■	■	S	T	E					
	■	■		C_S	C23_Principle		■				■				■					M				■
		■		C_S	C3_Phys		■			■					■	■		T	E		■			
		■		D_T	C3_Mech1		■			■			■					T					■	
		■		D_T	C3_Mech2		■			■		■						T				■		
		■		E_T	C3_Elec		■		■					■				T				■		
		■		E_T	C3_Mech		■				■													
■	■	■			C123_Coach	■		■							■	■		T	E		■			
			■	F_S	C4_Phys		■				■				■	■		T	E			■		
			■	F_S	C4_Bio-Chem1		■	■							■		S				■			
			■	F_S	C4_Bio-Chem2	■			■						■	■	S	T	E		■			
			■	F_S	C4_Math1	■					■				■					M				■
			■	F_S	C4_Math2		■		■						■					M	■			
			■	G_T	C4_Phys-Chem	■				■					■	■	S	T	E			■		
			■	G_T	C4_Bio	■		■							■		S				■			
			■	G_T	C4_Elec		■			■					■	■		T	E			■		
			■		C4_Coach	■		■							■	■	S	T	E		■			

[a] for information on the cases: see **Table 3**

[b] pseudonym of participating teacher: case(s) in which s/he participated _ school $_{\text{focus of education}}$ _ subject(s) s/he taught

[c] no indication means not declared

Abbreviations

iSTEM	integrated Science, Technology, Engineering, and Mathematics
S	secondary education with a focus on science
T	secondary education with a focus on technology
F	female
M	male
Bio	biology
Chem	chemistry
Elec	electricity-electronics
Math	mathematics
Mech	mechanics
Phys	physics
Eng	engineering
5B	short-cycle tertiary education (ISCED level 5)
BEd	bachelor in education (ISCED level 6)
BSc	bachelor of science (ISCED level 6)
MSc	master of science (ISCED level 7)

APPENDIX 2 - DETAILED DESCRIPTION AND EXAMPLES FOR EACH DESIGN ACTIVITY IN THE CASE-BASED MODEL

PHASE **Design activity** *average duration*[a]		**Description (actions)**	**Occurrence**	***Example(s) from the cases***
CONTEXT ANALYSIS				
Target-group identification *1 week*	TGI	The big group decides on the target group of students (i.e., grade and study program) of the learning materials	C1 C2 C3 C4	*The teachers in C1 chose students of grade 7 as target group, to inspire them for STEM already from the beginning of their secondary school career.*
Specific context analysis *2 weeks*	SCA	The big group analyzes the curricula of the separate STEM subjects of the target group in order to determine the standards that must be achieved by the target group. For each STEM subject, the teachers extract the STEM contents that must be learned by the target group.	C1 C2 C3 C4	*The teachers in C2 explored the national curricula for students of grade 9 in the study options 'Sciences' and 'Industrial sciences'. They also looked into the curricula of the prior grades (7 and 8) to familiarize themselves with the expected prior knowledge. And they looked forward to what these students were supposed to learn later-on (grade 11). The teachers examined the curriculum standards defined for the subjects 'natural sciences', 'physics', 'technology', 'applied sciences', 'engineering', and 'mathematics'.*
THEME SELECTION				
Brainstorm on learning contents and themes *2 weeks*	BCT	The learning contents extracted from the separate STEM curricula (SCA) are categorized to identify one or more overarching themes. Some learning contents are then re-categorized, in order to finally get logical, coherent, well-defined themes for the 'work packages' / units for which the learning materials need to be designed. A logical sequence is chosen in which the themes will addressed during the school year.	C1 C2 C3 C4	*The teachers of C2 identified the following physics-math oriented themes and arranged them in the following order: (1) 'optics' (covering 1 trimester), (2) 'kinematics 1D' (1 trimester), (3) 'forces' (1/2 trimester), (4) 'kinematics 2D' (1/2 trimester).* *Determined to integrate also biology and chemistry, the team members of C4 were going back and forth between ideas for themes such as 'hydroculture', 'batteries', 'composting', 'geothermal energy', 'bioplastics', 'algae', and 'water treatment', 'with a discernable preference for the latter two, to cover 1 semester.*
TDT formation and content division *1 week*	TFD	The big group of teachers is split up by the coaches into smaller, multidisciplinary teams (TDTs) of teachers from different schools, with knowledge in different STEM disciplines, with differing classroom or practical experience, with differing degrees, and with teaching assignments in different grades.	C1 C2 C3 C4	*In C1, the group split up into several TDTs to develop the different themes (e.g., 'electric circuits', 'biotopes', 'robots', and '(bio)plastics'). The TDT we followed was assigned the theme 'biking', which it broadened to 'Motion 1D'.* *The teachers who formed the TDT that was studied in C3 were very determined to do something with quadratic equations, trebuchets and cars. They were therefore assembled by the STEM@school coaches before activity BCT took place.*
BRAINSTORM				
Learning-content identification and linking *2 weeks*	CIL	The TDT lists the learning contents relevant to the assigned theme (TFD) and categorizes them per discipline (S, T, E, M). The TDT collectively establishes cross-disciplinary links between these contents. In cases in which this activity occurred a second time, the TDT added extra learning contents and cross-disciplinary links that appeared necessary to solve the formulated challenge (CF).	C1 C2 (2x) C4 (2x)	*The TDT members in C4 mentioned the learning contents (extracted from the curricula for grade 11) they wanted to integrate in the scope of the themes 'water pollution' and 'algae': w.r.t. biology: photosynthesis, mitosis, the connection with growth charts (math), lipids, proteins, nutrients; w.r.t. chemistry: concentration and dilution, acidity, separation and extraction techniques; w.r.t. engineering and electricity: spectrophotometry, the link between the concentration of water pollution particles, the light spectrum, LDRs, phototransistors, and electric current.*
Subteam formation and content division *1 week*	SFD	The TDT divides the learning contents relevant to the assigned theme (BCT) among its team members per discipline (S, T, E, and M). The TDT splits up into smaller, monodisciplinary subteams to continue designing learning materials per discipline.	C3	*The TDT of C3 split up as follows: (1) different subteams of engineering teachers who focused upon (i) the design of a ball launcher, (ii) the design of a ballistic pendulum to determine the initial speed of a launched ball, and (iii) the design of a stepper-motor car to catch the launched ball; (2) a subteam of math teachers who focused upon the quadratic function describing the position of a launched ball, and (3) a subteam of physics teachers who focused on experiments regarding launching a ball.*
Challenge formulation *3 weeks*	CF	The TDT searches for a student challenge that is fun to the target group, that includes design or inquiry, that is more or less situated in a real-world context. After activity RFS, the TDT (re)formulates this challenge so that (1) solving it will create a need to learn and link the targeted STEM contents (CIL) and (2) the requirements and feasibility of the challenge (RFS) are taken into account.	C2 (2x) C3 C4	*The TDT of C2 came up with the idea to formulate an engaging student challenge as a means to address the identified learning contents and to incorporate engineering design. After activity RFS, they returned to the challenge to make it more open-ended.* *The TDT members of C4 expressed their concerns on whether the applications of algae they came up with would be "fun enough" for students. They finally found a consensus in the open-ended, creativity-fostering challenge "Grow algae, monitor their growth, and use them for an application of your choice".*
Requirements and feasibility study *2 weeks*	RFS	The TDT identifies the requirements and constraints of the chosen challenge (CF), checks these constraints for allowing enough student creativity and open-endedness. The practical feasibility of the formulated challenge is checked: the TDT inventories the equipment needed to solve the challenge and lists extra constraints based on what is (not) possible.	C2 C4	*In C4, the TDT visited four research centers and consulted experts and literature on water treatment and algae cultivation. The prospects of a bad smell in the classroom, made the TDT of C4 divert from its focus on water treatment. The expeditions made the TDT of C4 realize that algae cultivation would provide their students with many opportunities for inquiry and for reflection in terms of possible applications and efficiency. Moreover, in the scope of this activity, the TDT members of C4 were often recorded referring to articles they had read about the measures and growth conditions for algae cultivation.*

PHASE **Design activity** *average duration*[a]		**Description (actions)**	**Occurrence**	*Example(s) from the cases*
Challenge breakdown in subproblems *2 weeks*	CBS	The TDT collectively identifies the different subproblems encompassed by the formulated challenge (CF).	C2 C4	*The TDT of C2 collectively went through the stages in which the formulated challenge could be solved, listing the different 'need-to-know' questions that would come up, from the students' perspective.*
Design of S, T, & M linking learning activities *2 weeks*	DLA	The TDT collectively determines *what* the target group will be doing in the classroom: the team members conceive cross-disciplinary learning activities for which the students would need a combination of concepts and skills from different STEM disciplines and rely upon previously learned concepts. Such learning activities involve theory processing and/or information gathering, exercises, programming, experiments and/or prototyping.	C1 C2 C4	*In C1, the teachers developed and gathered ideas for exercises, thinking and physical experiments to gradually introduce the concepts of position, time, and speed to students, requiring them to think, measure, graph, reason, deduce.* *The TDT of C4 decided to include a combination of design and inquiry. They talked about experiments to measure the effect of several parameters on the growth of the algae, and about the design and calibration of a spectrophotometer that would be used to determine their concentration.*
Experiment tryout, prototype production, and documentation *7 weeks*	EPD	The TDT is involved in the design and construction of a prototype, or tries out some of the conceived experiments (DLA) related to the formulated challenge (CF). The TDT members order sample components and equipment and keep notes on the prototypes and experiments, such as required materials, code, drawings, results.	C2 C3 C4	*In C3, a long period of time was devoted to developing and redeveloping the parts of the ball launcher and car prototypes, creating 2D and 3D drawings, a program code and software manual, and gathering information on where to order the electronic components.* *In C4, the TDT set up algae cultures in two schools: one to try out the whole process of growing and harvesting algae to produce oil, and one to test the influence of several factors (such as CO_2 and light) on the concentration of the algae. Meanwhile, they kept notes on their observations.*
REPORTING				
Reporting and exchange of feedback *1/2 week*	REF	At this milestone meeting, planned by the coaches at the beginning of the design process, all TDTs present their ideas thus far on the learning activities with regard to the theme they were assigned (BCT) and they exchange feedback.	C1 C2 C3 C4	*In C4, also school inspectors and pedagogical advisors were invited to this feedback round. Some members of the TDT in C4 obviously and enthusiastically seized this opportunity to gather as much feedback as possible from their fellow TDTs on their design ideas thus far.*
Theme planning revision *1/2 week*	TPR	The big group of TDTs collectively revises the initial scheduling of the themes (i.e. verifies if the learning contents are addressed in a logical sequence in the school-year scheduling of the themes (BCT)). In case of doubts about the sequence, the group balances pros and contras for switching the themes in the school-year planning and collectively decides upon the final scheduling.	C2 C3	*In C3, a vivid discussion took place among teachers of the different TDTs on whether (a) to schedule the implementation of the ball-launcher unit in the second semester of the school year, AFTER students had learned about quadratic functions, so they would be able to apply this concept in the learning unit, or (b) to schedule the implementation of this unit in the first semester, as an incentive for students to learn about quadratic functions. For reasons related to relevance and meaning-making, the group finally agreed upon the latter option.*
DEVELOPMENT				
Script writing *3 weeks*	SW	The TDT coach writes the scenario (script) for solving the challenge (CF). The coach includes scaffolding questions. Meanwhile, the coach identifies gaps within the conceived learning activities (DLA) and communicates them to the TDT members.	C2 C3 C4	*In C2 and C4, the coaches relied on the subproblems identified in activity CBS.* *In C3, the coach tried to combine the documents she received from the different subteams of the TDT on the ball launcher, stepper-motor car, and ideas for launching experiments. The script in C3 finally consisted of several subproblems, with per subproblem (1) a teaser introducing the new subproblem of the challenge, (2) a reference to instructions, theory or experiments to tackle the subproblem, and (3) recap questions to check students' understanding of the STEM contents they had just learned by solving the subproblem.*
Syllabus finalization *3 weeks*	SF	The TDT members elaborate the conceived learning activities (DLA), taking into account the feedback from the other TDTs (REF) based on the information gathered earlier (RFS & EPD).	C2 C4	*In C4, the teachers delivered a lot of theoretical texts and references, but also descriptions of experiments.*
Learning-material bundling *2 weeks*	MB	The TDT coach bundles the script and the syllabi.	C2 C3 C4	*In C3, the coach received only practical information from the TDT members: technical drawings, program code, software manuals, and mere ideas for experiments).*
Syllabus review & fine-tuning *2 weeks*	SRF	The TDT members individually review the bundled learning materials. The coach fine-tunes them based on their feedback. No major substantial changes are made during this activity.	C1 C4	*In C1, the coach had the final materials also checked by a physics education expert, who suggested to clearly state the targeted learning goals above the related learning activities and to adapt some activities so they would better correspond with these goals.*

[a]at the rate of 1/2 day per week (on average)

APPENDIX 3 - ACTIONS PER DESIGN ACTIVITY

(Process starts with a big, motivated group of STEM teachers)

TGI

- deciding for which target group of students (i.e., grade and study program) to develop

Outcome: the target group of the learning materials

SCA

- analysis of the curricula of the STEM subjects (science (or more specifically physics, chemistry, biology, geography), technology (or applied sciences, computer science), engineering, math) of the target group to determine:
    - the prior knowledge of the target group
    - the standards (curriculum goals) that must be achieved by the target group
- extracting from these curricula the contents that must be learned by the target group
- discussing these learning contents

Outcome: prior knowledge and STEM curriculum standards prescribed for the target group

BCT

- grouping/categorization of learning contents to identify overarching themes based on the separate STEM curriculum standards
- identifying/choosing overarching themes
- choosing a sequence in which the themes will be scheduled in the students' school year based upon logical succession of learning contents

Outcome: themes for the learning materials, and a sequence in which to address them

TFD

- splitting up the big group of enthusiasts into "smaller", multidisciplinary teams (TDTs) of teachers with differing discipline-specific knowledge, and differing classroom or practical experience in one or more of the STEM disciplines, with differing degrees and/or teaching in different grades, of different schools
- allocating the chosen themes to the formed TDTs

Outcome: small(er) multidisciplinary TDTs

(Big group of STEM teachers is now split up into teams of about eight teachers from different STEM disciplines)

CIL

- collaboratively listing the learning contents relevant to the theme per discipline (S, T, E, M),
- collaboratively establishing cross-disciplinary links between these contents,
- (when iterated) collaboratively adding learning contents to the list and cross-disciplinary links, necessary to solve the formulated challenge,

Outcome: list of learning contents from different STEM subjects with cross-disciplinary links

SFD

- dividing the relevant discipline-specific learning contents
- splitting up the team of teachers into small, monodisciplinary subteams

Outcome: small monodisciplinary subteams

CF

- collaboratively searching for a challenge
    - that is fun / *meaningful* to the target group
    - that includes purposeful design or inquiry
    - that is more or less authentic / situated in a real-world context
- (when iterated) collaboratively fine-tuning the challenge so that the targeted STEM contents will be addressed in a meaningful way and linked when solving
- (when iterated) collaboratively adjusting the challenge, taking into account the studied the requirements and feasibility (e.g., open endedness)

Outcome: a central student challenge

RFS

- consulting experts in the field of the chosen theme
- collaboratively identifying the requirements and constraints of the chosen challenge,
- collaboratively checking these constraints for allowing enough student creativity, and for open-endedness
- collaboratively checking the practical feasibility of the formulated challenge: making an inventory of the accommodation and equipment needed to solve the challenge and listing extra constraints based on what is (not) possible

Outcome: requirements and feasibility criteria for the student challenge

CBS

- collaboratively identifying the different subproblems encompassed by the challenge

Outcome: list of successive subproblems to be encountered when solving the challenge

DLA

- collaboratively determining *what* the target group will be doing: brainstorming cross-disciplinary learning activities per subproblem
  - that form the bridge between the challenge and the targeted learning contents;
  - that address and link learning contents from different STEM disciplines, e.g., via modeling
  - that rely on previously constructed learning contents
  - in which students are actively engaged: involving
    - theory processing and/or information gathering,
    - making exercises
    - programming
    - experimenting, performing an inquiry

Outcome: collection of learning activities

EPD

- designing a prototype, or
- trying out experiments related to the challenge
- ordering sample components / equipment
- keeping documentation*:*
  - codes, drawings, experiment results
  - required equipment

Outcome: experiment guidelines, prototypes, drawings, building plans, order lists, practical tips

REF

- presenting intermediary ideas and drafted learning activities to other TDTs (of the big group) and to other stakeholders
- listening/being updated about the other TDTs' ideas and activities
- collaboratively giving feedback on the other TDTs' ideas and activities
- collaboratively documenting feedback from the other TDTs on own ideas and activities

Outcome: feedback (suggestions for improvement/adjustment) of the materials

TPR

- collectively revising the initial scheduling of the themes (i.e. verifying if the learning contents are addressed in a logical sequence in the school-year scheduling of the themes)
- in case of doubts about the sequence: balancing pros and contras for switching the themes in the school-year schedule
- collectively deciding upon the final scheduling of the themes within the target group's school year

Outcome: an approved theme planning

SW

- writing the scenario (script) for solving the challenge, based on the identified subproblems
- including scaffolding questions that successively introduce students to a new subproblem, and scaffolding questions that recapitulate what students (should) have learned when solving that subproblem and reconnect with the challenge
- identifying gaps among the outlined learning activities and communicating them to the TDT members

Outcome: script (scenario) for the learning activities, starting from the student challenge

SF

- elaborating the drafted learning activities, taking into account the feedback from the other TDTs
- gathering information based on the notes and information gathered during the experiment tryout and prototype design

Outcome: elaborated syllabi

MB

- bundling of the script and the syllabi

Outcome: a coherent collection of syllabi

SRF

- individually reviewing the syllabi
- fine-tuning the syllabi based on the feedback of the TDT members

Outcome: an approved set of iSTEM syllabi (the designed learning materials)

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European Journal of STEM Education,
2021, 6(1), 11
ISSN: 2468-4368

ArtsSciences Design-a-thon: Solving Complex Problems in Interdisciplinary Teams

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Citation: Bremmer, M., Heijnen, E., Hotze, A., Pijls, M., Beamer, E. and Roos, N. (2021). ArtsSciences Design-a-thon: Solving Complex Problems in Interdisciplinary Teams. *European Journal of STEM Education*, 6(1), 11. https://doi.org/10.20897/ejsteme/11342

Published: November 11, 2021

ABSTRACT

In this empirical study, the one-day project Robot Love Design-a-thon was designed for an interdisciplinary group of preservice teachers (in arts, sciences, and primary education), and evaluated through observations and learner reports. An analysis of the observations and the learner reports showed that having to go through a complete design process in a single day worked well: it facilitated the exchange of ideas and critical discussions between students concerning the project's socially engaged theme 'Tenderness and Technology'. In addition, interdisciplinary collaboration emerged as an important learning outcome. All students found working in mixed teams a relevant and educational experience as they could profit from each other's expertise.

Keywords: interdisciplinary education, STEAM-education, ArtsSciences, Design-a-thon, preservice teachers

INTRODUCTION

To solve complex cultural, technological, economical, ecological, and political challenges, there is a growing need for highly qualified professionals who can look beyond disciplines and excel in 21st-Century Skills such as critical thinking, problem-solving, cooperation, and creativity (Davies and Devlin, 2010; Ministry of Education, Culture & Science, 2015). This need for a new type of professional has increased the interest of higher education in interdisciplinary education (Berganton, 2017; Newell, 2009). Traditionally, higher education has focused on teaching disciplines with their own theories, methods, and contents (Squires, 1992). Davies and Devlin (2010) note that the term discipline is used to describe a discrete area of study, normally not cooperating or coordinating its academic effort across disciplinary boundaries. Yet, a comprehensive understanding of a complex societal problem is often facilitated by a cross-disciplinary approach because complex problems related to societal issues like digitalization, climate change, and health touch on a manifold of disciplines (De Greef, Post, Vink and Wenting, 2017; Newell, 2007). Hence, interdisciplinary courses can offer students opportunities to develop an understanding of a problem 'through the integration or derivation of different concepts, methods and epistemologies from different disciplines in a novel way' (Rogers, Scaife and Rizzo, 2005, p. 3).

A particular form of interdisciplinary practice that is of interest for the development of a new type of professional is found in contemporary hybrid arts and sciences practices. These practices raise questions at the intersection of the arts and sciences and combine non-traditional ways of researching, such as *design research*, *speculative design*, and *critical making* with more established ones to explore complex problems (Gabrys and Yusoff, 2012; Miller, 2014). Root-Bernstein, Siler, Brown, and Snelson (2011) coined the term ArtScience to describe these types of practices. In this article we have changed that term to the plural ArtsSciences to indicate the many arts and sciences that can be drawn on. Through courses based on these ArtsSciences practices, students in higher education learn to blend different forms of expertise, theories, and methodologies, that can lead to innovative and thought-provoking insights into societal issues (De Greef, et al., 2017; Zwijnenberg, 2013).

Although these courses are relevant to many students, they are specifically relevant to preservice teachers due to the internationally emerging paradigm of STEAM-education, which evolved from STEM-education (Hogenes, Diepenbroek, Bremmer and Hoogerheide, 2021). STEAM-education integrates science, technology, engineering, arts, and mathematics in primary and secondary education, and often anchors its pedagogy in Inquiry- and Design-based Learning (Liao, 2016; Sanders, 2009). Due to its interdisciplinary nature, its novel pedagogical approach and focus on societal problems, STEAM is regarded as a fruitful way to develop the 21st-century skills of pupils. Currently, as an alternative to the acronym STEAM, the term ArtsSciences-education is emerging in the Netherlands (Heijnen and Bremmer, 2019).

Before teaching any type of education that integrates arts and sciences, preservice teachers should be familiarized with its pedagogical strategies (Lam and Chan, 2011), learn to cooperate with teachers from different disciplines (Hotze et al., 2019), learn to cross the border of their discipline (Akkerman and Bakker, 2011), and learn to develop a communal language with teachers in other disciplines (Wilschut and Pijls, 2018).

To aid preservice teachers in developing knowledge and skills needed to design *and* teach any form of integrated ArtsSciences education, the platform *Education at the Intersection of Arts, Science and Technology* initiated the interdisciplinary, one-day project Robot Love Design-a-thon. This project was designed integrally for preservice art teachers, preservice science teachers, and preservice primary education teachers. It aimed to provide them with the experience of working on a complex ArtsSciences problem in interdisciplinary teams and through Inquiry- and Design-based Learning, so they would be able to apply this in primary or secondary education. The goal of the accompanying research study was to evaluate the Robot Love Design-a-thon and to gain insight into the interdisciplinary working process of the preservice teachers, their learning outcomes, and the pedagogical approach of the supervisors.

In this article, we will first take a closer look at the strengths of ArtsSciences-education. We will also describe how Design-a-thon, a pedagogical approach within ArtsSciences-education, was translated to the project Robot Love Design-a-thon. Furthermore, the research methodology for evaluating the project and the findings that could lead to the improvement of such ArtsSciences projects will be discussed.

ARTSSCIENCES IN EDUCATION

ArtsSciences-education is a specific form of interdisciplinary education in primary and secondary schools, with its own unique strengths. First of all, it could be considered a strength that pupils learn to critically solve problems in a '*hands-on*' way through Inquiry- and Design-based Learning. 'Critically' is traditionally associated with critical thinking: an abstract, linguistic, and internal activity (Heijnen and Bremmer, 2019). Ratto (2011) observes, however, that one can critically think through the process of making – and therefore talks about 'critical making'. By producing and assessing, generating, and judging designs, pupils can be stimulated to make/think critically in and about the world (Quigley and Herro, 2016). Moreover, pupils can enter a critical making process with tools and technologies stemming both from the arts and sciences (Bogers and Chiappini, 2019).

Secondly, education plays an important role in preparing pupils for the challenges in future societies (Groenendijk and Heijnen, 2018). In this context, schools need to address the development of 21st-century skills such as problem solving, creativity, technology literacy, and cooperation, as these will enable pupils to positively contribute to a globalized and ever-changing society (Heijnen, Bremmer, Koelink and Groenendijk, 2020; Hogenes et al., 2021). Research studies demonstrate that when pupils learn these types of skills in isolated school subjects, they find it difficult to transfer them to different domains (Pellegrino and Hilton, 2012; Van Merriënboer, 2013). However, we assume that by integrating arts and sciences in curricula, pupils will not only have the opportunity to develop those 21st-century skills, but also to apply them across subjects more easily than when learned in isolated subjects (Marshall, 2014).

Lastly, an asset of ArtsSciences-education is that it can be based on existing professional ArtsSciences practices, such as the architectural human rights investigators of Forensic Architecture or the research of spider webs by Studio Tomás Saraceno. These practices can provide educators with insights into which themes, materials, and working processes are pivotal in ArtsSciences (Heijnen, 2015).

DESIGN-A-THON

A compact pedagogical strategy suited to teaching ArtsSciences-education is the Design-a-thon method. The Design-a-thon method was originally developed for primary education by Emer Beamer in 2014 and combines elements of Design Thinking, Inquiry- and Design-based Learning, and Maker-education (Beamer Cronin and Hyman, 2018). In general, Design Thinking and Inquiry- and Design-based Learning are based on how scientists and designers approach problems in real-life settings (Kraaij, 2015). The Design-a-thon method consists of a structured workshop facilitated by education professionals of the foundation Design-a-thon Works, in which pupils invent, build and present their solutions to a social or environmental problem (Beamer, 2017). The workshops can last two to six hours, are structured through works sheets and provided with a Maker-kit containing, amongst others, motors, led lights, switches, ventilators, alarms, and wheels (Beamer Cronin and Hyman, 2018). The Design-a-thon workshops all follow the same design cycle as demonstrated in **Figure 1**.

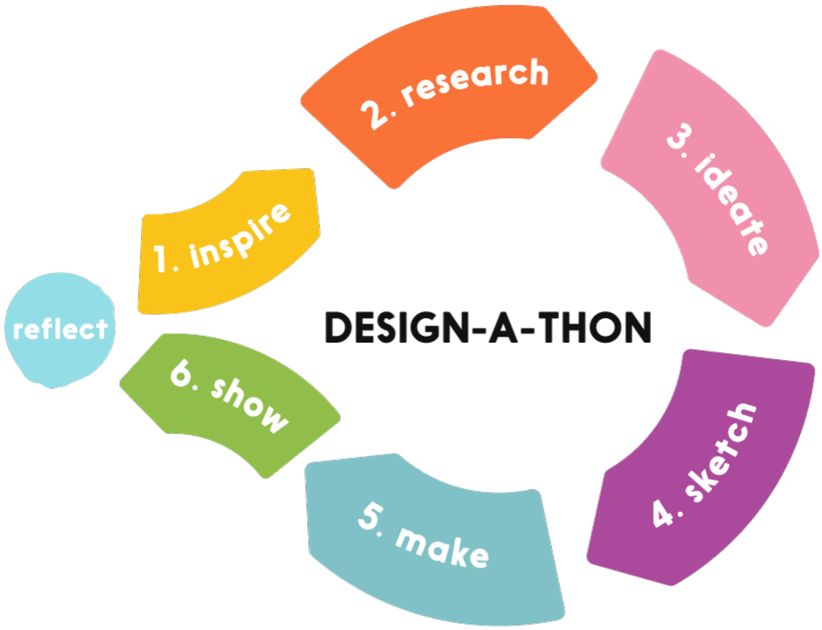

Figure 1. Phases of the Design-a-thon method (Beamer, 2017)

In the phase of 'Inspire' a societal or environmental theme, such as waste, mobility, food, or water is introduced to inspire and to invite pupils to (philosophically) discuss problems within that theme. In the phases 'Research' and 'Ideate' pupils investigate problems within the offered theme and choose a problem they want to work on. In the 'Sketch'-phase, pupils visualize ideas to solve the problem (design concept), and in the 'Make'-phase they transform a design concept into a prototype with materials, amongst others, from the Maker Kit. In the phase of 'Show' and 'Reflect' pupils present their prototypes to each other and reflect on the design process and the prototype.

ROBOT LOVE DESIGN-A-THON

Together with the educational professional of Design-a-thon Works, the researchers translated the Design-a-thon method to the context of higher education. First of all, a meaningful environment was chosen for the preservice teachers' Design-a-thon: the provocative exhibition Robot Love in Eindhoven, the Netherlands. The exhibition explored how we can accept – or even love – robots. The artists *Lancel & Maat*, whose work intersects at arts, science, and technology, were asked to introduce the exhibition's theme and to give a tour through the exhibition that included their work. Secondly, a real-life problem relating to the exhibition was presented to the preservice teachers: 'How can technology promote tenderness between people'? The preservice arts, science, and primary education teachers had to investigate and critically discuss this problem in interdisciplinary teams, whilst being supervised by the artists and a supervisor from Design-a-thon Works. Lastly, based on their design concepts, the preservice teachers had to develop prototypes, using a combination of low-tech (e.g., sensors, leds) and other materials (e.g., paper, clay, rope). During the testing phase, they discussed their prototypes with their peers, the artists, and supervisor, asking for their critical feedback to improve their prototypes. The Design-a-thon ended with a presentation of all the prototypes.

METHODOLOGY

Research Questions and Research Design

To date, empirical research exploring ArtsSciences projects for preservice teachers in higher education is scarce (Hotze et al., 2019). This study, therefore, aimed to collect data that shed a light on how the design and execution of similar projects might be improved. Consequently, the research questions were:

- How does the interdisciplinary working process of preservice teachers develop during the *Robot Love Design-a-thon*?
- What kind of feedback (process- or product-orientated) do the supervisors provide during the design process of the preservice teachers?
- What are the perceived learning experiences and outcomes of the preservice art, science, and primary education teachers regarding the *Robot Love Design-a-thon*?

An evaluation research was chosen to answer these questions. The purpose of this type of research is to evaluate the impact of an (educational) intervention (Powell, 2006). The results of such research are then used to modify or adapt a programme to enhance its success (Powell, 2006).

Participants

Next to the artists Lancel & Maat and a supervisor from Design-a-thon Works, nineteen preservice teachers of four Universities of Applied Sciences in the Netherlands took part in the Design-a-thon (see **Table 1**). The preservice teachers were placed into five interdisciplinary teams.

Table 1. Preservice teachers participating in Design-a-thon

University of Applied Sciences iPabo	primary education teachers	3
Amsterdam University of the Arts	art teachers	13
Fontys University of Applied Sciences	science teachers	2
Teacher College Windesheim	science teacher	1

Research Methods

Two research methods were applied in this evaluation study. First of all, a non-participant, structured observation was used: each interdisciplinary team was observed by a researcher throughout the different phases of the Design-a-thon. As an observation tool, a spreadsheet was used containing the following three themes:

1. The role the different preservice teachers take on during the different phases of the Design-a-thon (problem solver, mediator, critic, initiator, listener, leader, or other);
2. The expertise different preservice teachers contribute during the different phases of the Design-a-thon (art, science, educational, or other expertise);
3. The way the supervisors guide the preservice teachers (product-oriented guidance and/or process-oriented guidance).

Secondly, a learner report was used: an open self-evaluation method allowing learners to describe what they learned or how they experienced an educational project or curriculum (De Groot, 1980). In this study, the open format of a learner report enabled the preservice teachers to report unexpected or unintended learning outcomes too (Van Kesteren, 1993). They filled out the learner reports anonymously immediately after the Design-a-thon. They answered the following three questions:

1. What did you learn or experience during the Design-a-thon?
2. What have you learned that is different to what you thought you would learn, or that did not work for you, or was not true?
3. What appealed to you the most or least regarding the Design-a-thon?

Each question gave examples of how the questions could be answered such as: 'I experienced', 'I noticed', or 'I learned that it is not true that...'

Data Analysis

The data of the observation tool was used to create a narrative of the design process of the teams, describing (1) the interdisciplinary working process and (2) the roles the preservice teachers took on, the expertise they exhibited, and (3) the way the artists and supervisor guided the preservice teachers. In this study, the narratives of two teams are presented (both composed of a preservice primary education teacher, two preservice art teachers, and a preservice science teacher) that were chosen on the basis of the selection criterium 'maximum variation cases' (Flyvbjerg, 2006).

Regarding the data of the learner reports: all statements of the preservice teachers were first placed into a spreadsheet. Afterwards, thematic coding was applied to analyse the data (Braun and Clarke, 2006). This meant that the statements were first coded deductively by two researchers with the following three themes: 'method Design-a-thon', 'interdisciplinary working process', and 'meaningful learning environment' (with a focus on the theme of the exhibition and the exhibited artworks).

During the thematic coding process, the researchers were open to new themes that could be found in the data. For instance, within questions 1 and 2 (What did you learn/experience?) 'technology' was found as an additional theme. Within question 3 (What appealed to you the most/least?) the theme 'curriculum materials' was found, and within the theme interdisciplinary working process a distinction could be made between the general working process and the composition of the team.

A third researcher re-coded all the statements with the developed codes. In the case of differences between researchers, a theme was chosen for the data on the basis of consensus. See **Table 2** for an overview of the themes that were used for analysis.

Table 2. Overview themes for analysis

Question: 1. What did you learn or experience during the Design-a-thon? 2. What have you learned that is different to what you thought you would learn, or that did not work for you, or was not true?	• Method Design-a-thon • Interdisciplinary working process • Meaningful learning environment (theme of exhibition, the artworks) • Technology • Other
Question: 3 What appealed to you the most or least regarding the Design-a-thon?	• Method Design-a-thon • Interdisciplinary working process: in general • Interdisciplinary working process: the composition of the team • Meaningful learning environment (theme of exhibition, the artworks) • Curriculum materials • Other

FINDINGS

Observations of Team One

Interdisciplinary working process: Based on the provided worksheets, the team members first started exploring the problem 'How can technology promote tenderness between people'. In the first hour, hardly any concrete ideas or solutions for the problem were discussed, and the team got stuck on the premise that it wanted to translate the solution to education. After one of the supervising artists made a concrete suggestion to the team (a robot who teaches children about tenderness), the process of brainstorming commenced. During this process, the idea of the artist was turned around: children who teach a robot about tenderness. Partly inspired by works from the exhibition, the team agreed that they should not design a mechanical robot, but somehow a 'soft robot'. It was striking that the phase of ideation was mainly driven by the exchange of preferences concerning shapes and materials for this 'soft robot'. The team experimented with the Maker Kit materials, but in the end the preservice art teachers preferred to stick to their design concept, because they found the materials 'too unattractive'. Meanwhile, the design concept had become more concrete: pupils who teach an interactive bean bag about tenderness via an interface. During the show phase the concept of the beanbag was deepened through three feedback rounds and the final presentation of the team was a convincing one.

Roles: This team consisted of two clear leaders. The preservice science teacher who structured the discussions and kept an eye on the planning, and one of the preservice art teachers who mainly played a pioneering role in terms of the content of the design concept. At key moments, this preservice teacher provided the ideas that were elaborated on by the team: turning around the idea of the artist (children teach a robot) and the idea of the beanbag. The other two preservice teachers did remain involved in the design process. The preservice primary education teacher kept notes of the discussions and, for example, questioned the design concepts during the research phase. The other preservice art teacher was cooperative and tried to connect ideas that arose in the discussions. In the ideate phase everyone contributed ideas, but these were mainly given more depth by the two leaders. The preservice science teacher focused mainly on the technical possibilities of the beanbag, bringing in some domain-specific knowledge about programming. The preservice art teacher was increasingly able to substantiate the design concept. She noted: 'At this age, touch and tenderness are quite a thing [for pupils]. Such a furry, sweet beanbag is more accessible to pupils than a real person.'

Supervision: The feedback of the supervisor of Design-a-thon Works was mainly process-oriented (e.g. how are you getting along with the worksheets?). Despite her feedback, the team initially got stuck in the design process. This changed after one of the artists provided product-oriented feedback. Her concrete proposal about a robot teaching children about tenderness, gave the team's creative process a boost. After developing a design concept, the supervisor of Design-a-thon Works encouraged the team to start making 'something'. However, the team continued to focus strongly on the conceptual aspects of their design during the make phase, instead of actually making a prototype of the concept. This reluctance seemed to be related to the resistance that the preservice art teachers felt towards the offered materials.

Observations of Team Two

Interdisciplinary working process: during the design process, the preservice teachers started by completing the worksheets and by having a broad conversation about the exhibition, their previous experiences with 'making' and technology, and whether or not a robot could actually be human. Then they discussed different ideas about robots in relation to tenderness and one of the preservice art teachers critically questioned the design problem: 'What if a robot is not functional? I think it could be funny when robots are just very dysfunctional.' These comments ended a further conversation on 'tenderness' in relation to robots and the team decided to focus on a robot that could cheer people up or on a robot that could help autistic children to make contact. The team gave little attention to visualizing their design concept, but at some point started building a robot from Lego. The peer feedback rounds helped to create a narrative for this prototype robot. In the presentation phase, the team presented a robot that could function as an interface between grandparents and their grandchildren: the robot should be programmed to make suggestions to the grandparents about which questions they could ask their grandchildren.

Roles: During the inspire phase of the Design-a-thon, the four preservice teachers contributed to the discussion about the theme 'technology and tenderness'. Two preservice teachers, however, seemed to be especially task-oriented: the preservice primary education teacher took the lead in the discussion and moderated it, and the preservice science teacher initiated and read the assignments, collected materials and cleaned them up. During the research phase, the two preservice art teachers took a highly critical stance and kept trying to change the proposed design concepts. The preservice primary education teacher tried to make a connection to education. 'Oh yes, [we could design] a robot with humour, for example for autistic children at school'. However, the preservice art teachers did not really want to integrate technology into the design concept. At one point, the two preservice art teachers more or less withdrew from the collective design process and commenced with the making phase by building a robot with Lego. The preservice science teacher used electronics to build a light for the robot. During the peer feedback rounds, it was mainly the preservice primary education teacher who discussed their design concept and started providing the robot with a narrative.

Supervision: The supervisor of Design-a-thon Works started off with providing process feedback: 'Are you going to get started [with the worksheets]?' When one of the artists came by during the ideate phase, the preservice teachers presented their preliminary design concepts: 'a kind of robot that makes people happy' and 'a robot for children with autism'. Subsequently, the artist elaborated on those concepts and also reacted critically: 'I think it's two different things: a robot that makes contact – a lot of research has been done into robots and autism, or a robot that provides you with humour to cope with a difficult situation'. The artist's critical comments were perceived by the team as a 'negative assessment' of their concepts. Afterwards, the design process seemed stifled and the team struggled with their design concept. The peer feedback and the fact that they had to present their design concept to peers, however, helped to sharpen the design concept and to develop its narrative.

Learner Reports

Straight after the Design-a-thon, the preservice teachers completed a learner report. **Table 3** presents the different themes through which the statements of question 1 and 2 were coded, gives an example of such a statement, and the number of statements per theme.

Table 3. Themes, examples of statements, and number of statements per theme regarding the questions: 1. What did you learn or experience during the Design-a-thon? And 2. What have you learned that is different to what you thought you would learn, or that did not work for you, or was not true?

Theme	Example statement	Frequency
Method Design-a-thon	'I have discovered that you can design a concept in a relatively short time, I had not expected that this was possible'	27
Interdisciplinary working process	'I have discovered that working with unknown preservice teachers stimulates you in a different way'	13
Meaningful learning environment (theme of exhibition, the artworks)	'I experienced how art and robotica influence each other or go together'	17
Technology	'I noticed it's also possible to use technology in an accessible way so that everyone can work with it'	10
Other	'I had few expectations beforehand so I find it difficult to answer this question'	5

The largest number of statements were made within the theme *Method Design-a-thon*, where preservice teachers indicated that they had learned a lot about this method. They particularly mentioned that experiencing a complete design process in a short period of time (one day) worked well: it facilitated their exchange of ideas and critical discussions about technology and tenderness. A primary education preservice teacher stressed the practical application of this method: 'I have learned that I can also do this in my classroom.' Also within the theme *Interdisciplinary working process*, all preservice teachers were unanimous: collaborating with preservice teachers from other disciplines was valuable and working with different ages was noted as a positive experience.

Within the theme *Meaningful learning environment* participants differed in opinion: preservice art teachers indicated that they found the exhibition inspiring and described their gained insights into tenderness and robotics. On the other hand, for preservice teachers without an art background, the exhibition was a less appealing experience: 'I found the exhibition was not what I expected it to be.' Within the theme *Technology*, it was striking that all the coded statements came from preservice art teachers. Many of them were surprised that the technology could be accessible and easy to apply.

Table 4 presents the different themes through which the statements of question 3 (concerning what appealed the most / least to the preservice teachers) were coded, gives an example of such a statement and the number of statements per theme.

Table 4. Themes, examples of statements and number of statements per theme regarding question 3 What appealed to you the most or least regarding the Design-a-thon?

Theme	Example statement	Frequency positive	Frequency negative
Method Design-a-thon	Positive: 'That we were guided through the design process by means of worksheets' Negative: 'The distinct large amount of childish worksheets'	11	18
Interdisciplinary working process: in general	Positive: 'Sharing ideas'	4	0
Interdisciplinary working process: team composition	Positive: 'The diversity of the group in background and age'	11	3
Meaningful learning environment (theme of exhibition, the artworks)	Positve: The exhibition was very interesting and I wouldn't have wanted to miss it. It made it relevant for me personally' Negative: 'I found the exhibition rather disappointing because nearly everything was just to look at. I expected more profundity'	14	3
Curriculum materials	Negative: 'I expected there to be real robotization, technology and knowledge to implement or do'	1	11

Most of the statements (29) related to question 3 could be connected to the theme *Method Design-a-thon* and showed a mixed picture. On the one hand, there were preservice teachers who appreciated the worksheets and working according to the set phases of the Design-a-thon method. Participants were also positive about the freedom they were given in exploring the theme, about brainstorming about their design concept, and developing a design concept. On the other hand, other preservice teachers were negative about having to systematically work through the design phases, and felt the worksheets were too structured: 'sometimes it came across as schoolish, in terms of filling in worksheets, and working in a structured way.' The preservice art teachers predominantly made negative statements in this theme (13 statements negative against 5 positive).

Four statements could be assigned to the theme *Interdisciplinary working process* (in general), all from science preservice teachers, except for one art preservice teacher. They appreciated the exchange of ideas and how well the team collaborated. Within the theme *Interdisciplinary working process* (team composition), art and primary education teachers were positive about working with different disciplines and ages. Criticism concerned the imbalance between disciplines within the teams: preservice art teachers felt it was especially a pity that so few preservice science teachers had taken part.

The statements in the theme *Meaningful learning environment* (theme of exhibition, the artworks) made clear that the exhibition and the theme mainly appealed to the preservice art teachers (13 out of 17 statements). Within the theme *Curriculum materials* it was striking that practically all statements were negative (11 negative, 1 positive). Ten of the negative statements were made by preservice art teachers, who indicated that they had expected more technology, and found the curriculum materials too simple or childish.

DISCUSSION AND CONCLUSION

In this evaluation study we set out to explore the preservice teachers' experiences with the design and execution of the Robot Love Design-a-thon.

Concerning the interdisciplinary working process, the findings showed that the Design-a-thon challenged the preservice teachers to exchange ideas and to critically discuss the theme 'technology and tenderness' during the whole design process. Thus, the starting point of the Robot Love Design-a-thon that preservice teachers should critically discuss a societal theme on the intersection of arts, science, and technology was achieved. Furthermore, due to the diverse disciplines in a team, different perspectives could be given on the theme, thereby deepening or broadening discussions (Gess, 2017). The prototypes used to visualize the solutions of the problem, ended up being rather basic. However, they were functional for explaining and critically discussing the design concepts and the innovative ideas underlying them. Finally, although seen by some as a positive aspect, other preservice teachers were negative about the structured approach of the Design-a-thon method, even though it did seem to bring focus in the design process.

Regarding the supervision, our observations showed the supervisor of Design-a-thon primarily giving process-orientated feedback and the artists critical product-orientated feedback. Interestingly, these two sorts of feedback seemed to be experienced both positively as negatively by the preservice teachers. Therefore, providing a combination would seem a preferred strategy: process-orientated feedback gives preservice teachers agency in developing a design concept but without product-orientated feedback the concepts might remain superficial. On the other hand, product-orientated feedback can push the creative design process forward but can be experienced as too directive, leaving too little space for personal interpretations and ideas.

Concerning the perceived learning experiences and outcomes, the findings demonstrated that the preservice teachers had learned how the Design-a-thon method works in practice and about the content of the theme 'technology and tenderness'. Research studies demonstrate that, if (prospective) teachers do not have any experience with a certain teaching method, such as for instance the Design-a-thon, they may feel apprehensive about its implementation (Van Casteren, Van den Broek, Hölsgens and Warps, 2014). On the other hand, (prospective) teachers who experience cross-curricular education themselves tend to apply this more often in their classroom (Kim and Bolger, 2017; Rinke, Gladstone-Brown, Kinlaw and Cappiello, 2016). By taking part in the Design-a-thon, the preservice teachers in this study were given concrete tools for cross-curricular education, enhancing the likelihood of applying it in their own classroom (Lam and Chan, 2011; Wilschut and Pijls, 2018).

Furthermore, the starting point of the Robot Love Design-a-thon that preservice teachers should learn to work in interdisciplinary teams was unambiguously confirmed as a positive experience: all preservice teachers noted in the learner reports that working in mixed teams (disciplines, ages) was relevant and meaningful and allowed them to take on different, complementary roles that enriched the design process. Obtaining these kinds of interdisciplinary experiences is important as the ability to collaborate with colleagues from other subjects plays an important role in carrying out cross-curricular education (Wilschut and Pijls, 2018).

Taking a more critical stance, the findings also indicated that some aspects of the Design-a-thon could be improved. First of all, the preservice teachers without a background in the arts did not find the exhibition meaningful: the art works and theme were not accessible or appealing to them. When redesigning such a Design-a-thon, all backgrounds of participating preservice teachers should be taken into account – for instance, in this study, a more extensive tour of the exhibition could have been given with explanations of the art works, making them more accessible.

Also, the preservice art teachers were especially critical about the curriculum materials which they found childish and not artistic enough. The materials were the same as used in a Design-a-thon for primary education – the idea being that the transfer of such materials to the classroom practice would be facilitated. A solution would be to provide the preservice teachers with materials at their 'own level' and to provide them with information about which materials could be used in primary and secondary education.

Furthermore, the observations made the team roles of the preservice teachers insightful: of all the preservice teachers, the preservice art teachers seemed to be able to question the problem ('How can technology promote tenderness between people?') and theme of the Design-a-thon in the most critical way. Yet at the same time, they could get stuck in their opinions, thus obstructing the interdisciplinary working process. These observations should, however, be interpreted with some caution as the preservice art teachers were in the majority and felt more at ease with the exhibition and its theme.

In conclusion, an ArtsSciences Design-a-thon seems to offer different entry points for preservice teachers to develop knowledge about and experience with pedagogical strategies and content for cross-curricular education. Working in interdisciplinary teams is a real advantage as teachers from other disciplines can offer new perspectives on problems. As such, ArtsSciences Design-a-thons in higher education can pave the way for innovative and thought-provoking education in primary and secondary schools.

ACKNOWLEDGEMENT

This article draws on and extends ideas from the Dutch peer reviewed article Hotze, A., Bremmer, M., Heijnen, E., Pijls, M., Beamer, E. and Roos, N. (2019).

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 12
ISSN: 2468-4368

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Last Generation Solar Cells in Outer Space: A STEM Outreach Project with Middle and High School Students in Colombia

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Citation: Perea, J. D., Gasca, D. C., Echeverry-Prieto, G., Quiroga-Fonseca, V., Orozco-Donneys, C., Díaz-Montealegre, L. C., Ortiz, A., Molina, G., Cruz, D., Persad, A., Redd-Kantareddy, S. N., Wachsmuth, J., Heumueller, T., Brabec, C., Rodriguez-Toro, V. A. and Salguero, C. (2021). Last Generation Solar Cells in Outer Space: A STEM Outreach Project with Middle and High School Students in Colombia. *European Journal of STEM Education*, 6(1), 12. https://doi.org/10.20897/ejsteme/11353

Published: November 18, 2021

ABSTRACT

As part of an unprecedented collaborative outreach effort, we implemented an innovative STEM outreach project, where more than 80 middle and high school students from different traditionally underrepresented school districts in Colombia -with no previous knowledge on material science or photovoltaics- created Last Generation Solar Cells (LGSCs) that were part of several suborbital spaceflight missions. As a result, the students were able to contrast visual and instrumental data obtained from the solar cells and modules that were launched to space with similar samples that remained on earth to measure the degradation that occurs during spaceflight conditions. At the same time, the students that participated were able to cultivate their curiosity, strengthen their scientific skills and increase their interest in pursuing careers in STEM fields.

These experiences were possible thanks to an extraordinary collaborative network between public and private entities and the use of project-based education as a powerful driver of development, especially for low-to-middle-income countries, such as Colombia. Here, we share our methodology for constructing photovoltaic devices in rural settings, and we show the progression and impact of this novel scientific outreach project.

Keywords: STEM education, science outreach, organic solar cells, last generation solar cells

INTRODUCTION

Increased community participation and understanding of the importance of the contributions of the STEM (Science, Technology, Engineering, and Mathematics) fields are thought to be drivers of social change (Kendall-Taylor, 2020). Since STEM education has the potential of strengthening a country's economy, educational programs with an emphasis in science, mathematics, technology, and engineering have become a worldwide priority (Quigley, 2016; Kelley and Knowles, 2016). A good example of how STEM education can generate a technology-based society is South Korea, where the National STEM program implemented educational strategies for teaching science, technology, engineering, arts, and mathematics in all school grades (Nationales MINT (STEM) Forum, 2014; Kang, 2019).

Because providing educational services and programs aimed at the democratization and appropriation of scientific knowledge requires large investments for the implementation of nationwide STEM educational strategies, integrating such strategies in the educational systems of low-to-middle-income countries has proven to be very difficult. That is, while the challenges of implementing STEM educational strategies vary from country to country, the lack of resources, the resistance to changes in the curriculum, and social inequality are very common issues in countries with high rates of poverty and poor infrastructure (Savage, 2018). For instance, Colombia has suffered from a diverse range of socio-economic issues that arise from widely spread corruption, drug trafficking, and an ongoing civil conflict that has severely affected rural communities for more than six decades. Even though the Colombian government signed a peace agreement with one of the many armed groups that have taken part in the armed conflict, other armed groups are still waging a war that continues to affect rural communities (LeGrand et. al, 2017). Hence, in the last few decades, governmental spending has focused more on the civil conflict rather than on improving educational strategies, making it very difficult to access basic educational services for rural students in certain regions of the country.

In a recent effort to strengthen STEM competences in public schools, the Colombian government changed from an educational model, where some students attend school in the morning, while others attend school in the afternoon, to an educational model where all students spend a full day in school. In this model, all students would focus on learning specific competences during the afternoon classes. In addition, the government implemented an after-school program for students in some of the most underprivileged communities to incentivize research and strengthen STEM competences (Salazar-Lara, 2020). Yet, even with all the governmental and private efforts combined, the most recent results from the Programme for International Student Assessment (PISA) show that the proficiency in mathematics, science and a new innovative domain in Colombia are below the mean. That is, while on average 11% of the students in OECD countries scored at Level 5 or higher in mathematics, only 1% of Colombian students are in the same category and a negligible percentage of students were top performers in science (OECD, 2019). These results show that there is a need for articulating different economic and academic sectors with international cooperation to implement active learning and project-based strategies at a national level that can focus STEM education to solve real and practical problems.

In search of strategies that can strengthen STEM education in different rural areas of Colombia, we have created a network of collaborations between public and private entities that have come together to work with middle and high school students, one of the population groups with the greatest potential for social transformation. Here, we present a methodology based on a collaborative scheme between several organizations that bring together highly recognized international scientific actors to collaborate in an *avant-garde* scientific experience that recreates real lab experiences in rural settings: first, the students learn the theory behind photovoltaic devices, and then they create last generation solar cells that are used in experiments held in outer space.

FROM HIGHSCHOOL TO SPACE: OUR METHODOLOGICAL APPROACH

Through the advancement of new technologies, space exploration has evolved from an endeavor that was only accessible and funded by powerful governments to become a commercial and academic enterprise driven by private initiatives (Smith et al. 2012, Bugga and Brandon, 2020; Ackerman, 2020). According to the Media Lab from the Massachusetts Institute of Technology, space exploration has the potential of reaching more citizens than ever before. Hence, to prepare the new generations of professionals that will dedicate their lives to space exploration, it is necessary to enhance educational initiatives in the STEM fields around the world.

Educational initiatives related to space exploration including CubeSats, Cubes in Space and Project Possum, amongst others, provide the infrastructure required for certain underrepresented groups to participate indirectly in space exploration through experiments that are sent to outer space. However, the lack of local infrastructure and the limitations of resources that are faced by students from low-to-middle-income countries, eclipse the relevance of their scientific contributions. In our case, the following considerations were made taking into account the vast limitations of the rural settings where our outreach program take place:

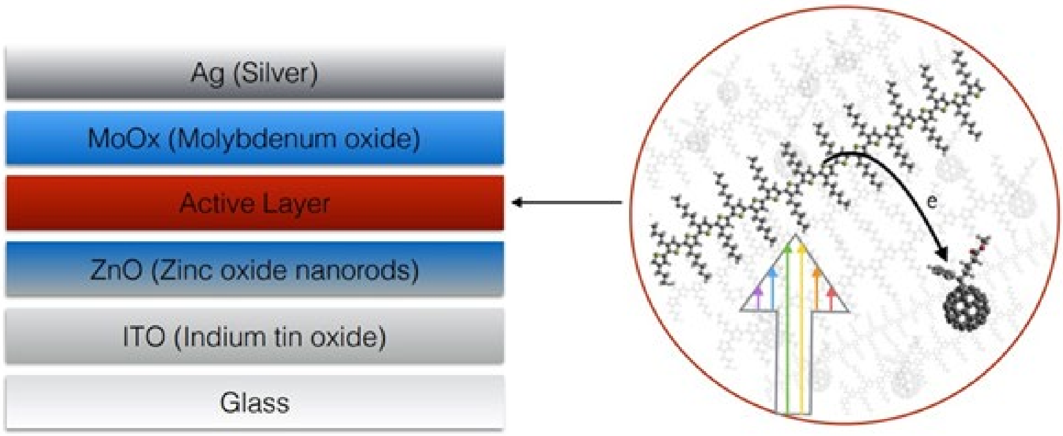

Figure 1. Illustration of the basic structure of organic solar cells showing the composition of the different layers (Perea, 2019)

- Knowing that a controlled atmosphere is difficult to guarantee in most rural lab settings, the devices are designed to minimize their immediate degradation.
- Since there is no access to solar monitoring systems in rural lab settings, a set of control Organic Solar Cells (OSCs) are built at the Friedrich Alexander University (FAU) facilities to help characterize their performance and visualize the near power conversion efficiencies.
- In-house made spin coaters are especially built to create a real lab experience in rural settings.

Since 2017, our team has been developing a unique lab experience for middle and high-school students from different public schools in which they could create a set of OSCs with the minimum technological requirements. Taking in consideration that the experiments involved in the production of solar photovoltaic devices often require expensive materials and sophisticated techniques, our team coordinated a successful -yet very simple- experimental design. For such purpose, our team received financial and scientific support from SENA, Science Clubs Colombia and the FAU in Germany, including Professor Christoph Brabec and Dr. José Darío Perea, who saw in the project a powerful way to motivate participants to achieve scientific vocations.

MAKING LAB-SCALE ORGANIC SOLAR CELLS IN RURAL SETTINGS

Before starting the experimental section, the students are introduced to the lab safety rules and the basic concepts involved in photovoltaic solar power. Once the students are able to understand basic concepts, the instructors can focus on the theories behind the experimental techniques and the specific procedures that are required to make organic solar cells.

Briefly, our students create OSCs with three parts that allow for the photo-generation and collection of charges, which consists of electrons and holes: the first part is an electron-collecting electrode or bottom electrode; the second part is composed of photoactive materials, such as polymers and small molecules that absorb the sunlight and generate free charges; and a third part that constitutes the hole-collecting electrode or top electrode (**Figure 1**). Hence, the direction of the photogenerated current is set by the different properties of the materials used in the top and bottom electrodes.

Each of the OSCs parts are composed of one or two thin layers of intermixed or pure materials. That is, the bottom electrode is a glass substrate coated with patterned Indium Tin Oxide that is spin-coated with a thin layer of Zinc Oxide, processable from solution, to facilitate the collection of electrons. In the second part of the OSCs, where the electric charge is generated, different organic semiconductors are used. For instance, semiconductors such as an electron donor called P3HT, and an electron acceptor that can be either a non-fullerene acceptor o-IDTBR or the fullerene electron acceptor PCBM can be used. In our case, intermixed solutions of P3HT:PCBM and P3HT:o-IDTBR were spin-coated to create the photoactive thin-film. For the top electrode, which is used to collect the holes, we used a thin layer of Molybdenum Oxide and a thicker layer of either Silver or Aluminum. These two layers were deposited in sequential steps by thermal evaporation.

To build OSCs in rural lab settings, our team created portable spin-coating machines using a computer case fan that was modified mechanically to act as the controllable rotating plate. The speed of the fan was controlled through a pulse-width-modulation that used a microcontroller Nano V3 Arduino board and a small LCD module as a display that was programmed to show the rotating speed, the time and the power of the potentiometers that control the duration of the coating. To catch the overflowing ink, the bottom end of the coating machine was covered with aluminum foil, while the top electrode layer was evaporated.

Figure 2. (Left) Cube holder illustration. (Right) The first launch of solar cells attached to an aerostatic balloon that reached an altitude of 37 km, from NASA's Columbia Scientific Balloon Facility in Ft. Sumner, New Mexico through the Cubes in Space Program. Photo Credit: Cubes in Space™.

Once the OSCs were created, the students are asked to prepare a scientific poster that includes a search for local applications of solar power devices and the proposal of new applications to contextualize the knowledge acquired during the sessions. The poster sessions are designed in such a way that the students not only have a chance to socialize their findings, while at the same time they get to improve their presentation skills, but they were also designed to ensure that the students appropriate all the concepts learned in the lab by generating ideas that can solve problems in their communities and in the world.

LAUNCHING OUR FIRST SOLAR CELLS TO SPACE

Space exploration and the democratization of outer space is currently facing challenges beyond our human developments in STEM fields, especially in areas related to food and energy production. Solar energy has been one of the main sources of energy used in space exploration (Perlin, 1999; Yang et al., 2020; Koehler, 2019). However, to minimize the area that is occupied by the solar modules, the materials used to generate energy during space exploration have been characterized by their high-power conversion efficiencies and ease of transport at the expense of increased costs associated with their production. The opportunities offered by novel materials - including organic molecules like polymers, fullerenes, small molecules, and perovskites- can be an alternative to conventional solar cells in terms of weight, flexibility, and costs (Dennler et al., 2009; Du et al., 2017; Cao et al., 2017; Brabec et al., 2020; Distler et al., 2020; Langner et al., 2020; Dowland et al., 2017). Despite the historically lower efficiencies of these novel materials, recent reports present efficiency values that challenge the use of traditional solar technologies. Therefore, it is necessary to establish the potential use of next-generation solar cells operating under outer space conditions.

Shortly after the organic solar cells were made by our students our team was able to win a spot in the Cubes in Space™ (CiS) competition, where teams of students from all over the world compete to test their experiments in near space conditions. The experiments that are selected can travel either by being attached to a zero-pressure scientific balloon, or inside an Orion Terrier improved rocket. Each type of space flight implies different environments for the samples allowing the teams to interpret two different sets of data.

As our first proposal was accepted, subsequent proposals for other space missions were presented. This allowed our team to mentor more students and researchers across Colombia, while at the same time exploring new materials in different space conditions. Thus, several different organic solar cells were included in two space missions: one attached to a scientific zero-pressure balloon launched from the NASA Langley Research Center in New Mexico, and another one inside an Orion Terrier Rocket, launched from the NASA Wallops Center in Virginia reaching an altitude of more than 150 km.

This part of the methodology takes the experimental results, and the knowledge gained by the students to a new level. That is, by confronting the students with the possibility of testing their solar cells in different atmospheric chemical conditions, including microgravity and electromagnetic radiation, which are only present in superior layers of the atmosphere, the students were capable of identifying whether these new generation solar materials were apt for space applications. In addition, the students were able to acknowledge the limitations of the materials in order to formulate a scientific hypothesis, and imagine the possible outcomes of the space missions. **Figure 2** shows an illustration of the cube holder experiment, and a picture of the first stratosphere experiment.

LAUNCHING DIFFERENT TYPES OF SOLAR CELLS TO SPACE

Through the years, our team has guided students from different rural regions of Colombia -some that are not even connected to the power grid and others that have been heavily affected by internal armed conflict- into creating solar cells using a wide variety of materials that have been tested in outer space. For instance, a set of six solar cells made by Colombian students including perovskites cells made by a group of indigenous students from a Wayuú Community in La Guajira, where potable water is scarce and there is no connection to the power grid or connectivity, were launched into the thermosphere inside the Orion Terrier Rocket. After an exhaustive state-of-art review, we learned that the research group of Professor Cardinaletti launched perovskite-solar cell modules into the stratosphere for the first time in 2017, but no other group had ever reported reaching outer space with their experiments on perovskites (Cardinaletti et al., 2018).

On another occasion, rural students from a conflict recovery zone (Oiba, Santander) (Science Clubs International, 2016) used blueberry extract as a photosensitizer to create a set of dyes sensitized solar cells that traveled to the stratosphere aboard a Zero Pressure Balloon. These cells, and other solar organic modules, were meant to measure the voltages and currents produced before, during and after sunlight exposure, as well as, to measure the effects of climatic variations and the rate of degradation. Currently, our team is working in alliance with students from an educational robotics group, named MyRobotTech and directed by David Bustamante. We are currently preparing for international competitions with their mini-arduino robot and their solar car.

MEASURING THE IMPACT OF OUR METHODOLOGY

Surveys and informational interviews at the end of the program have shown that 81% of middle and high-school students that have participated in our outreach initiatives have a particular interest in pursuing careers in different STEM fields. Thus far, one of our alumni has had the chance of joining the Space Cubs hosted by NASA with the sponsorship of Coursera CEO Latin America, while two others started a biochemistry engineering collaboration project with ICESI University, which offers a promising future for today's world that depends on advances in technology and biochemical transformation processes to be applied in outer space.

In an effort funded by the Colombian Ministry of Science, we were able provide an international academic experience in Germany to four of our students. In coordination with Dr. Perea, Dr. Cruz, and Professor Brabec, the students were able to explore the Bavarian Centre for Applied Energy Research (ZAE Bayern in German) and the FAU facilities at EnCN in Nuremberg, where they were introduced to inorganic perovskite-based solar cells, and were able to create a set of lab-scale devices. They also attended multiple academic events and met outstanding researchers in the photovoltaic field such as Professor Aldo Boccaccini, Professor Markus Antonietti, as well as a short visit with Professor Gerhard Ertl, Chemistry Nobel Prize Laureate, at the Max Planck facilities in Berlin. This life-changing week allowed our students to experience the life of a scientist and get a wider perspective about careers in STEM.

Finally, to include a gender perspective aimed at propelling scientific exploration for girls from ethnic communities in Colombia, we are searching for private sponsorship to bring a group of girls from underrepresented backgrounds to Boston for a scientific and educational experience. **Figure 3** was made to summarize all the projects enrolled in our methodological approaches.

CONCLUSIONS

Our results show that cutting edge research can reach decentralized sectors of society and produce extraordinary outcomes. By carefully planning and preparing experiments out of the laboratory settings and in alternative learning contexts, we have guaranteed the participation of students from different rural areas that have no previous scientific background.

Our team has counted with the support of several active academics, including professors and graduate students that are interested in the democratization of science as a driver for social change. Our project gained momentum thanks to their contribution, and it allowed the involvement of new actors that escalated the replication and continued execution of our methodology.

Hence, our project stems from a cooperative approach that not only develops STEM education in rural areas, where it is needed the most, but it also contributes to the strengthening of scientific culture in different communities and regions. It is our hope that in the near future, the students that benefited from these types of programs could help increase the sustainable development of their communities.

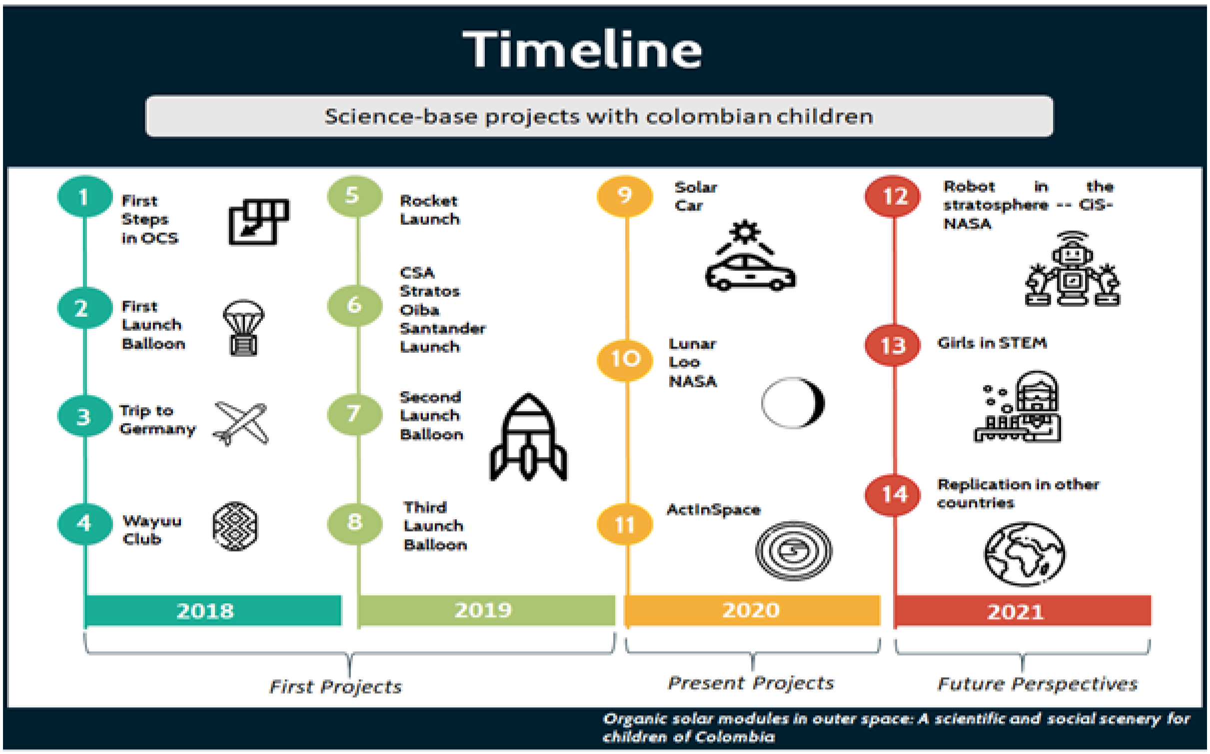

Figure 3. Timeline of the projects that have been implemented by our team in the last three years, and the projects that are in the pipeline for 2021.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 13
ISSN: 2468-4368

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Defining STEAM Approaches for Higher Education

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Citation: Carter, C. E., Barnett, H., Burns, K., Cohen, N., Durall, E., Lordick, D., Nack, F., Newman, A. and Ussher, S. (2021). Defining STEAM Approaches for Higher Education. *European Journal of STEM Education*, 6(1), 13. https://doi.org/10.20897/ejsteme/11354

Published: November 18, 2021

ABSTRACT

In an increasingly complex interconnected world, STEAM practices have gained attention in Higher Education (HE). The integration of Sciences, Technology, Engineering and Mathematics pedagogies with those from the Arts takes many forms with myriad intentions, processes and outcomes. Common aspirations pertain to equipping students with interdisciplinary skills required for the jobs market, increasing intellectual curiosity and collaboratively developing creative, socially equitable responses to complex global challenges. The Erasmus+ project *STEAM Innovation and Curriculum* involves seven European partners who have been pioneering STEAM approaches and methods. Using workshops, discussions, hacking processes and reflective practice, this collaborative work is the first comprehensive attempt to systematically analyse and showcase European approaches to STEAM in HE. Project outputs relate to the three project phases and include defining STEAM and a Handbook on STEAM approaches (Phase 1), the development of new STEAM methods (Phase 2) and developing evaluation frameworks (Phase 3). The Handbook collects and codifies HE STEAM approaches and provides a working definition highlighting key elements of STEAM projects and processes as well as guidance and inspiration for those looking to develop and introduce STEAM approaches in their institution. This paper focuses on Phase 1 outcomes and insights to help foster STEAM thinking and to tackle issues around joint STEM/Arts standards, and concerns in the HE arena such as modes of intellectual investigation, curriculum planning and the case for inter- and transdisciplinarity.

Keywords: higher education, STEAM approaches, STEAM methods, European STEAM practice

EMBEDDING STEAM IN HE

To date STEAM (Science, Technology, Engineering, Arts and Mathematics) approaches and projects have gained traction for pre-school, primary and secondary education (e.g., Bertrand and Namukasa, 2020; Burnard et al., 2020; Timotheou and Ioannou, 2021). Surprisingly little specific focus has been given to Higher Education

(HE) applications in terms of potential diversity in opportunities, as well as attention to challenges and barriers (e.g., Kim et al., 2018). While there is a wide range of individual, institutional and national STEAM projects and perspectives, through our research connections and in the literature consulted, we, alongside others (e.g., Mejias et al., 2021), noticed a sparse coordinated effort to understand the ambiguities and tensions within the STEAM umbrella term, and what a shared understanding of STEAM in a HE context might, or should, encompass. For example, what are essential STEAM qualities for tertiary education, research and collaborations? What range of curricular and extra-curricular approaches and methods already exist? How well prepared and engaged are HE staff to embrace STEAM and what kind of training is, or should be, available for administrators, academics and senior management staff? How could we (better) monitor and evaluate STEAM activities in HE?

STEAM INC, an ERASMUS+ supported three-year project (2019-1-UK01-KA203-062032)[1], aims to address this gap. Its partners are universities and HE-related organisations across Europe that have pioneered or experimented with a range of STEAM approaches and developed specific STEAM methods for engaging and upskilling staff, students and external stakeholders. The drivers are the increasingly complex societal and environmental challenges as well as a necessity for transdisciplinary working. For the latter, recognising the diversity and power of embedding Arts in STEM subjects and for Arts-related subjects to foster closer alliances working with people grounded in the Natural and/or Social Sciences is key. An underlying assumption is that specialist and mono-disciplinary approaches are no longer sufficient for preparing students for the job market or for addressing the complexity of society's problems and needs (e.g., Anonymous, 2016; Segarra et al., 2018).

As a consequence, this may challenge existing identities of students, teachers and researchers in HE in relation to their 'home discipline', knowledge base and nurtured abilities. STEAM can open up and enable different spaces, skills and competencies to form; but this does not mean that artists have to become scientists and scientists need to become artists. It seems, however, a timely exercise to examine the following questions: 'What does a STEAM framework and/or university STEAM culture look like?' and 'How is it, or should it be, institutionalised in HE?'

This paper adopts a reflective practitioner approach to elicit the multiple interpretations, perspectives and nuances of university-level STEAM-working and projects. It details some of the learning and insights gained to date from engaging critically and with curiosity to identify common denominators and key principles that can become useful anchors for meaningful and effective future STEAM work in the HE sector. Rather than following a conventional paper structure of Literature Review, Methodology, Results and Discussion this article is a reflective narrative but includes all of the above elements. It draws on the STEAM INC project partners' experiences and perspectives as well as the wider literature as appropriate. The STEAM INC workplan is the basis for the methodology, to help structure the reflections and findings, focusing specifically on the first 18 months of the project.

Based on a thorough online search for 'STEAM+approaches+HE' material at the time of writing of the STEAM INC project proposal, this is the first comprehensive attempt to collect and codify European approaches to STEAM in Higher Education. As such, the work has been exploratory, is contestable and should not be considered conclusive or exhaustive. For this paper, we have identified work that shares similarities in aims, particularly work led by Laura Colucci-Gray as part of a project funded by the British Educational Research Association (BERA). This work critically discusses the multiple policy directions and cultural traditions of STEAM in educational practice highlighting the multi-layered experiences, limitations, possibilities and relational understandings of STEAM education (Colucci-Gray et al., 2017, 2019; Colucci-Gray, 2020). However, while very relevant to the tertiary education level, their work was conducted for the primary and secondary school educational context and largely UK-focused rather than capturing an explicit wider European/international and HE perspective.

Specifically, and in parts aligning with but also going beyond Calucci-Gray's work, this contribution aims to elicit and discuss some tensions and ambiguities as experienced in the early parts of the STEAM INC project which appear to be of wider and fundamental relevance yet are difficult to find in the current literature (a notable recent contribution is by Meijas et al., 2021). Published STEAM projects and programmes tend to focus more on the positive aspects and their promising contributions rather than discuss various (mis-)understandings and 'uncomfortable' parts of STEAM experiments and expansion. This seems an opportune time to start eliciting and examining ambiguities and potential/actual barriers to STEAM working as well as highlighting the need for radical openness and reflectivity to guide and progress STEAM applications and uses in HE.

[1] The project is funded under Call 2019 Round 1 KA2 - Cooperation for innovation and the exchange of good practices, KA203 - Strategic Partnerships for higher education.

Table 1. The STEAM INC partner organisations and main contributors

Organisation, Location	Main Contributors
Birmingham City University (Lead Partner) *Birmingham England, UK*	Laura Veart (Project Manager, STEAMhouse)
	Tom Cahill-Jones (STEAMhouse)
	Claudia Carter (School of Built Environment)
	Kathryn Burns (School of Fashion and Textiles)
	Annette Naudin (School of Media)
	Charmaine Stint (Research, Innovation & Enterprise)
Central Saint Martins College, University of the Arts London *London, England, UK*	Nathan Cohen (Course Leader of MA Art and Science programme)
	Heather Barnett (Pathway Leader on the MA Art and Science)
	Adrian Holme (Lecturer - MA Art and Science)
Science Gallery Dublin, Trinity College *Dublin, Ireland*	Shaun Ussher (Learning and Engagement Researcher)
	Mairéad Hurley (Education & Learning Manager, Science Gallery Dublin)
Aalto University *Helsinki, Finland*	Eva Durall (Department of Media, School of Arts, Design and Architecture)
	Jaana Brinck (Department of Art, School of Arts, Design and Architecture)
	Teemu Leinonen (Department of Media, School of Arts, Design and Architecture)
Amsterdam University *Amsterdam, The Netherlands*	Frank Nack (Informatics Institute, Faculty of Sciences)
	Natasa Brouwer-Zupancic (Faculty of Science)
	Jacobijn Sandberg (Faculty of Science; creator of Bachelor in Humans, Society and Technology programme)
Dresden Technical University *Dresden, Germany*	Daniel Lordick (Institute of Geometry; Geometric Modelling and Visualization)
	Henriette Greulich (Center for Interdisciplinary Learning and Teaching)
	Robert Fischer (Chair of Industrial Design Engineering)
	Lisa Katharina Nickolaus (Geometric Modelling and Visualization)
Ars Electronica *Linz, Austria*	Andrew Newman (Producer of European Projects for Digital Humanism)
	Veronika Liebl (Managing Director, Festival Prix / Exhibitions)

Table 2. STEAM INC's work programme and main outputs

Outputs	Goals	Co-ordinator
Handbook on HE STEAM Approaches STEAM working definition Training workshops Website	Guide HE STEAM-based course and module design, and extracurricular STEAM approaches and methods clarifying points of intersection between the different interpretations and applications of STEAM. Training HE professionals in how to identify and communicate these points of intersection.	Birmingham City University (BCU)
STEAM Tools Training workshops	Learning from across the partnership and own critical reflective practice, develop 'new' STEAM methods for HE that reflect/embed STEAM characteristics as signalled in the working definition.	Central Saint Martins (CSM)
STEAM Evaluation Process and Guidance Training workshops	Develop evaluation frameworks for the project and wider applications to help measure the impact of STEAM approaches and methods and aid holistic and ethical STEAM applications.	Science Gallery Dublin (SGD)

THE STEAM INC PROJECT

The Erasmus+ project 'STEAM Innovation and Curriculum' (short STEAM INC) is a collaboration between seven European partner organisations who have been pioneering STEAM approaches and methods (**Table 1**). The project started in October 2019 and finishes in January 2023 (extended from August 2022 due to the impacts of the COVID-19 pandemic).

The project objectives and associated workplan (**Table 2**) are three-fold:

1. Identify points of intersection across current European HE STEAM approaches and develop a collaborative definition of HE STEAM.
2. Produce methodologies for the implementation of STEAM thinking in HE education, policy and engagement.
3. Create an evaluation framework for measuring the effectiveness of STEAM processes in HEIs and HE partner organisations.

At the time of writing this article, the project was roughly halfway, with the first objective completed, the second underway and the third in preparation. The STEAM INC Methodology includes project partner meetings, local workshops, short training events, multiplier events and conferences. Most meetings, workshops and other events have been held online due to the COVID-19 pandemic. The one exception is the first project partner meeting held in Amsterdam in December 2019. Specific tools have included templates for data collection, peer review, reflection, developing persona / user profiles, and 'hacking' (involving deconstruction, translation/selection, evolution and hybrid recombination stages).

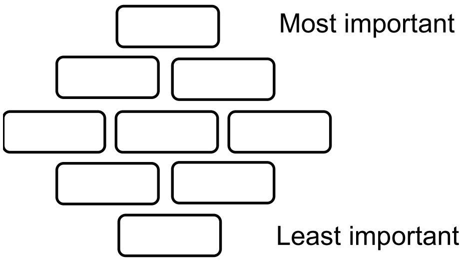

Figure 1. The Diamond Nine method

To address Objective 1 (the main focus of this paper) we identified commonalities and core elements across our different experiences, interpretations and applications of STEAM in Higher Education and HE-related ventures. The following paragraphs explain in some detail the methodology for developing a shared baseline of essential qualities for STEAM approaches in HE and how we arrived at our working definition and classification (structured into four stages). This section finishes with a brief outline of the Methodology for addressing the second and third objectives.

Eliciting Points of Intersection across European HE STEAM Approaches

Stage 1: Creating a definition

Before our first project meeting, each partner completed a template writing down individually or as a team their working definition of STEAM, detailing and reflecting on essential characteristics and outlining the specific context(s). It also probed into whether agreed definition(s) of STEAM existed at the institutional/organisational level. Partners presented their STEAM definitions at the first partner meeting. We progressed with collecting key words that were, in participants' opinions, representative of STEAM. Working in groups, we used the 'Diamond Nine' technique (**Figure 1**) to select, evaluate and collectively prioritise nine STEAM characteristics in a diamond shaped matrix. While not intended to be definitive, rather to promote discussion, several participants found the method prescriptive and 'forced'. This sparked useful debates and helped our understanding and appreciation of the plurality of STEAM perspectives, the diversity in ways of working and associated preferred collaborative/discursive methods and approaches.

Based on the outcomes of the Diamond Nine method, STEAM INC participants structured the key words to produce a definition that could encapsulate the broad, emerging collective understanding of what is encompassed by a STEAM approach. A major consideration was what kind of 'categories' fitted those attributes or competencies. Seven categories emerged which then helped to structure and synthesise the initial set of definitions from the group work into one working definition, through analysing and identifying the key and most common words used in those definitions. Finally, this resulted in a set of baseline attributes a STEAM practitioner or process might exhibit. The results of this Stage 1 work are presented in sections "HE-specific STEAM Context and Characteristics", "Ambiguities and Tensions" and "A Working Definition of STEAM for HE".

Stage 2: Collecting and reviewing approaches

Using the working definition established through stage 1, project partners then identified approaches from within their institutions that clearly expressed dimensions of STEAM. The selection of examples was flexible and included a broad range of applications across Higher Education, but with particular interest given to those examples relating to Higher Education **courses & curriculum development**, internal and external **engagement** and **policy**. The approaches were then shared at an online international training event held in March 2020. The outcomes of this review process are presented in section "Generating a Typology of STEAM Approaches".

Stage 3: Providing reflections

Transdisciplinary experts from within the partnership were invited to consider what was distinctive and/or notable about the collected approaches based on their institutional perspective and personal experience (key points from those discussions are captured in section "Ambiguities and Tensions"). The raw opinions were grouped according to approach and theme, and insights across these distilled for inclusion in the HE STEAM Handbook (stage 4).

Stage 4: Producing practical guidance

Having collected the approaches and identified themes, members of the partnership discussed and outlined the main practical considerations when developing and introducing STEAM approaches in Higher Education Institutions; also for inclusion in the Handbook.

The Handbook (Burns et al., 2021) is a 'stripped-down' publication featuring short overviews of a selection of the STEAM INC project partners' STEAM approaches, with more detailed information on specific approaches (and forthcoming methods under Objective/Phase 2) to be published on the project website (https://www.steaminnovation.org/resources). Importantly, the Handbook is written in plain English, avoiding (or explaining) jargon, and designed for ease of access to those in, or working with, HE institutions wishing to develop a STEAM curriculum, HE policy or wider engagement activities.

Sections "Creating New Methodologies" and "Creating Evaluation Frameworks" outline our method generation (the meta-method) to provide a clear overview of the entire project's aims and outputs. The full process, outputs and insights gained from work under the second and third objectives of the project will be reported in full in subsequent published outputs.

Creating New Methodologies

The second objective of the project involves developing new STEAM methods for implementation across the diverse HE contexts and considers their implications for HE policies. The focus is on developing a comprehensive methodological framework to support the integration of STEAM thinking in curriculum design through, for example, speculative design, art thinking, process-based research and participatory practice. The project partners' combined expertise in the field of inter- and trans-disciplinary education is well positioned to support investigations into developing the methods and processes to implement STEAM pedagogical approaches.

Through a process of deconstruction and the 'hacking' of existing methods, partners have generated a set of new STEAM methods, which have been tested in their individual contexts (universities and galleries/festivals). Once reviewed and evaluated, these methods will be compiled into an online educational resource, with consideration given to a range of potential users and possible applications. The intention is that methods created through the project will inspire and be adopted and adapted by diverse stakeholders across education, engagement and policy. The resulting methodologies and techniques will allow for creative appropriation and exploration of different points of view and, with the associated guidance, facilitate deeper enquiry and purposeful application.

Creating Evaluation Frameworks

Alongside the development of new methodologies is the creation of evaluation tools to assess the effectiveness of interdisciplinary cooperation across STEAM disciplines. These will facilitate eliciting the value of unconventional transdisciplinary approaches and methods arising from STEAM endeavours, to assess their efficacy and advance their potential expansion within curriculum design, engagement and policy. The project will use a STEAM process building upon the 'design science research process model' (Vaishnavi et al., 2019) to help identify problems, aid concept development, design and implement the evaluation frameworks within the project as well as making the methods available for wider use.

The process will address the following specific aspects:

- Evaluation of the new methods generated through the project and development of evaluation tools for wider dissemination and implementation.
- The development of a self-assessment tool which will allow students to better understand and position their STEAM competencies and to examine the benefits of participation in STEAM initiatives.
- A meta-level evaluation of the project as a whole to assess the partnership, the modes of collaboration and the resulting outcomes – utilising the STEAM definitions and competences generated within the project.

Collectively, the three objectives – the STEAM Handbook, New Methods and Evaluation Framework – aim to provide a comprehensive critical assessment of the current status and practice of STEAM within Higher Education as well as providing a practical tool kit which will enable and engender expansion of the field.

DEFINING STEAM

STEAM Origin and Rationales

STEAM arising from STEM has had multiple influences and contexts, including educational, political and economic agendas. One dominant argument has been that STEAM leads to innovation that in turn strengthens the economy (e.g., Catterall, 2017; De Fay, 2005; Girão et al., 2018). Another key strand has been that STEAM approaches and methods make students more creative and empathetic (e.g., Catterall, 2017; Guyotte et al., 2015). A third reason mentioned (especially for the US context) is to make STEM subjects more attractive and reverse the fall in Sciences and Engineering students (e.g., Billiar et al., 2014; Catterall, 2017; Drozd et al., 2017; Segarra et al., 2018). Furthermore, the emergence of the term STEAM in the USA in the 1990s initially seems to have been driven by funding being channelled towards STEM subjects and drastic cuts for the Arts; the relevance of Arts-based enquiry and methods for STEM-learning and research thus needed to be showcased (Catterall, 2017). It is, however, also important to note that STEAM initially developed outside formal curricula (Burnard et al., 2021), with MakerSpaces and similar endeavours. Several authors have commented on how using STEAM for economic or political gain, however, is problematic. This may be through 'mandating STEAM' but not actually training teachers and adequately resourcing schools, colleges and universities; or through exploiting the bandwagon and producing kits and resources under the label of STEAM that fall short of its key characteristics (Catterall, 2017).

It is noteworthy that not all relevant projects and programmes actually use the term 'STEAM' and many relevant approaches and methods may have no label or a different acronym. For example, since the 1960s, Frank Malina and son Roger F. Malina have worked on connecting Sciences and Engineering with the Arts, Design and the Humanities. This is illustrated in 'Leonardo' – the not-for-profit International Society of Arts, Science and Technology (ISAST) – and its publications as well as its sister organisation, L' Observatoire Leonardo des Arts et des Techno-Sciences, based in Paris. More recently, a series of White Papers were produced by authors belonging to the international Science, Engineering, Arts and Design Network to help convert ideas and a plurality of practices into concerted action (Malina et al., 2015). While led by American authors the scope of reach and contributions has been international (Thill et al., 2016). Furthermore, aligned with STEAM's focus on innovation and economic impact (not necessarily education), the European Commission launched the STARTS (or S+T+ARTS) initiative to foster innovation at the nexus of Science, Technology and the Arts in 2015. Similarly, its predecessor/related programmes – ICT&ART; FET-ART (e.g., supporting the FEAT project[2]); ICT&ART Connect – have also focused on the inclusion of artists in innovation projects and non-artistic domains, such as Future and Emerging Technologies (FET) and Information and Communications Technologies (ICT). Their main aim has been to foster interdisciplinary encounters and create 'added value' and unexpected interesting results from such collaborations (Van Gansbeke and Groenewould, 2020, p5).

General STEAM Characteristics

The previous section helped explain the multiple interpretations of STEAM across countries and different contexts. In their work, Colucci-Gray et al. (2019) described STEAM as a "portmanteau term" (p1) which "draws together twisting points of definition, forming collections, configurations, and multiplicities of logic and practice" (p4). With STEAM gaining popularity, the variety of interpretations, programmes and projects is likely to grow further. Maybe this plurality is unavoidable, reflecting creativity and STEAM's driving forces. However, intentions, quality and the underlying paradigm(s) matter because they are likely to lead to different kinds of processes and outcomes. Therefore, defining this ground for collaboration is important in ensuring that participating in STEAM activities, be it in ways to enable and strengthen opportunities or supporting existing approaches and ventures, benefits individuals (e.g., to deepen and extend their knowledge, skills and competencies) and wider society.

Table 3 presents generic qualities of STEAM as highlighted in the literature, which include curiosity, creativity, critical thinking, cultural sensitivity, communication and collaboration. These show strong overlap with the '4 (and sometimes 5) Cs of 21st century learning' (Partnership for 21st Century Skills, 2007), namely Critical thinking, Collaboration, Creativity, Communication, and some add Confidence. Of these critical thinking and creativity seem to have attracted particular attention in the educational context (e.g., Bertrand and Namukasa, 2020; Chappell et al., 2019; Timotheou and Ioannou, 2021). STEAM INC discussions raised the question of 'How do we define critical thinking?' Is there a difference in its definition(s) between the Arts and STEM subjects? Artistic enquiries tend to start with considering the people, the context and the problem definition. In STEM those are less often questioned and explicitly examined; 'problem' definition is seen as given or 'apparent'. Also, does STEAM creativity in HE mean something different from STEAM in primary education, for example?

For example, the EU CREATIONS project, probing into creative pedagogical features within the primary and secondary education sector, identified eight characteristics: Balance and Navigation; Dialogue; Empowerment and Agency; Ethics and Trusteeship; Immersion and Play; Individual, Collaborative and Communal Activities for Change; Interdisciplinarity; Possibilities; and Risk (Chappell et al., 2019). These align closely with STEAM, with the exception that STEAM advocates inter-/transdisciplinarity and collaboration in all instances whereas creativity in STEM education could operate on an individual and mono-disciplinary basis as reflected in the CREATION project's definition of creativity in Science education (Chappell et al., 2019, pp 297-298):

[2] https://cordis.europa.eu/project/id/686527

Table 3. Overview of qualities associated with STEAM working and thinking

Qualities / Characteristics	Sources
Balance and Navigation	Chappell et al. (2019)
Collaboration, Cooperation, Reciprocity	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017); Guyotte et al. (2014); Pollock et al. (2017); Segarra et al. (2018)
Communication, Dialogue	Bequette and Bequette (2014); Chappell et al. (2019); Guyotte et al. (2014)
Connecting (people, knowledge, environment, processes), Contextualisation, Bigger Picture	Bequette and Bequette (2014); Burnard et al. (2021); Chappell et al. (2019); Clark and Button (2011); Drozd et al. (2017); Guyotte et al. (2014)
Creativity; Creative Thinking; Synthetic Thinking	Bequette and Bequette (2014); Chappell et al. (2019); Conradty and Bogner (2018); Guyotte et al. (2014)
Critical Thinking/Reasoning; Realising of Strengths and Weaknesses	Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014)
Cultural Sensitivity	de la Garza (2019); Segarra et al. (2018)
Curiosity	Bequette and Bequette (2014); Bertrand and Namukasa (2020)
Empowerment and Agency; Make/Do	Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014)
Empathy	Guyotte et al. (2014)
Ethics; Trust	Chappell et al. (2019); Guyotte et al. (2014)
Experimentation and Failure; Iterations	Bequette and Bequette (2014); Bertrand and Namukasa (2020)
Holistic	Drozd et al. (2017); Guyotte et al. (2014)
Inclusivity	Bequette and Bequette (2014); Pollock et al. (2017); Segarra et al. (2018)
Imagination	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Chappell et al. (2019)
Immersion and Play	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017)
Innovation, Advancing knowledge/methods	Bertrand and Namukasa (2020); Kim et al. (2018)
Interdisciplinary; Transdisciplinary	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017); Guyotte et al. (2014); Pollock et al. (2017)
Meaning-making	Guyotte et al. (2014); Segarra et al. (2018)
Problem-based (problem-finding, -framing, -solving); Authentic	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Clark and Button (2011); Drozd et al. (2017); Guyotte et al. (2014); Kim et al. (2018); Segarra et al. (2018)
Process-orientated	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014)
Project-based; Partnership	Drozd et al. (2017); Guyotte et al. (2014)
Reflection	Bertrand and Namukasa (2020); Guyotte et al. (2014); Segarra et al. (2018)
Risk-taking	Bequette and Bequette (2014); Chappell et al. (2019)
Shared language; Common language	Guyotte et al. (2014); Van Gansbeke and Groenewould (2020)
Tolerate ambiguity; Lack of specificity	Bequette and Bequette (2014)

> "Purposive and imaginative activity generating outcomes that are original and valuable in relation to the learner. This occurs through critical reasoning using the available evidence to generate ideas, explanations and strategies as an individual or community, whilst acknowledging the role of risk and emotions in interdisciplinary contexts."

Creative pedagogies have shown to enhance pupils'/students' engagement and ingenuity (Chappell et al. 2019: 297). Conradty and Bogner (2018) in their paper unpacked the different meanings and implications of 'creativity', including that it opens the mind and leads to meaningful processes and ideas; allows sensitivity to problems and recognises gaps in knowledge; helps solve problems; facilitates fluid/associative thinking and the ability to change perspectives. Furthermore, they draw attention to two elements of creativity: Flow (explained as intuitive and a state of consciousness: being mentally immersed and feeling enjoyment and energised) and Act (explained as a cognitive process that can be taught/learnt and centres on deliberation).

A valid point of inquiry relates to whether STEAM qualities, and especially creativity, are (or should be) present in STEM. Why is there the perception that STEM subjects are non-creative (Chappell et al., 2019)? While a relevant and interesting question we have not focused on this element within the STEAM INC project. However, the presence of creative design processes across STEM and Arts disciplines were raised as an important case in point (and counter-argument to the above) which is also a point made by Bequette and Bequette (2014) and Guyotte et al. (2014). The following section focuses on the specific context and characteristics of STEAM in HE.

HE-specific STEAM Context and Characteristics

Most attention in the current STEAM-related literature seems to be about STEAM curricular and extra-curricular practices and outcomes, as a specific aspect of creative and inter-/transdisciplinary pedagogies, methods and programmes. Fundamental aspects or the bigger picture (e.g., HE policies; public engagement) seem less covered. The STEAM INC partnership mix (**Table 1**) purposefully reflects a wide range of HE-relevant STEAM opportunities and diversity of STEAM initiatives championed by or including universities and other Higher Education bodies. Agreeing a working definition for STEAM in HE from STEAM INC participants' and partner institutions' perspectives provided a rich collection of viewpoints with ensuing critical debates as to what distinguishes STEAM from other creative or inter-/transdisciplinary approaches and which could be agreed to be the essential ingredients or characteristics.

Through the methods described in section "Eliciting Points of Intersection across European HE STEAM Approaches" we identified constituent elements or 'building blocks' seen as important for practical and meaningful applications and inspiration. STEAM approaches need the simultaneous use of a range of key ingredients and the structures, funding, skills etc. to provide a strong and lasting impact. Furthermore, the integration of STEAM qualities, capacities, and mindset is not only relevant between different people but also for each participant; i.e. being radically open to and actively engaged in learning and changing as part of STEAM ventures. Thus, STEAM 'connecting' and connectedness is more than forming relationships between disciplines, extending to all kinds of linkages between people/learners, environment(s) and philosophies to generate exciting new perspectives, methods and approaches of thinking and working. Relational acts (i.e. relating to and connecting) thus play a core role (Chappell et al., 2019; Berthoin Antal and Debucquet, 2019; Burnard et al., 2021).

In developing a working definition for STEAM in HE our emphasis was less on a finite definition but one that is sufficiently flexible and appealing to the wide range of involved disciplines and contexts. Furthermore, we looked for a definition that was distinctly 'STEAM' – as opposed to generally inter- or transdisciplinary. Hence, a central question and reminder for shaping the definition was to reflect: What characteristics made something STEAM? This discussion highlighted the importance of process (rather than outputs), and the specific characteristics relating to skills, competencies and mindset. Furthermore, what is the motivation for engaging with STEAM?

In the educational sector, there is usually a need for 'assessments' to measure the extent of learning outcomes achieved by students. In relation to HE engagement and policies there may also be the need to evaluate and demonstrate 'impact'. However, testing and assessing STEAM qualities such as critical thinking, creativity, holistic working as well as defining and measuring impacts of STEAM policies and events can be tricky. With regard to teaching and learning, different 'cultures' of assessments exist. For example, exam-based assessments are common for Mathematics and Natural Sciences whereas the Arts use more artefact, process and project-based assessments. STEAM INC participants regarded the former as tricky and the latter as more suitable for STEAM curricula. There will thus be scope to learn from Arts subjects how to assess fairly and meaningfully.

Furthermore, STEAM may require exploring different ways and new contexts for learning and conducting assessments (e.g., societal placements, community projects or industry/business collaborations). Immersion into the subject area and sense-making in STEAM projects are likely to go beyond cognitive and critical thinking abilities requiring the range of senses and emotional engagement by participants and learning through doing/making (Guyotte et al., 2014). Currently, HE STEAM often operates through extra-curricular knowledge-exchange (KE) and outreach activities, where outcomes and success may be measured in terms of 'new products' created or number of people involved (e.g., Birmingham City University's 'STEAMhouse'[3]). Since universities increasingly also have commercial wings, the question arises to what extent STEAM will sit in mainstream education (modules and courses) and/or be extra-curricular, research-focused or commercial?

It is clear, however, that whichever specific or multiple ways STEAM is being embedded in HE, it requires training the trainers to design and implement effective STEAM policies, projects, modules and courses. While some guides, White Papers, methods and policy reviews are available to 'teachers' (although largely US-based; e.g., Allina, 2018; Colucci-Gray et al., 2017; Drozd et al., 2017; Huser et al., 2020), there is so far little discussion and specific support available for academics at an institutional level or during their training. This needs attention, resources and some (fundamental) changes in organisational structures and administrative processes so that STEAM thinking and working are not just aspirations or isolated cases.

Ambiguities and Tensions

Ambiguities about STEAM start with its name: is it a collective and convenient abbreviation or a definitive list of disciplines/subject areas? Specifically, Science(s) as a stand-alone word tends to be interpreted as the 'Natural Sciences' rather than including 'Social Sciences'. Also, the Humanities, except for the Arts, are absent in the list yet STEAM examples in the literature and courses, projects and approaches by STEAM INC partners include subjects such as philosophy, history, human geography and politics. Overall, it seems that the term STEAM is used flexibly as to the composition of specific disciplines and subject areas involved but it is unclear whether to be STEAM a certain mix has to be ensured (e.g., a minimum of one Arts-related and one STEM-related discipline). Beyond bringing different disciplines and disciplinary knowledge together, STEAM INC participants also highlighted the importance of working at the boundaries or margins of the various disciplines. We discussed the need to reach beyond current academic knowledge and distinguishing STEAM from 'traditional' interdisciplinary

[3] https://steamhouse.org.uk/

working. In comparing our approaches, we found that artists can be characterised as 'catalysts', although artistic and creative elements should not be seen as only pertaining to the Arts.

In parallel, a core ambiguity is how the 'A' is interpreted and integrated (e.g., what the 'Arts' component includes and whether it is central, equal or an add-on). While Design shares characteristics with STEAM aspects such as the emphasis on ideation and problem-solving strategies that support outside-the-box thinking (e.g., design thinking), how Design relates to the Arts is debatable; is it part of the Arts or a distinct separate field alongside Art? Rather than putting disciplines and people into boxes, and debating disciplinary definitions and boundaries, some STEAM INC participants proposed to use the term 'artistic qualities' and emphasised to look beyond simplistic conceptions of Art and Design (as common amongst 'non-artists'). This seems fitting as different perspectives co-exist, and STEAM seems at least partly about eliciting different perspectives.

For example, the S+T+ARTS Collaboration Toolkit published in 2020 aims to aid collaborative projects with artists and sees the Arts/Artist component as central. It is heavily artist-focused, innovation/technology driven and aiming to maximise outcomes (Van Gansbeke and Groenewould, 2020, p. 4). It conceives creativity as central and rooted in artistic practices and describes innovation as linked to imagination (and artists as particularly good at coming up with new concepts and ideas). Similarly, STEAM INC project discussions highlighted the role of Arts as a philosophical driver in terms of engendering modes of critical inquiry which are reflective and questioning (Danvers, 2003; Wang and Huang, 2018).

Many projects and academic articles are written from a STEM perspective where the Arts are introduced to STEM subjects (e.g., Chappell et al., 2019; Drozd et al., 2017; Segarra et al., 2018). While this may reflect specific contexts and needs, it is also a significant matter of the kind of mindset, preparations, objectives and methodologies adopted. In terms of the different knowledges accessed, sought or regarded as 'suitable evidence', natural sciences, for example, generally encourage explicit knowledge whereas the Arts often draw on tacit, embodied or haptic knowledge (Gardner, 1993; Barrett and Bolt, 2010, 2019; Robinson, 2011). Therefore, whether STEAM is approached from a predominantly Arts or predominantly STEM perspective may be significant. Guyotte et al. (2014) and Burnard et al. (2021) advocate a move away from Arts servicing STEM and the need to put both on an equal footing; a point also highlighted by Mejias et al. (2021). This should facilitate learning, experimenting and critical reflections by and between all participants. Furthermore, Burnard et al. (2021, p. 113) strongly argue for post-humanist transdisciplinary pedagogies and relational matters, for example reconciling "object-focused thinking" (abstraction; generally more typical of STEM subjects) with "contextually focused thinking" (more prominent in Arts and Design thinking and especially transdisciplinary endeavours).

Based on STEAM INC participants' experience, we observed that students and staff from Arts based faculties/courses more readily engage with STEAM opportunities than students and staff from STEM subject areas. Whether this relates largely to time constraints or is reflective of the cultural, institutional and disciplinary differences or mindsets (mental attitude) would be imprudent to assert (as we have not explicitly examined this). Still, there may be a greater readiness in artistic-focused individuals to experiment and be radically open to inter- and transdisciplinary research. Several STEAM INC participants (especially those from an Arts background working with students from STEM background) commented that some 'unlearning' is required alongside (social) learning to embrace STEAM working; for example, not jumping at usual paradigms and methods but being open to approach a topic from several different perspectives. Similarly, holistically framed education systems, such as found in Finland, may facilitate engagement with STEAM activities and thinking more readily.

Written from an Arts-based perspective, Van Gansbeke and Groenewould (2020, p. 9, 11) characterise the different influences of 'Art' on 'Technology' as: (i) questioning technology; (ii) inspiring technology and mission-driven projects; (iii) humanizing technology (e.g., inspiring prototyping); and (iv) influencing science by taking science out of the lab. They also emphasise the need to find a common language. The range of different artistic influences and importance of clarifying language (and concepts) were also highlighted in STEAM INC's phase 1 and kept recurring as important aspects of inter- and transdisciplinary working. Schnugg (2019, p. 37) highlights artists' role in terms of 'contextualisation' as follows:

> "Contextualization can help to understand the questions scientific and technological work implies; it can point to both opportunities and downsides. These opportunities and downsides only become tangible when the newest research outcome is applied in real-life situations. Artists can ask these questions and invent scenarios—utopian, dystopian, and neutral ones—based on the information about scientific work and cutting-edge technologies. Thus, contextualization and implications of this work can be discussed before they become reality."

With regard to the role of A+STEM, STEAM INC partners commented that claims are made about STEAM working and thinking that are not necessarily measured or clearly evidenced. It is also unclear whether benefits of engaging with a STEAM project or module or other activity are short-lived or trigger lasting changes in 'agency', collaborations, sharing of power, and use of more holistic approaches. Some Arts-based STEAM INC participants saw STEAM as intricately bound into 'activism' and 'agency', especially with STEAM ventures linked to the complexity of current social-ecological changes and crises. However, some STEAM projects and endeavours are closely tied to business and industry and tend to be more product/output-driven; radical openness and activism would pose a challenge or risk. A relevant question that deserves further research and scrutiny is whether we overload the 'A' as part of STEM if we are expecting it to be disruptive (at least to some extent). This returns then to the argument of whether STEAM is conceived as applying A to STEM or (just as much) applying STEM to A. In any case, the 'A' should not mean 'Anything goes' but for STEAM to fully adopt the material and critical process base of the Arts that can be critiqued just as much as the data, information and processes deriving from STEM disciplines.

Stereotyping of disciplines may also be unhelpful. For example, STEAM INC participants shared experiences where in their own university-settings or in outside events/encounters the Arts were sometimes characterised as being more visual and context-based, whereas STEM subjects as being more text- and formula-based. These stereotypes are by no means unanimously supported; a point also evident in the literature (see e.g., Root-Bernstein, 2002; or Woodward, 1984). The role that is, or at least can be, played by aesthetics, imagery and other creative conceptions along with emotions and senses holds significance across the Natural and Social Sciences, Humanities, Engineering, Technology and Mathematics. For example, 'feeling' and 'knowing' could be seen as 'pairs' rather than different 'paradigms', as expressions such as 'knowing what one feels' and 'feeling what one knows' illustrate.

As apparent from some of the above discussions and context-setting, STEAM in the US and across Europe has a strong economic driver and industry/innovation link. While on the one hand enabling or supporting STEAM projects, they may also limit STEAM thinking and scope. For example, the expressed goal to make students fit for 21st century employment is closely tied to environmentally unsustainable goals of national/global economic growth and monetary profit for some rather than enabling 'blue sky' and less product/output-tied opportunities for society and the planet. Another driver for embedding STEAM in (higher) education is the social-ecological complexity of our 21st century world to enable more holistic and better development/solutions. Based on our literature search and sources consulted for this paper, no detailed investigation has been conducted on whether one of these drivers (and if so which) has dominated influencing STEAM endeavours and whether there may be a difference between 'red brick' (long established 'traditional' and research-focused) universities and those that are more vocational and employer-orientated ex-'polytechnics' (in the UK post-1992 'new' universities). All universities (in the UK at least) have become more neo-liberal and business-like, and university league tables employment-focused; both possibly fuel product-/goal-orientated STEAM approaches rather than more exploratory learning. This in turn may foreground STEAM projects with Art and Design influences focused on making/doing (e.g., Makerspaces), knowledge sharing and 'solutions', rather than 'new' knowledge, disruptive aesthetics and (design) activism (Gooding-Brown, 2000; Markussen, 2013). Although both can create positive outputs/outcomes for society, the latter is potentially revolutionary. In our project meeting discussions, we tentatively proposed that STEAM endeavours by nature should move beyond the academic/education context and relate to societal issues and/or challenges.

Most colleagues within the STEAM INC project had 'picked up' STEAM out of their own interest and through interdisciplinary degrees or transdisciplinary project experience. Does STEAM require the involvement of 'experts' or special training? Much of the current STEAM education literature focuses on how STEAM helps educate children and students; relatively less on training/supporting the teachers and what kind of level and mix of 'experts' this should involve. Chappell et al. (2019, p297), reporting on their earlier extensive CREATIONS project literature review, state that:

> "(…) when delivered by skilled teachers, supported by effective training and sustainable, embedded pedagogical transformation transcending short-term partnership (Ben-Horin, 2015), STEAM pedagogies had the potential to be generative and exciting, enabling discussion and access to abstract scientific ideas, and facilitating understanding of pupils' thinking."

These findings clearly highlight the need for a long-term STEAM budget, professional STEAM training and sharing STEAM experiences. It is unclear, however, to what degree the direct involvement and learning from (external) experts is a necessity at the tertiary level. Thus, there is no clear picture as to the need for specific inquiry and knowledge from different parts of the STEAM delivering institution, their partners or stakeholders; and then how to use and mesh these.

Finally, Guyotte et al. (2014), amongst others, highlight conceptualising Art and Engineering (and STEM more generally) as social practices. This implies that universities (staff and students) will increasingly engage with external communities near and far. However, community engagement is often sporadic and via specifically targeted events rather than embedded into curricula or common HE practice. Even exhibitions of coursework or research projects are not always open to the public or external partners. STEAM has the opportunity to increase interactions with the public and societal affairs through changes in teaching spaces, assessments and designing new programmes and collaborative projects. This in turn will help practice-based learning, critical feedback and testing of ideas, improving cross-disciplinary and 'plain' language communication skills, increasing social-ecological awareness and sensibilities in students and staff.

A Working Definition of STEAM for HE

STEAM INC's aim was to be decisive in expressing a working definition for the HE context that is inclusive but not vague in its core make-up of 'principles'. Our initial collection of what partners classed key characteristics and fundamental aspects of their STEAM work and understandings were sorted into what emerged as seven categories: Competencies – Paradigms – Motivation – Qualities & Characteristics – Process (methodologies etc.) – Mindset – Prerequisites. This then helped to structure and synthesise the initial set of definitions from the group work into one working definition, through analysing and identifying the key and most common words used (these are **bolded** in the bulleted definition below). Some terms featured under several categories (e.g., student-centred can be a paradigm but also a process). Out of these, critical thinking was the most frequently identified quality of a STEAM approach in Higher Education. However, critical thinking is not necessarily considered the core competency that in itself suffices. On the contrary, our discussions illustrated the importance of the combination of qualities and attention to the underlying paradigm(s) as key. By employing these characteristics together, STEAM creates a (mental, physical, creative) space that adds value, new perspectives and fresh thinking. Our agreed STEAM definition adopted the following format.

A Higher Education approach to STEAM (potentially) involves:

- a culture (or cultures) that puts the Arts and Sciences on an **equal** footing
- operating within a paradigm that is **process-driven**, student-centred, holistic and provides permission to fail alongside being comfortable with uncertain end-results
- being **collaborative**, diverse and delivered through safe spaces
- establishing a mindset of **radical openness**, flexibility, reflection, experimentation and **curiosity**
- generating qualities that **promote learning**, cooperation and multi-modality
- supporting practices that are transdisciplinary and emphasise **prototyping and making** whilst considering modes of assessment
- developing competencies of **critical thinking**, creativity and communication whilst investigating how these can be applied to generate solutions.

While not viewing this outcome as 'final', the partnership agreed that the working definition clearly signalled the set of baseline attributes a STEAM practitioner or process might exhibit.

GENERATING A TYPOLOGY OF STEAM APPROACHES

In light of the diversity of STEAM approaches in (higher) education contexts, devising some kind of classification may help distinguish between different modes of intellectual investigation, aid curriculum planning and support the case for (group-based) trans-/interdisciplinary working. STEAM INC collected and mapped different examples of STEAM approaches in a HE setting with the intention to identify themes that link the approaches, so that routes to embedding STEAM in HE can be more easily discerned and followed. After reviewing the STEAM INC partners' approaches as a group, it was agreed that four themes could be used to best describe the scope and nature of the information collected. These were Behaviour, Cultures, Engagement, and Spaces.

Behaviour here means the way that a person or group of people act, particularly in relation to collaboration. **Cultures** is about the collective values, beliefs and modes of operation which are advocated by STEAM practitioners. **Engagement** concerns the processes which promote open involvement and stimulate wide interest. **Space** denotes the places from which STEAM activity is delivered; this is traditionally a kind of shared studio or working space, but increasingly (and due to the COVID-19 pandemic) virtual spaces through digital technologies and facilitating software. Within and across these categories a huge breadth and variety in time scales, spatial scales, participatory scales, outputs/creations exist. The STEAM INC Handbook (Burns et al., 2021) illustrates the application of this typology and summarises the outcome of the work under Objective 1 (section "Eliciting Points of Intersection across European HE STEAM Approaches") and outlines what STEAM in HE means and comprises.

Finally, in terms of categorisation, discussions at the Amsterdam workshop led to drawing a distinction between a 'STEAM approach' and a 'STEAM method'. In general, the former can be considered the wider expression, covering strategies, programmes, fields, and philosophies, whereas the latter relates to specific techniques. Of course, examples exist and can be imagined where overlap occurs but the fundamental perspective in our view is that STEAM methods can be seen to sit within STEAM approaches.

REFLECTIONS ON IMPLEMENTATION OPPORTUNITIES AND BARRIERS

There appear to be two predominant routes to implementing STEAM approaches within HE curricula, influenced by the persisting structural and epistemic difficulties in the integration of STEAM disciplines (see e.g., Costantino, 2017; Mejias et al., 2021). Especially, the latecomer 'A' remains ineffectively integrated with STEM. This is borne out in the two perspectives, as discussed in section "Defining STEAM", of choosing between adding A to STEM or adding STEM to A. The first route (A to STEM) consists of embedding STEAM activities, methods, processes and exercises into existing STEM curricula. This necessitates cross-faculty exchange and coordination between STEM academics to introduce STEAM approaches that have predominantly been developed within the Arts. Alternatively, or additionally, this first route of introducing STEAM approaches to STEM students can be implemented through university-wide art programmes such as those undertaken at Aalto University, Finland (https://www.aalto.fi/en/uwas), or through the active promotion of extra-curricular engagement with STEAM.

The second route (STEM to A) sees the implementation of STEAM into HE curricula through the full development of STEAM-centric degree programmes. Current examples include the MA Art and Science at Central Saint Martins, University of the Arts London (https://www.arts.ac.uk/subjects/fine-art/postgraduate/ma-art-and-science-csm) and the Bachelor of Creative Intelligence and Innovation at the University of Technology Sydney (https://www.uts.edu.au/future-students/transdisciplinary-innovation/undergraduate-courses/creative-intelligence-and-innovation). This route focuses more on learning objectives that prioritise transdisciplinary thinking informed by art and design practices and encouraging a broad understanding of STEM, but not necessarily a deep knowledge of specific STEM disciplines.

Neither of these two existing routes is necessarily better. The establishment and running of STEAM courses and projects seem to rely on persistence by academics to experiment, gain support (amongst peers and the organisation's executives) and be creative in light of structural barriers, limited/no training, and limited resources (including lack of funding to retain STEAM-experienced staff and lack of support for longer-term programmes). Most university faculties and departments still have mono-disciplinary structures for running courses, funding and administration, with careers and research impact fast-tracked through specialisation rather than transdisciplinary working (e.g., Schuitema and Sintov, 2018). This then seems to have led to many relatively small scale and extra-curricular STEAM activities rather than STEAM modules, courses and cross-faculty programmes. Many universities rely on external funding to develop STEAM expertise and collaborations. This not only brings financial uncertainty but also means that existing HE structures may be slow to adjust or transform to facilitate transdisciplinary STEAM working.

There is however, not just a structural barrier but also more deeply underlying issues relating to ontology and epistemology as expressed in different disciplines having different paradigms; and this creates barriers. Does STEAM need new paradigm(s) or is it sufficient to try and make connections between existing disciplinary paradigms? Since, STEAM tends to be modelled on transdisciplinary working (as opposed to multi-or interdisciplinary), radically open processes and meaningful longer-term STEAM collaborations across and beyond the HE sector are likely to mainstream novel ways of working and perceiving, framing and studying social-ecological issues in their economic and political context. Such endeavours align closely with post-modern post-humanist transdisciplinary pedagogies. Still, with the plurality of STEAM approaches, would this create somewhat superficial STEAM identities and adapted ways of thinking but not necessarily achieve new relational ways of thinking and working? Thus, STEAM needs defining and underlying values and drivers made explicit for specific STEAM applications, advocating critical reflection on the different strands and sometimes opposing aspects, goals and approaches to STEAM.

CONCLUSIONS

The STEAM INC project reviewed personal, institutional, national and international perspectives to produce a shared understanding of what STEAM in Higher Education might encompass. Our work shows that embedding STEAM approaches and methods in HE will continue to be a worthwhile endeavour. Employers are increasingly seeking the combination of creative/design and technical/scientific capabilities (Cultural Learning Alliance, 2017) nurtured by STEAM. Likewise, societies will adopt STEAM processes to solve the bigger issues and reduce a dependence on economic oriented measures of achievement. Successful STEAM approaches do not shoehorn Arts – in its widest interpretation – into STEM as a catalyst for learning and innovation (e.g., Burnard et al., 2021).

On the contrary, they carefully consider the process and intended outcomes as well as the mindset and attitudes of participants. The following subsections offer some conclusions on STEAM HE challenges, barriers and opportunities using the different relevant parts of our STEAM HE definition at the start.

STEAM Standards and Support

"generating qualities that promote learning, cooperation and multi-modality"
"flexibility, reflection, experimentation and curiosity"

STEAM has been described as a social practice and increasing ecological awareness (e.g., Guyotte et al., 2014). It has the potential to move from a marginal pursuit or 'add-on' to facilitating a fundamental shift in the way we explore, define and frame social-ecological challenges and the way we structure and deliver education. Inspiration, guidance and reference to STEAM principles, as expressed in our working definition, can provide a useful baseline to promote holistic perspectives and avoid narrow short-term 'bandwagon' activities in the HE context.

STEAM thinking and practice has changed over time. For example, we have seen an evolution from MakerSpaces (hands-on) to more discursive, reflective and philosophical 'labs'. Artificial and virtual reality technologies have pushed explorations and practices from 2D to 3D. The use of a wider range of techniques, including 'play' have become more accepted as effective and safe ways of experimentation and embracing 'failure' as an inherent part of the experimental process and a positive driver to innovation. While many STEAM activities are still extra-curricular or only occupy a very small space within the curriculum, research and attention to STEAM has been steadily increasing, in part evident in the volume of STEAM publications and STEAM education and research programmes.

The success and impact of STEAM learning, skills and competencies may not easily be captured with existing assessment and evaluation tools. This is therefore an area that the STEAM INC project is developing to facilitate demonstrating the value of STEAM approaches and methods. Indeed, STEAM cannot be expected to happen without effort. While it does not need to be high-cost or high-tech, it does require funding, expertise and institutional support. Increasing STEAM practices will require the training of teachers/STEAM-practitioners all the way from kindergarten to tertiary education, research and professional practice. This must include a recognition of the need for artistic curiosity and endeavours as empathetic and positive life skills to enable wider, more holistic, perspectives and meaningful (and benign) endeavours. Such training and support for STEAM requires dedicated funding and expertise with long-term programmes to avoid a brain-drain.

The focus on future and emerging technologies / the digital revolution, while on the surface exciting, may become a red herring and trap (as pressure over natural resources increase, environmental impacts escalate and negatively impact on societies – especially affecting those less well-off). Interestingly, some STEAM projects have explicitly focused on inclusion and reaching out to minorities, underrepresented or disadvantaged groups (e.g., Claville et al., 2019; Pollock et al., 2017) and international students (e.g., de la Garza, 2019).

Drivers and Modes of Investigation

"a culture (or cultures) that puts the Arts and Sciences on an equal footing"
"establishing a mindset of radical openness"
"developing competencies of critical thinking, creativity and communication whilst investigating how these can be applied to generate solutions"

The diverse drivers of STEAM can cause some tensions. Putting the Arts and STEM subjects on an equal footing and not seeing either as subservient to the other has emerged as an important point in STEAM INC discussions. STEAM is a holistic venture, which challenges participants to engage cognitively, emotionally and imaginatively in diverse and new ways. The 'Flow' and 'Act' analogy (in the "General STEAM Characteristics" section) highlights the importance of connecting to our inner self, being intuitive and developing faculties from within rather than being brainwashed; being critical and creative in knowledge acquisition (rather than formal education driving out creativity and intuition). Creativity can help identify problems (open eyes) and solve problems (make a change).

Whatever mode of intellectual, experiential or emotional investigation, STEAM requires being radically open and reflective. In transdisciplinary working, attention to language is key; communicating in a way that is inclusive and accessible, open to discussion and being challenged, ready to explain and clarify. Desired outcomes and suitable processes may need negotiation and adaptation to suit specific endeavours and participants.

Curriculum Planning (and Beyond)

"operating within a paradigm that is process-driven, student-centred, holistic and provides permission to fail alongside being comfortable with uncertain end-results"
"being collaborative, diverse and delivered through safe spaces"

Student-centred learning has become the aspirational norm, and is done in many different ways. While problem-centred and collaborative approaches are not new, how to design and facilitate these effectively is the decisive factor. Students need to feel safe to share progress, explore options, without fear of 'looking stupid' or failing in front of peers and tutors. Some STEAM scholars also emphasise the need to move from being problem-centred to being process-focused that allows exploratory, aesthetic and accidental elements (e.g., Pollock et al., 2017). This relates to the issue of opening up what the actual (underlying) problems are and can facilitate breaking out of technological and policy path 'lock-ins' to explore more promising and sustainable futures. Also, STEAM can open up a wider set of styles of learning (e.g., performing or visual Arts for Mathematics and Sciences) and knowledge sharing by both tutors and students. Authentic, real world tasks can lead to deeper understandings within and beyond assignment/project tasks. The STEAM INC Handbook provides some insights into the wide range of long, short, simple, complex approaches that have already been developed and tested in the European HE context.

The Case for Transdisciplinarity

"supporting practices that are transdisciplinary and emphasise prototyping and making whilst considering modes of assessment"

Transdisciplinary working includes a range of disciplines within and outside education settings, encompassing research, policy and practice perspectives to explore issues and address challenges. In STEAM, the Arts are sometimes used as a handmaiden to STEM, but is best involved in its own right as well as in rediscovering the Arts-based qualities in other disciplines or indigenous cultural thinking and learning (e.g., holistic rather than reductionist; critical rather than narrow theories; e.g., de la Garza, 2019). We have outlined and discussed enabling factors and tensions for transdisciplinary STEAM working and these need addressing through changes in HE policies, structures, administration and individuals' mindset. Including more practice and collaborative process-based learning and assessments such as advocated in 'flipped curriculum' activities are a good starting point. However, for STEAM to truly take roots and become embedded across the HE sector, faculty and course structures may have to open up to allow more pick and mix choices and more diverse assignments that reflect STEAM qualities as described in our working definition and foster STEAM competencies and skills as outlined in **Table 3**.

Lastly, in response to 'What is STEAM and what does it mean for HE?' we do not claim full consensus and our working definition is certainly open to being contested. However, we are sure that STEAM should be challenging and pull people out of their comfort zone.

ACKNOWLEDGEMENTS

This paper has been informed by the varied formal presentations, working sessions and informal discussions and exchanges that took place writing the project proposal and then delivering the project. A big thank you to all STEAM INC participants as listed in **Table 1** and the following: Andre Nusselder, Jean O'Shea, Caroline Singh Belmar.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 14
ISSN: 2468-4368

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My Daughter a STEM-career? 'Rather not' or 'No problem'? A case study

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Citation: Ardies, J., Dierickx, E. and Van Strydonck, C. (2021). My Daughter a STEM-career? 'Rather not' or 'No problem'? A case study. *European Journal of STEM Education*, 6(1), 14. https://doi.org/10.20897/ejsteme/11355

Published: November 18, 2021

ABSTRACT

If one wants to close the gender gap in STEM, girls need to start STEM courses. The stereotypical socialization does not lead girls in the direction of science and technology. And although the influence of parents does decrease with age it is often still present in the initial choice of study. Therefore, this study explores the role of the parents on girls' choice for a career in STEM. Qualitative individual semi-structured interviews with parents of girls in the last grade of primary education were conducted. Results show that specific characteristics of the parents can possibly have a positive influence on their children's school career and choice for STEM.

Keywords: parents, stem, girls

INTRODUCTION

Several countries, including Belgium, are faced with a lack of students and skilled professionals in the STEM-field. This problem will become even more acute in the coming years, due to an increasing number of technicians, engineers, and scientists who will retire and need to be replaced. This shortage could hinder economic growth and the further development of the knowledge society (e.g., Van den Berghe and De Martelaere, 2012). One of the causes of this shortage in STEM-professionals is the gender gap in STEM (Hammond et al., 2020).

Although girls are just as talented (e.g., Blickenstaff, 2005; Ceci and Williams, 2010; Eddy and Brownell, 2016), they are remarkably less likely than boys to choose a discipline in different domains of science, technology, engineering and mathematics (STEM) (Dasgupta and Stout, 2014; Hammond et al., 2020). Girls are already less interested in a future in STEM than boys, when they are just twelve years old (Denessen et al., 2015). This untapped potential talent is a waste on a personal, social, and economic level (Van den Hurk et al., 2019).

A student who chooses her/his courses based on strengths will not only have a better chance of success but will also be a richer and better addition to the work field. Especially in times of STEM shortages, a society cannot afford to leave this much professional talent behind. To cope with current global challenges (e.g., viruses, climate change, artificial intelligence) new answers and insights are required, and most likely a different approach of these challenges. Gender equality within STEM (science, technology, engineering and mathematics) can be a solution as it can bring more diverse perspectives, talent and insight into the field.

On top of this it leads to missed opportunities for economies and an inefficient allocation of labor and talent (Hammond et al., 2020).

In the academic year 2019-2020, there were hardly any girls (5%) in vocational STEM education in Flanders (Vlaamse overheid, 2019). Girls are also underrepresented in most STEM disciplines in higher education, in 2019-2020 less than one in five students in engineering and technology was a girl (AHOVOKS, 2020).

The reasons for this dropout of girls in STEM courses and careers are multifaceted and sometimes difficult to trace. Cultural and social beliefs, policies, school systems, economic and work-related developments all, directly and indirectly, influence student behavior. Other possible causes of this so-called STEM-gap are the lower self-image of girls within STEM subjects, a learning environment that does not stimulate enough, the lack of female role models and the stereotypical image of only white men and 'geeks' who seem to fit within STEM professions (e.g., Bøe et al., 2011; Ceci and Williams, 2010; Eccles, 2007; Watt, 2006). For these reasons, girls and women often do not feel at home in a STEM-related study (Cheryan et al., 2009; Murphy, Steele and Gross, 2007; Stout et al., 2011).

The low representation of girls in STEM, and more specifically in technology, is a common and certainly not recent phenomenon (Chesky and Goldstein, 2018; Eccles and Jacobs, 1986; Rosenwald, 2006). Over the past 30 years, researchers have dedicated themselves to studying these differences in career choice (Wang, 2012). Many initiatives and measures already taken were found to be ineffective in addressing this problem. As there is no single cause for the underrepresentation of girls and women in STEM and technology directions and professions, it has become clear that there is no one-size-fits-all solution to solve this problem.

A variety of factors seems to contribute to the lack of interest from girls and women in studies and careers in STEM fields. Following Eccles' (1983) expectancy–value theory we could distinguish three major components, psychological factors, biological factors and socialization factors such as the influence of school and teachers, peers and family. These socialization factors have an influence on the development of self-beliefs, goals, interests, and values (Wang and Degol, 2013), and are therefore relevant for further investigation.

From previous studies (Wang and Degol, 2013; Eccles et al., 1990) we know parental influence has a significant impact on children's study choices. Therefore, this study will focus on parental influence on girls'decision for a STEM domain when starting secondary education, in their own words.

Parental Influence

The influence of parents does decrease with age but is often still present in the initial choice of study options in higher education. Research has shown that teenagers are also usually open to the opinion of their parents (Van den Berghe and De Martelaere, 2012). On top of this, in regions where the vast majority of students are financially dependent on their parents during their studies, parents can even prevent their son or daughter from following a specific course of study.

Jacobs et al. (2006) have also shown that the professional expectations of 15-year-olds are significantly related to their parents' expectations. A study by David et al. (2003) showed that boys 'allow' their parents less to interfere with school, while girls are more open to talk about school and choice of study with their parents. Another study (Van Langen et al., 2006) found that girls' choice of math and science was influenced by their family background, whereas the study choices of boys were not. In any case, the influence of the parents on the choice of study is greater than that of teachers and friends. Hauttekeete (2007) says three out of four young people indicated that their parents had influenced their choice of study.

As youngsters under 12 spend a lot of time at home, and their parents are still a larger influence than their peers, the home life consists of several aspects that directly or indirectly influence the interests or disinterest of girls. It is the most important setting outside of the school in shaping student motivational beliefs (Wigfield et al., 2006; Xie and Shauman, 2003). From childhood, cultural influences often unconsciously reinforce traditional role patterns. Parents influence the academic motivation, achievement, and educational and career interests of their children through the home environments they create, the values they endorse, and the experiences they provide (Spera, 2005).

Parents' education and profession

From an early age, children form an image of what a scientist or engineer should look like. If they do not recognize themselves in this, their motivation decreases (Blickenstaff, 2005). Regularly bringing female and counter-stereotypical role models into the classroom has a positive influence on girls' and boys' attitudes towards women in STEM (Galdi et al., 2014; McGuire et al., 2020; Shin et al., 2016). People need multiple and mutually reinforcing examples to see counter-stereotypes as evidence of trends (Miller et al., 2014; Richards and Hewstone, 2001). The use of female role models can also improve that important feeling of belonging in STEM (Blickenstaff, 2005). The most effective role models are those with a similar background to the participants; this similarity can encourage girls to imagine they might one day end up in those positions (Zirkel, 2002).

Sjaastad (2012) found that teachers and parents were the main source of inspiration for Norwegian university students' STEM-related educational choice. Parents who engaged in STEM themselves were models for their children making the STEM-related choices familiar to them.

A large-scale quantitative study (Ardies et al., 2015a) showed how when mothers have a technological job, their children, both male and female students, are more likely to pursue a technological career. This effect is not stronger for female than for male students. Having a parent in a STEM profession increased a child's chances of majoring and working in STEM, this effect was greater for girls (between 10-17%). Moreover, girls with mothers with a STEM profession were 7% more likely to work in the 'hard sciences' (Cheng et al., 2017), which is comparable to the results of Ardies and colleagues (2015c). Mothers who obtained a higher education degree have a significant negative effect on the technological career ambitions of students (Ardies et al., 2015c). Maternal role models and growth mindsets can help close the gender gap.

Toys and leisure

Boys and girls are often encouraged by parents to play stereotypical male and female games that are consistent with their gender (Kollmayer et al., 2018), but boys and girls also prefer different types of toys themselves (Hines, 2015). Caplan and Caplan (1994) have argued that many stereotypical male toys and activities encourage the practice and development of spatial skills, while traditional female play enhances other culturally valued attributes such as communication and collaboration.

On average, girls play less with spatial toys than boys (Jirout and Newcombe, 2015), so they have fewer opportunities to practice these skills. Even if the effect of differential exercise of spatial skills provides only a modest initial benefit for boys, the effect may increase as children enter adolescence and start to select leisure activities and hobbies that they enjoy and are skilled at performing.

Parental attitudes and gender-stereotypes

A largescale survey (n=2197) into the mastery of the attainment targets for technology in the first stage of Flemish secondary education also examined students' interest in technology, among other things (Ardies et al., 2015c). The parental attitude towards technology was also questioned. The attitude of the parents towards technology was positively related to both the performance and the interest of the students. However, the relationship between parents' attitude and interest is less pronounced for girls than for boys (Willem et al., 2019).

Already over 30 years ago Eccles and colleagues (1986; 1990) found that mothers' gender stereotypes about math ability affected their perception of their children's skills. If mothers thought gender stereotypically about girls and STEM, their rating of their daughter's ability was lower than would have been predicted by the teacher's ability rating. In particular, Eccles and Jacobs (1986) found that maternal beliefs had a greater impact on children attending additional math courses than their children's actual performance. They concluded; "these data suggest that the stereotypes of parents by sex are a major cause of gender differences in students' attitudes towards mathematics." (Eccles and Jacob, 1986).

How parents think (positively or negatively) about STEM affects their children's math skills and performance in STEM. Cheng, Koptic, and Zamorro (2017) found that this effect influences girls twice as much as boys. Science-oriented professions are still, stereotypically, seen as male (e.g., Struyf et al., 2017). This might be one of the reasons for the fact that women perceive STEM domains as a hobby, in contrast of a possible future job (Van Houte et al., 2013).

Acknowledging all of the above findings in the literature we wish to further explore the role of the parents on girls' choice for a career in STEM.

METHODOLOGY

The present study extends existing work related to parental influences on gendered STEM study choices by determining parental characteristics and their relationship to the process of the daughter's decision making for a STEM course in secondary education. We held individual interviews with parents of girls in the last grade of primary education who already subscribed for a future study course in secondary education. For the planning of the interview, the interview itself, its transcription and analysis, the guidelines described in Cohen, Manion and Morrison (2007) were followed. We chose an informal conversational interview where questions emerge from the immediate context and are asked in the natural course of things. This method increases the salience and relevance of questions (Patton, 1980).

In Flanders students are free to choose any type of course when they are transferring from primary to secondary education at age 12. Next to the general courses which all students receive in secondary education (math, sport, biology, language, etc.), schools offer different 'packages' of courses from which students have to choose one.

Participants

Participants are parents of girls from 6th grade (age = 12) who have opted for a course of study in secondary education. They were recruited after they filled in a short initial questionnaire about the choice of study of their daughter and their own professional background. We made two subgroups of girls: those who chose a STEM course (4) and girls who did not choose a STEM course (5). We strived for similarities in family situation among both groups. All parents interviewed are in a traditional heterosexual relationship. Different family compositions are included. Some girls have only brothers, only sisters, both siblings or are only children.

For this research we opted for an equal spread of girls that have chosen either a 'STEM-package' (science, technology…) or a 'non-STEM package' (e.g., classic or modern language, art, extra sport…).

Interviews and Data-analysis

The interviews were conducted at the parents' home. In most cases, both parents were present, once only the mother and once the daughter was also present at the conversation. General questions were asked at the beginning, such as the level of education and the current profession of the parents. Afterwards, open questions were asked, to deepen our understanding about family characteristics and attitudes, with the interviewer recording the answers.

The authors analyzed the data using the steps of thematic analysis to identify, analyze and report patterns in the data (Howitt and Cramer, 2008). The interviews were analyzed by adding codes to the answers on the interview. All authors independently worked through the data and labeled "units of meaning" as codes. After this we collaboratively grouped similar codes into thematic categories, which became our codebook for systemically combing through the data (Howitt and Cramer, 2008). We distinguished (1) parental characteristics like parents' educational level and profession; (2) family characteristics such as toys present in the house and leisure activities and (3) parental attitudes and gender roles in the family, including how household tasks are divided between the parents. Of course, we also measured the extent to which the girls chose a STEM-related study.

The answers of the parents in these different categories were divided into a table to determine similarities and differences between the answers. Different respondents were presented in the columns, as we put the different categories in the rows. By doing so we obtained a clear picture of the different answers per category and a short summary of the answers of the respondents could be made per category. These summaries are shown below.

RESULTS

Parent Influence

Parents' education and profession

We examined whether the educational level of the parents had an influence on whether or not girls chose a STEM course in secondary education. We first looked at the mother's level of education. Here we see that both with the girls who chose STEM and those who did not, the majority of the mothers had a degree of higher education.

Concerning the father's level of education, we found that the majority of the fathers from the girls who chose STEM did not attend higher education. In the other group we see the opposite. Here the majority of fathers have a degree in higher education.

In the interview, parents themselves often made the link with their profession. For example, a parent of a girl who chose a STEM direction replied: "Because of our profession (veterinarian and chemistry process operator) we both have an interest in STEM." A parent of a girl who did not choose a STEM direction replied: "We ourselves have an interest in technology and science. We express this by using technology in our lessons (parents are kindergarten teacher and primary school teacher). And we also make a lot of technical things with our daughters."

Nevertheless, when looking at parents' profession and the interest in STEM, we found that in our case study the parents of girls who chose STEM did not necessarily have more interest in STEM than the other parents.

Toys and leisure

We also questioned which leisure activities were offered by the parents which could possibly arouse interest in STEM. We examined what kinds of toys were offered to their daughters, whether they were technical or non-technical and how they were or will be played with. We also asked the parents about their gendered ideas of these toys and whether they think they are something for boys or girls or both. Subsequently we focused on the participation in extracurricular workshops and the influence of STEM related family trips.

In both groups the majority of the girls possessed technical toys. All parents in the group of girls that opt for a STEM-course believed that technical toys are suitable for both boys and girls. One of the parents said: “Our daughter mainly has technical toys such as construction toys. She likes building according to plan.”

All participating parents told us they take their daughters to museums or technological and scientific theme parks. Therefore, no significant influence was found.

When it comes to participating in an extracurricular STEM workshop, we see that this seems to be related to the perceived interest of girls in STEM. The majority of girls who chose for a STEM course already participated in an after-school workshop on STEM. The majority of girls who did not choose a STEM course have never participated in an after-school workshop on STEM, and if they came in contact with such a workshop it was at a birthday party of a friend.

Parental attitudes and gender stereotyped thinking

In our study, we examined whether the parents consciously deal with gender expectations and awareness in the education of their children and whether this has an influence on girls to choose a STEM direction in secondary education. Half of the parents of girls who chose STEM did not explicitly provide a gender neutral or conscious upbringing. The parents who took it into account, in all areas, replied: “Our daughter plays football, is member of a youth club and mainly wears boys’ clothes.” and “Our daughter plays with football as well as dolls. This has happened automatically. We are more inclined to be gender neutral in our upbringing, but find it difficult to convey this. When she was even younger, we bought neutral clothes for her. We ourselves were raised fairly gender-neutral. For example, the father did ballet and I myself was not a ‘skirt-wearer.’”

Almost all parents of the girls who did not choose STEM take gender neutral or conscious upbringing into account, at least in some areas. These parents specifically name boys or girls toys: “Her older brothers brought her into contact with boy toys a lot. Girl toys were offered, but she was more interested in “neutral” toys.” Or define their daughter as “girly”. “She used to be more of a ‘girl-girl’”. On the other hand, these parents noted that children must learn to make their own choices and these choices are not necessarily gender specific.

We also examined the division of roles within the families who participated in the study, because we wanted to find out if there could be a link between growing up with more traditional role patterns or with a more progressive example and whether this has an influence on the choice of girls for a STEM course in secondary education. We made a subdivision into different, common household tasks and questioned the parents as to which they usually perform.

First, we looked at the more problem-solving tasks like chores in and around the house. There seemed to be no clear distinction between the families. In half of the families of girls who choose STEM, chores are mainly done by the father: “I do this because I have the most time, because I work in shifts.” In one family this is done by both the mother and father and in one family chores are done by the whole family: “We do this together as a family, the roles are divided.” In two families of girls who did not choose a STEM course, chores are mainly done by the mother. In one family mainly by the father, in one family by both mother and father and in the other family this is done as a joint activity.

Who fixes computer problems in the household seems also to be divided, sometimes the mother takes care of this (as an ICT-teacher), sometimes the father or external help is sought. Similar results are found when it comes to repairing a bicycle. Mothers and fathers do this, or this is outsourced. Nevertheless, for the majority of girls who did not choose STEM, the bicycle is repaired by the father.

Secondly, we asked about at the more daily tasks: For the majority of girls who did not choose a STEM course, the mother cooks the meal and does the laundry. One family prefers to cook together with the family. The parent of the latter family replied, “Our daughter loves to cook.” When both mother and father prepare dinner or do the laundry, their daughters in this study are 50/50 divided over STEM and non-STEM courses.

Choosing for STEM

Finally, we look at the direct influence that parents have on their daughter’s choice process. Earlier research shows that parents influence the choice of study both directly and indirectly. Young people are open to the opinion of their parents, and girls in particular would be open to discussing school and study options with them. The influence of the parents on the choice of study is even greater than that of teachers and friends (David et al., 2003; Hauttekeette, 2007; Van den Berghe and De Martelaere, 2012).

We noted that the majority of parents whose daughters chose a STEM course said their daughter made this choice on their own. One girl did this in consultation with the parents. The latter replied: “We consulted on the basis of all the study options available. We have taken her interests into account.”

In the case of two girls who did not choose a STEM direction, the choice of study course was made by the parents. One other girl made this choice alone, and another girl did this in consultation with her parents: “She can choose something herself, but she has to start at a high level. We did make the decision together by asking her what profession she wants to do.", another girl got a recommendation from her teacher. The parents of the latter girl replied: "The teacher recommended this to her. We want her to follow a general course for the first 3 years and afterwards she can choose for herself."

CONCLUSION AND DISCUSSION

The focus of this study was to determine the parental influence on girls' decisions to choose a STEM course in secondary education. As was already known from previous research (e.g., David et al., 2003; Hauttekeette, 2007; Van den Berghe and De Martelaere, 2012) our study confirms that parents do have an influence on their children's school career. By conducting in-depth interviews, we determined specific parental characteristics of girls who chose STEM and tried to clarify how the decision process ran. All participating girls have a present mother and father figure and thus have both a female and male role model in their lives. In this study we chose to interview both parents together. For further research we suggest to explore a different approach where parents are interviewed separately and the daughter as well. This to overcome socially desirable answers.

In this case study, we first looked at the education and professional characteristics of the parents and their influence on the decision of their daughter for a course in secondary education. We did not find a relation between mothers' level of education and daughters' choice for a STEM course. However, highly educated fathers in our respondents seemed to be less inclined to opt for a STEM course for their daughters. The fathers' profession does not appear to be a major factor in the choice of study, since some of the participating fathers have a STEM profession and some do not.

Girls in our study who chose a STEM course tend to have a mother with a STEM profession, which could possibly indicate that girls are influenced by the profession of their mother in making a study choice. The participating girls see their mothers as role-models, which is in line with research from Ardies et al. (2015a) and Sjaastad (2012).

Most of the participating parents indicated that they were interested in STEM. This was mainly reflected in their profession, and in the use of home automation, technical gadgets at home, activities during holidays, literature available, etc. No direct relation was found with the girls' choices.

Children learn about gender roles and gender expectations at a very early age (e.g., Eccles et al., 1990). The stereotypical role of a woman teaches girls to focus on having and caring for children and family (Konrad et al., 2000) and according to the male stereotype, boys are expected to focus on their hands and are primarily engaged in activities that focus on problem-solving thinking (Buck et al., 2002).

Nevertheless, when inquiring parents whether they take into account a gender-neutral or -conscious upbringing, it is striking that especially the parents of girls who did not opt for a STEM course made a more conscious decision. Especially parents with girls who have one or more brothers opted for a gender-neutral approach. These girls automatically came into more contact with "boy toys" and play along with their brothers. These parents also stated they wanted children to make their own choices that are not necessarily linked to their sex. This could indicate that a gender-neutral or conscious education is therefore no guarantee that girls will develop more interest in technical and scientific professions. In this modern age, most households are still mostly done by the mother and chores are done by the father or in some cases these tasks are shared between both parents (Islam and Asadullah 2018; Blumberg, 2015). However, there is a slight tendency towards a non-traditional division of labor between the parents within the group of girls who opt for a STEM direction. This could mean that girls who grow up in a household with a less traditional chores division look at gender expectations differently and are therefore less inhibited in their choice for STEM.

Most girls in this case study who did not choose a STEM course did not make this decision alone. It was either their parents who decided or it was recommended by someone in the school environment. For one of the girls, the decision was made by the parents because, as they stated, she has autism and a familiar environment with her friends is important for her well-being. With another girl, the parents want her to follow a more general course for the first three years, after which she can choose for herself. The other parents want their daughters to start 'high', in a more academic and general course in order to offer them some challenge.

In the group that did choose a STEM-course, the girls more often made the decision more autonomous, whether in consultation with their parents or environment. They did this mainly based on interest.

Because the majority of girls who did not choose STEM have not chosen themselves, we do not know where their interests lie and whether they would have chosen a STEM direction in other circumstances. We suggest that the influence of parents seems to influence the school career and later professional career of girls. The results of our case study suggest a link between girls who choose STEM, mothers with a STEM profession, and less stereotypical gender roles in the household at home. These girls could be more likely to make independent decisions in their choice of study.

It is striking how in the group of girls who chose STEM all parents provided toys for their daughter that are (stereotypically seen as) for both boys and girls. The majority of these parents also mainly offered technical toys. The parents of these girls indicated that their daughters mainly played with science and test boxes, looking for things themselves to copy and build with construction toys according to plan. Girls in our study who did not choose a STEM-course were offered toys mainly for girls during their childhood. This is in line with previous research of Ardies (2015c) that stated that the presence of construction toys is a predictor of the interest of girls in technology. As discussed earlier, offering stereotypical male toys can encourage spatial skills development (Caplan and Caplan, 1994). This spatial learning can be a reason for the increased interest in STEM disciplines.

More than half of the girls in our study who chose a STEM course have previously followed an after-school workshop compared to a minority of girls who did not choose a STEM direction. They did this on their own initiative or out of interest in their parents' profession. This confirms the research by Anderson and Gilbride (2003) that participation in a program with a STEM focus increases girls' interest in science and technology. Boeve-De Pauw and colleagues (2020) also found that even a one-day intervention (visiting technology and science workshops) can have a positive impact on girls' interest in a STEM career. By focusing more on design and technology workshops and making them more accessible to girls by letting them develop their own design, opportunities can be created to make the hard sciences more attractive (Ardies et al., 2015b; Boeve-De Pauw et al., 2020).

First of all, it is noticeable that all parents who participated in the study come from a white, western and middle-class background, so there is nothing to conclude about the cultural influence of families on girls' interest in STEM. Because of the limited number of respondents in this qualitative study one should be conscious to extrapolate the conclusions given. Nevertheless, we can conclude that there are a number of aspects which one can focus on to motivate more girls and their parents to choose a technical or scientific direction.

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EUROPEAN JOURNAL OF STEM EDUCATION
European Journal of STEM Education,
2021, 6(1), 15
ISSN: 2468-4368

Oceans of Inspiration: A Marine Based STEAM Project

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Citation: Boyle, J. (2021). Oceans of Inspiration: A Marine Based STEAM Project. *European Journal of STEM Education*, 6(1), 15. https://doi.org/10.20897/ejsteme/11356

Published: November 18, 2021

ABSTRACT

This paper describes a set of project-based learning activities focused on a theme of the oceans and marine life. Whilst still providing a clear link to existing physics curricula, the STEAM (Science, Technology, Engineering, Art and Mathematics) design tasks embrace oceanography's interdisciplinary nature and its scope for allowing students to appreciate the complexity of the real world, affording connections to be made between science and art. By encouraging such links to be made, we exemplify how to effectively communicate to students that imagination and creativity is essential to successful scientific research and we highlight activities that can make physics more accessible, relevant, and interesting to a broader range of students. We also analyse the activities' effects upon the students' attitudes to physics and their spatial ability, manual dexterity, grit, patience and creativity.

Keywords: oceanography, biomimicry, e-textiles, STEAM, smart materials

INTRODUCTION AND BACKGROUND

In 1959, the physicist and novelist CP Snow famously argued that the two cultures of the sciences and the arts were dangerously divided and that better communication between them would be required to successfully address the world's interconnected problems (Snow, 1959). Snow's lecture discussed the way in which physics and the arts are pigeonholed as markedly disparate fields and that this is perpetuated by an education system that does not encourage individuals to embrace them both. Most people are aware the polymath Leonardo da Vinci provided significant contributions within physics and art, but historically there have been more individuals bridging the two fields than some may initially think. Whilst studying the polarisation of light, the Scottish physicist Sir David Brewster invented the kaleidoscope. Similarly, whilst trying to copy his calculations and notes, the English astronomer Sir John Herschel invented the cyanotype process. His strikingly beautiful cyan-blue prints became incredibly influential in the art of photography. Indeed, Einstein was known to have said 'The greatest scientists are artists as well' (Calaprice, 2000). Now, with the advent of digital technologies such as 3D printers and pens as well as smart materials, the borders between physics and art are arguably becoming increasingly blurred. For instance, the appropriate selection of materials for use with a 3D printer requires an understanding of pressure, tensile strength and elastic moduli. To comprehend how metamaterials function relies upon a grasp of electromagnetic waves and refractive indices. To follow how magnetorheological materials and piezoelectric materials work needs an understanding of the physics of magnetic and electric fields.

One of the present-day physicists making art is Dr Robert J. Lang who used to work for NASA and is also one of the foremost origami artists. He has highlighted how the mathematics of origami has led to safer airbags and Brobdingnagian space telescopes. In reverse, examples of contemporary artists using physics in their work include Fabian Oefner who places paint on rotating platforms to create spectacular visualisations of the relationship between centripetal acceleration and tangential velocity. The fashion designer Iris van Herpen's haute-couture collections have become renowned for combining the most up to date science and technology with artisanal craftmanship, to the extent that her work is no longer simply found in ladies' wardrobes but is now exhibited in numerous international art museums. Such pieces are often heavily steeped in physics, including transparent organza sewn to display moiré fringes and garments composed of various shapes found in cymatics. She used magnetic fields to manipulate material made from resin impregnated with iron filings and she attributed the ideas behind her collection titled Magnetic Motion to her visits to CERN (van Stel, 2019).

Various new research establishments, such as the MIT Media Lab, have formed in recent years to reflect the fact that many projects increasingly cut across disciplines and require a broader range of skill sets to develop solutions. Formal collaborations between artists and laboratories like CERN and Fermilab have further melded physics with art (Loek, 2019). Soft-matter physicist Tom McLeish has noted the similarities between scientists and artists and challenged the commonly held belief that scientists use less imagination and creativity (McLeish, 2019). This argument is supported by Root Bernstein's finding that

> "Nobel laureates were significantly more likely to engage in arts and crafts avocations than Royal Society and National Academy of Sciences members, who were in turn significantly more likely than Sigma Xi members and the US public" (Root-Bernstein, 2008).

This suggests that not only does science require a form of creativity, but that there is a connection between scientific and non-scientific creativity (Root-Bernstein et al., 2019; Root-Bernstein and Root-Bernstein, 2013; Root-Bernstein, 2015). According to the World Economic Forum (2016), creativity and cognitive flexibility are becoming increasingly important and felt to by employers to be among the most sought-after skills. A greater emphasis has also recently been placed upon a student's ability to adapt and to be resilient (Sant, 2013) and interdisciplinary skills are being viewed as vital for innovation (Paletz, et al., 2011). Projects showcasing the intersection of science and art are being touted as addressing such concerns and as promoting teamwork and aiding problem-solving and communication skills. As Shlain (1991) said:

> "Integrating art and physics will kindle a more synthesized awareness which begins in wonder and ends with wisdom".

It has been increasingly acknowledged within recent decades that science as well as art possesses an aesthetic element. However, it is worth noting that the movement towards including the arts within STEM education has rarely focused on secondary physics, though the benefits of such integration within physics at university level (van der Veen, 2007) has been explored. Indeed, a report on STEAM education from the BERA Research Commissions (Colucci-Gray et al., 2017) summarised some examples of school science projects that successfully integrate the arts, but none of them were physics based. Instead, they tended to be predominantly based in younger primary school years and focused on mathematics and biology, such as puppets being used to encourage discussions (Simon et al., 2008), dance being used as a mathematical teaching tool (Helsa and Hartono, 2011) or poetry being used to communicate neuroscience (Brown, 2015). In Ireland, McGlynn et al. (2019) have outlined a marine science and art project involving papier-mâché activities based around the theme of hydrothermal vents, but once more this was aimed at primary children and showcased how links can be made between pupils' understanding from biology. Again, it did not encompass physics.

Much attention has been paid to the relatively low number of females entering post-secondary courses in physical science and engineering (Mack and Walsh 2013). Logically, this has been associated with the low number of girls taking physics at A level (Silim and Crosse, 2014). Donnelly (2014) explored gender differences amongst undergraduate physics students at the Universities of Edinburgh, Hull and Manchester and found 'no overarching differences in the approach or reasoning of male and female students' nor differences in their reasons for choosing physics. Donnelly concluded that:

> "This suggests that in order to improve the gender equality of both secondary school and undergraduate populations, the gender issue needs to be targeted earlier in students' primary and secondary education, a point at which students are often influenced".

Action research has shown that girls in particular are more likely to switch off from physics if they are not convincingly shown how it fits into the bigger picture of society. Tsai (2004) commented that within secondary schools, the

> 'way science is presented, the language it uses and the examples and applications it addresses imply science to be masculine.'

Similarly, Carlone (2004) reports:

> "Recent literature in science education suggests that, to transform girls' participation, learning, and identities within school science, we must think about ways to engage girls in different kinds of educational activities that promote broader meanings of science and scientist."

Carlone (2004) highlighted the need for:

> 'a response to the traditional physics curriculum to make physics more accessible, relevant, and interesting to a broader range of students.'

OCEAN THEMED PROJECT-BASED LEARNING

The oceans have historically been a popular theme for science and art collaboration, with Captain James Cook taking the painter William Hodges with him to capture Antarctic seascapes. Ocean science is ideal in its ability to demonstrate the application of physical principles within an interdisciplinary context and the oceans provide the power to inspire students to a greater awareness of environmental conservation. Education research has shown that the most successful initiatives in improving students' attitudes towards science and mathematics are the ones that show the connection to real-life experiences, are hands on and relevant to the student's own life (Mosatche et al., 2013). Perhaps testimony to this is the attention generated by hyperbolic crochet, which was discovered by Cornell mathematician Dr Daina Taimina. This has now been developed by the Institute for Figuring to create the Hyperbolic Crochet Coral Reef project; a taxonomy of reef lifeforms bursting with vibrant hues, such as kelps, anemones and coral (Wertheim and Wertheim, 2015). This celebration of non-Euclidean mathematics is now one of the biggest art/ science/ environmental projects in the world, having been viewed by more than three million people and skilfully crafted by in excess of seven thousand individuals.

Marine life has long since featured in the world of high fashion, with Coco Chanel being so enthralled with pearls that they became a key feature of her fashion house. Alexander McQueen's devotion to marine life often featured in his work, which included digitally enhanced prints featuring manta rays as well as outfits crafted out of mussels, oyster shells and razor clams. With the recent sea shell jewellery trend and Disney's remake of the Little Mermaid currently set for release, the ocean theme has certainly grabbed the public's attention.

All of this, along with their mesmerising beauty, meant the oceans were felt by those involved in this study to be an ideal way to fuse the teaching of art with physics. This paper's study focuses on exemplifying how this extracurricular theme can form the basis for STEAM activities aimed at eleven to twelve-year olds. It was felt that the activities and subject matter may perhaps particularly appeal to girls and therefore perhaps attract a more diverse demographic than more traditional STEM clubs. This age group was selected as it has been shown that a decline in attitude towards science amongst girls generally begins in the final year of primary and early secondary (Murphy and Whitelegg, 2006).

RATIONALE OF CURRENT STUDY AND RESEARCH QUESTIONS

Spatial ability is aptly defined as 'the ability to generate, retain, retrieve, and transform well-structured visual images' (Lohman 1996, p. 112). Regrettably, this important dimension of nonverbal ideation has often been largely ignored within the traditional school physics laboratory, particularly as it has been shown to be critical in terms of determining both continuance and success within the subject.

Shea, Lubinski, and Benbow (2001) tracked the progress of 563 individuals identified at age 13 as being within the top 0.5% of the population in general intelligence. At the point at which they were identified as being academically talented, their spatial skills were assessed. Those who subsequently earned STEM degrees and were still following STEM careers 20 years later were shown to have typically displayed higher levels of spatial ability as young adolescents. Similarly, Webb, Lubinski, and Benbow (2007) found that amongst 1,060 adolescents identified as being within the top 3% of the population in academic ability at age 13, those who possessed higher levels of spatial ability proceeded to follow STEM careers. Heyer's PhD thesis (2012) established an empirical relationship between the spatial thinking skills of university students studying non-science subjects and their conceptual understanding of astronomy.

Spatial skills have been identified as key to success in the sciences, mathematics and engineering (Pallrand and Seeber, 1984; Kozhevnikov, Motes and Hegarty, 2007; Uttal, Miller and Newcombe, 2013, Mac Raighne, 2015). To problem solve in physics, students need to be able to visualise complex situations and imagine the effect a change of variable would have upon a graph. Spatial skills can act as an effective predictor for both future performance and the likelihood that an individual will follow STEM career pathways (Wai, Lubinski and Benbow, 2009; Hegarty, 2014). It has been shown that there is a stronger correlation between an individuals' future propensity for innovative thinking and their spatial skills than their scores in mathematics exams. One only has to think about chirality, the double-helix structure of DNA or planetary motion to appreciate how it is an inherent cognitive requirement for all of the sciences.

Research has documented a clear relationship between spatial ability and motor skills (Voyer and Jansen, 2017). Therefore, it is not surprising that various studies have shown a correlation between motor proficiency and scholastic performance (Baedke, 1980; Beilei et al., 2002; Haapala et al., 2014; Geertsen et al., 2016), and more specifically that of motor proficiency and mathematical achievement (Luo et al., 2007; Kim et al., 2018). Of note, fine motor skills, such as manual dexterity, have been shown to be a better predictor of mathematical performance than gross motor skills (Fernández-Méndez et al., 2020). Fine motor skills are clearly necessary to perform most manufacturing engineering duties and many tasks within a physics laboratory. Indeed, Brychta et al. (2017) showed the influence of fine motor skill level (finger dexterity) upon the ability to make accurate measurements and Ackerman (1987) found that in pilots' later learning phases, their motor skills are the best predictors of their achievement. There is existing research showing the effects of origami (Bae, 2013) and fidget spinners (Cohen et al., 2018) on hand dexterity.

Knitting and crochet clearly require mathematical thought and can be used to convey complicated topological concepts (Henderson and Taimina, 2001; Kucukoglu, J. G and Colakoglu, 2013; Osinga and Krauskopf, 2004). There is also growing attention being paid to the use of knitting to teach basic maths skills to young children (Gresalfi and Chapman, 2017). Mathematical thought is inherently essential to the study of physics. The process of learning to crochet and knit does not lead to instant gratification. One would assume their fiddly and complicated nature means that to develop these skills an individual would need to possess grit and patience. Similarly, success in physics generally requires hard work and discipline, since students need to acquire a vast body of unequivocal knowledge and to memorise many formulae, protocols and rules. One could say that to continue with physics an individual requires grit and patience. Grit and patience have been previously shown to have a positive impact upon students' academic achievement (Duckworth et al., 2007; Strayhorn, 2014; Kallick and Costa, 2008; Costa, 2008; Costa, 2009) and their retention within the subject. Interpreting crochet patterns requires a degree of spatial ability and the use of hooks demands manual dexterity. To design and personalise woollen creations also presumably requires a certain degree of creativity. School level physics provides the pathway towards careers that require a high level of spatial ability, manual dexterity and creativity. Stathis and Eva (2018) called for

> 'more empirical evidence for the potential of the arts to foster in students a change of outlook as a result of learning science'.

This interplay between spatial skills, fine motor skills and STEM led to the following research question being proposed:

Research Question 1: Can STEAM activities focused around the making of marine life textile artforms help develop spatial ability, manual dexterity, grit, patience and creativity?

In agreement with previous studies (Guay, 1978; Voyer et al. 1995; Linn and Petersen, 1985.), Maeda and Yoon (2013) found after measuring individuals' 3-D mental rotation ability using the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R) that there was evidence of apparent male superiority. However, suggestion has been made that part of the reason males in general perform better than females in spatial ability tests may be due to a lack of confidence amongst the girls stemming from gender stereotypes (Cooke-Simpson and Voyer. 2007; Moè. 2009; Moè and Pazzaglia 2006; Ortner and Sieverding. 2008). Another factor thought to be contributing to this heterogeneity is the fact girls are more likely to be deprived of spatially rich activities in childhood (Reilly, Neumann and Andrews, 2017). Spatial toys are currently still being marketed to boys, much like computers were in the 1980s. With the strongly held belief that this gendered-marketing is a significant contributory factor to the current male dominance in the IT sector (Henn, 2014), researchers believe it is beneficial to provide girls with learning experiences that develop their confidence in performing spatial tasks.

Research shows spatial competence is not immutable and that practice can yield substantial improvement (Uttal and Cohen, 2012; Sorby, 2009a,b; Brus and Boyle, 2009; Allam, 2009; Hamlin, Veurink and Sorby (2009); Schmidt, 2015). Halpern et al. (2007) recommend teaching this to girls and advise that they should be provided with spatial skills training. Miller and Halpern (2012) looked at the effect of 12 hours of spatial training among a mixed sex sample of highly gifted STEM undergraduates. They found that although the training initially narrowed gender differences and improved examination scores in physics for a short time after the training, the effects had worn off after eight months. They concluded that the

> 'results suggest that sustained exposure to spatially enriching activities over several semesters or years may be necessary to address gender gaps in spatial skills'.

Therefore, it was felt that this study could also answer a secondary aim of establishing whether e-textiles can provide an effective means for increasing the level of participation of girls within physics. That is, we sought to answer:

Research Question 2: Can integrating textile art into a science club widen the appeal of STEM and more specifically help address the gender imbalance within physics?

METHODOLOGY

Learning Activities

The activities were designed and delivered by the author of this paper. They were trialled by seven students within the youngest year of a Scottish secondary school (aged eleven); six of whom were girls. As this research attempts to explore avenues to address the existing gender imbalance within Physics, it could be argued that it would have been more appropriate to have selected a sample group that was more balanced in terms gender, so that a comparison could have been made between attitudinal change amongst the boys and girls. However, it was felt unethical, inappropriate and unfair to choose who could attend an extracurricular club based solely upon gender and so the club was instead offered to everyone within the youngest year of this school. The very fact six of the seven students electing to attend were female does in itself confirm that the ocean-based textile activities were successful in their attempt to appeal to a higher proportion of girls than more traditional STEM clubs. In terms of validity of data, it clearly would have been better to have opted for a larger sample size. However, the practicalities of conducting the project with children and the fiddly nature of the activities, including the use of crochet hooks and needle work, led the author to deem it beneficial to limit the club to only this year group as otherwise the size of the practical group would have been less manageable. Had there been more facilitators available, then a wider sample size in this study could have been an option. For each of the studies, the control groups comprised of pupils within the same year of the school who did not take part in this STEAM club. The control groups had an equal balance of boys and girls. One may conjecture that it might have been best to compare the girls in the STEAM group to girls in the control-group. However, as the sample size of seven was already so small, it was felt best to consider the STEAM group as a collective whole, rather than then subdivide it further into boys and girls.

The first session showcasing the nexus of physics and art involved students making jellyfish cartesian divers using hex nuts, plastic pipettes, disposable gloves and drinks bottles. The second activity involved making artwork based on the layers of the ocean. The iridescent effect of the pearlescent particles made it look akin to mother of pearl, which sparked discussion on the interference of light and the work by physicists at the Cavendish lab to recreate the steps of molluscs to form nacre-inspired bioactive materials (Finnemore et al., 2012). The students then made their own ‘ocean in a bottle’ with cooking oil, water and blue food colouring (**Figure 1**).

Figure 1. Ocean in a bottle showing stratification of water columns

The simple zoetrope perfected by James Clark Maxwell has been experiencing a resurgence, having gained recent attention with the likes of Veerle Coppoolse’s 3D version depicting the lifecycle of a butterfly and Jiří Zemánek’s use of the EggBot Pro to robotically etch mathematically generated patterns onto Christmas ornaments (Zemánek, 2018). The trend extends to food art with cake zoetropes featuring in a prominent supermarket’s advertisement campaign. The basic physics principle behind these contemporary reworkings was explored with the students making thaumatropes and replicas of the classic leaping whale zoetropes (**Figure 2**).

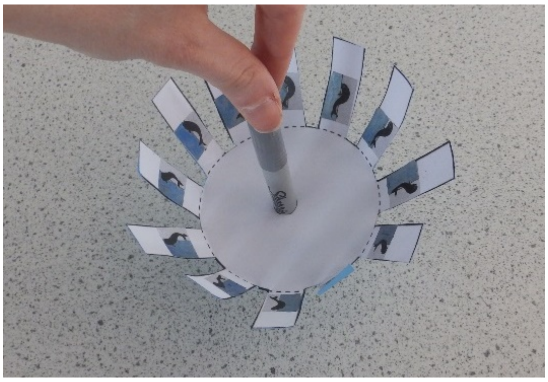

Figure 2. Ocean thaumatrope and whale zoetrope

Since delicate corals are destroyed by sea temperatures increasing, it was felt that painting coral patterns with thermochromic pigments would be a captivating visual way of demonstrating the deleterious effects on ocean ecosystems and the effects of coral bleaching (**Figure 3**). During this time, the students had access to prints from Ernst Haeckel's Art Forms in Nature. Haeckel was a German zoologist who is particularly remembered for his work on marine organisms such as cnidarians (jellyfish, anemones and corals) (Haeckel, 2000).

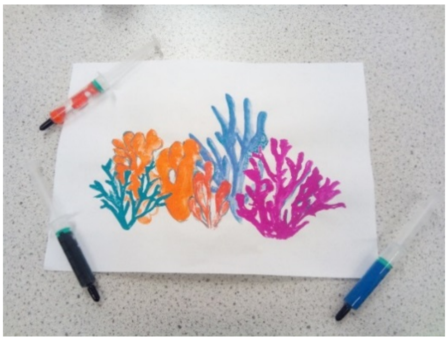

Figure 3. A painting of delicate corals made using thermochromic pigments, highlighting the damage of rising sea temperatures

The next activity took its inspiration from the work of Sachiko Kodama, a sculptor with a degree in physics and a PhD in art. She makes 3D liquid sculptures by controlling ferrofluid with magnetic fields (Kodama, 2008). The students poured ferrofluid onto a glass plate placed on top of a magnet and found the ferrofluid quickly assumed the shape of a sea urchin (**Figure 4**). Interestingly, a new space exploration tool has been modelled on a sea urchin's teeth and their spines have inspired crack resistant cement. Furthermore, the ability of a sea urchin to rapidly change the elasticity of the collagen in its skin could provide novel applications such as bio-inspired brain implants for patients with Parkinsonism, implantable biosensors and treatments for skin aging (Mo et al., 2016).

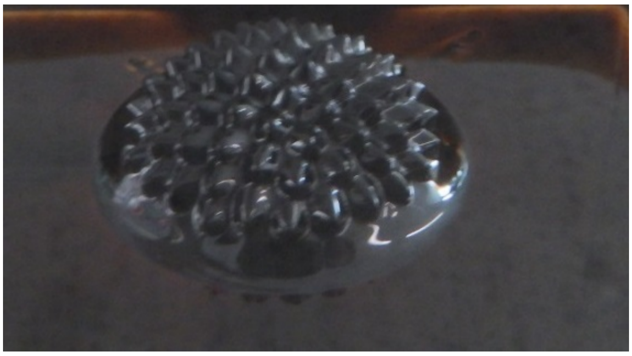

Figure 4. A ferrofluid sea urchin

Squishy circuits (Johnson and Thomas, 2011) were then introduced with the students making conductive and insulating play dough as outlined in Boyle (2019), which they then fashioned into bioluminescent octopuses, jellyfish and seahorses and sea turtles (**Figure 5**).

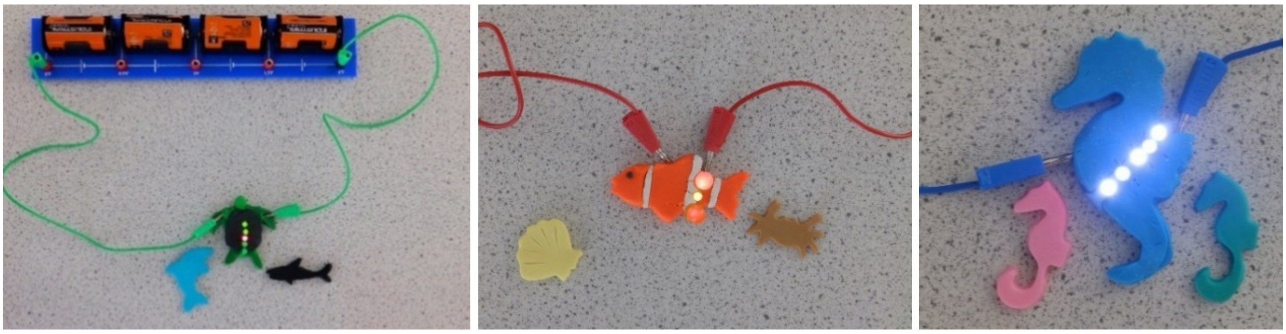

Figure 5. Squishy circuits made from conductive and non-conductive dough: a bioluminescent seahorse

The following week commenced with the students making pop-up cards from origami marine life (**Figure 6**). They then formed paper-circuits by using copper foil tape and conductive ink pens to add LEDs to their cards (**Figure 7**). As certain sea turtles have recently been discovered to exhibit bioluminescence, perhaps the turtles festooned with red and green LEDs were more scientifically accurate than some of the other creations. During the next few sessions, the students progressed on to making memory wire origami cranes and herons. They used shape-memory alloy to actuate paper (**Figure 8**) by following a set of instructions and pattern from MIT Media Lab's simple beginner's project (MIT Media Lab, n.d).

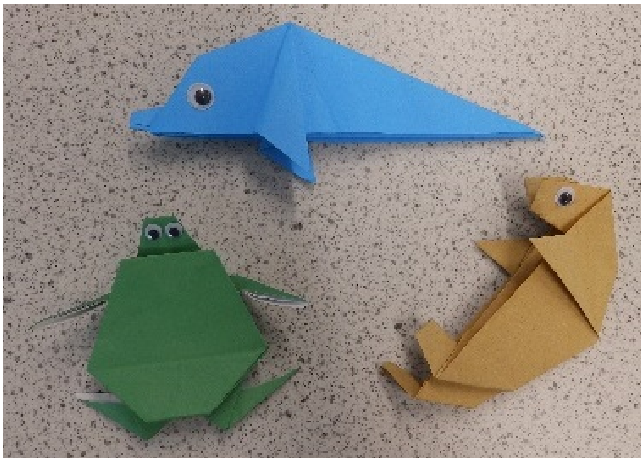

Figure 6. Origami otter, dolphin and sea turtle

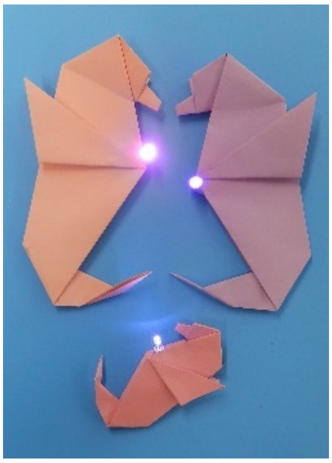

Figure 7. A paper circuit whose design was based upon bioluminescent seahorses

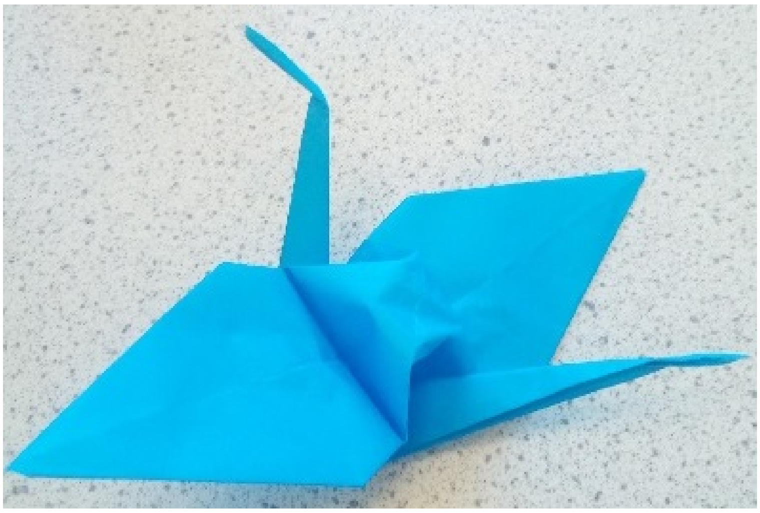

Figure 8. An origami crane with memory wire placed inside to make the wings flap

The squishy and paper circuits consolidated the students' understanding of basic circuitry and electronics, such as charge, polarity, current, voltage, resistance, short circuits and open and closed circuits. By then they were equipped to start working with e-textiles. They took their inspiration from those working in wearable technology industry, such as the likes of Kitty Yeung who has been using her physics background to harmonise science with fashion, creating garments embroidered with LEDs that blink according to the wearer's heart rate (Yeung, 2017). Using conductive thread, they each stitched a cell holder, LEDs and a push switch inside either a felt jellyfish, seahorse or sea turtle (**Figure 9**). A more complicated circuit was then attempted, with students sewing a magnetic switch and LEDs inside a felt penguin, narwhal or seal. They then stitched a magnet inside a felt fish and adorned it with sequins resembling scales. When they placed the fish on their felt bird or mammal, it activated the circuit with the LEDs, making the animal's face light up (**Figure 10**).

Figure 9. A felt circuit jellyfish and seahorse

Figure 10. Circuits involving magnets sewn into felt fish and magnetic switches sewn into felt narwhals, seals and penguins

Before introducing hyperbolic structures, the students were first taught crochet skills through making amigurumi animals. They began with either the simple jellyfish or octopus (**Figure 11**) and they were interested to know that such creations are thought to benefit premature babies as their tentacles resemble the umbilical cord and reduce the amount the infants pull at incubator monitor cords (Smith et al., 2018). They then progressed onto more complicated projects such as seahorses (**Figure 12**), sea urchins (**Figure 13**) and sea turtles (**Figure 14**). Some opted to use a pompom maker to create the anemones used by boxer crabs (**Figure 15**). Others chose to make starfish and added electroluminescent wire (Adafruit, 2012) to replicate their bioluminescence (**Figure 16**). Crocheting the electroluminescent wire itself resulted in something resembling Singapore's 'the urchins' art installation. A few at this stage chose to focus on creatures affected by climate change (**Figure 17**).

Figure 11. Crocheted jellyfish

Figure 12. Amigurumi seahorses

Figure 13. Amigurumi sea urchins

Figure 14. Amigurumi porpoise, sea turtle, lobster and clam

Figure 15. Amigurumi boxing crabs with pompom sea anemones

Figure 16. Crocheted sea urchin and bioluminescent starfish formed using electroluminescent wire

Figure 17. Amigurumi animals affected by climate change

From there, they continued on to make crocheted plankton (**Figure 18**), adding LEDs to dinoflagellates to make them appear bioluminescent (Instructables Craft, n.d.).

Figure 18. Crocheted plankton: coccolithophore, bioluminescent dinoflagellate, radiolarian and a circular diatom

To crochet their hyperbolic coral structures, the students progressively increased the number of stitches in each row (**Figure 19**). Some decided to modify their design to form a coral reef scrunchie for their hair.

Figure 19. Hyperbolic crochet coral including hyperbolic plane, pseudosphere, seed-pod and double hyperbolic plane

The next design task was based around the Venus' flower basket, a living embodiment of the fusion of science and art, with its distinctive lattice-like structure being mimicked in architectural design, such as the Gherkin building, and its silica fibres being studied to help make better optical fibres. They even contain a uniquely romantic story by housing a male and female shrimp. Young shrimps enter the sponge when they are small but as they grow, they become trapped inside, remaining with the same mate for life. They are offered as wedding presents in Japan as they symbolise eternal love. After this introduction, the students then crocheted their own Venus' flower basket (**Figure 20**) and adorned it with optical fibres connected to LEDs.

Figure 20. Crochet baskets fashioned to resemble Venus' flower baskets

The original intention was for the students to then make a snow globe based on the concept of marine snow, the continuous shower of organic detritus that delivers energy to organisms living deep down in the ocean. They were to use magic snow as the detritus and polymorph moulded into the shape of deep sea creatures. However, the organisms living in the murky depths of the aphotic zone were quickly discounted by the students as offering little visual appeal. So, they instead followed the more endearing task of making festive penguin pipe cleaner snow globes (**Figure 21**).

Figure 21. Pipe cleaner penguins inside a snow globe, surrounded by magic snow

They then fashioned autoheal self-repairing polymer into jellyfish designs resembling Blaschka's glass models (**Figure 22**). This particularly matched the bio-inspired theme since, amongst other developments, scientists have created a polymer inspired by ocean mussels and adhesive patches for wounds based on octopuses. Moreover, jellyfish have recently led to the development of water resistant self-healing artificial skin and seaweed extract has been used by bioengineers to create a hydrogel adhesive that can bind tissues together. The students were then told about research being conducted locally into digitally fabricated biodegradable structures made from chitin, a polymer that is found in crustacean shells.

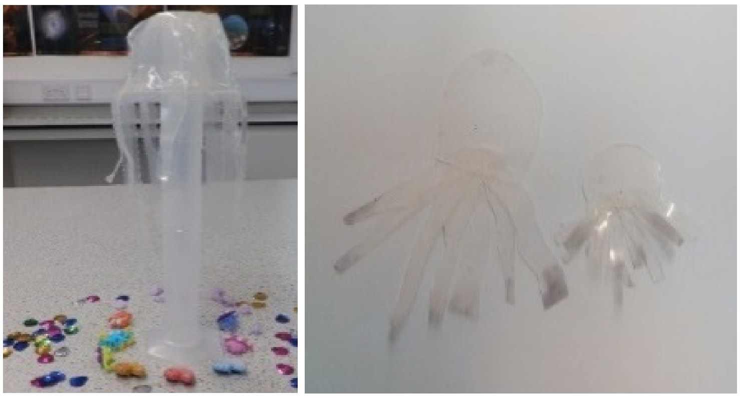

Figure 22. A jellyfish artwork constructed out of autoheal self-repairing polymer

The next activity involved the pupils making 3D ocean creatures by using ultraviolet light boxes to cure liquid resin (**Figure 23**).

Figure 23. 3D shapes made using ultraviolet light to cure liquid resin

The students then studied Anna Atkins' books of cyanotype impressions of algae (Atkins, 1843). Numerous artists and fashion designers have been resurrecting this 19th century technique with contemporary twists. In an attempt to replicate such work, the students used potassium hexacyanoferrate III solution, ammonium iron III citrate and UV light boxes to form a photochemical reaction (**Figure 24**).

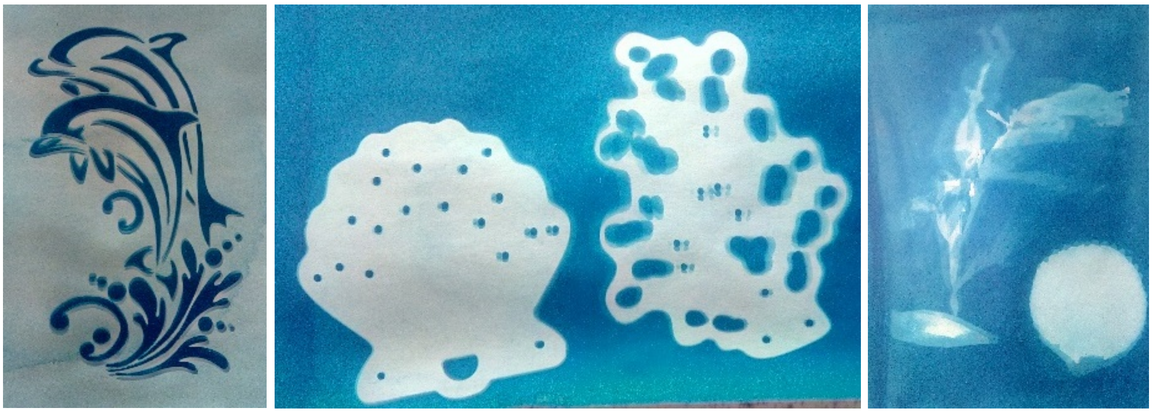

Figure 24. Cyanotype paintings of seaweed, scallop shells and dolphins

The quirky artform of diatom arrangement also dates back to Victorian times and has gained renewed interest with Klaus Kemp creating contemporary versions. There are many overlaps between algae and physics, such as the fact that researchers have discovered that algae living in low light intensity conditions can switch a quantum coherence on and off to maximise the light they collect for photosynthesis. Moreover, the psychedelic jewel like arrangements in diatom art resemble that of a kaleidoscope. So, the next design task selected for the students involved asking them to construct their own 'diatom' kaleidoscope a cardboard tube and mirrors (**Figure 25**).

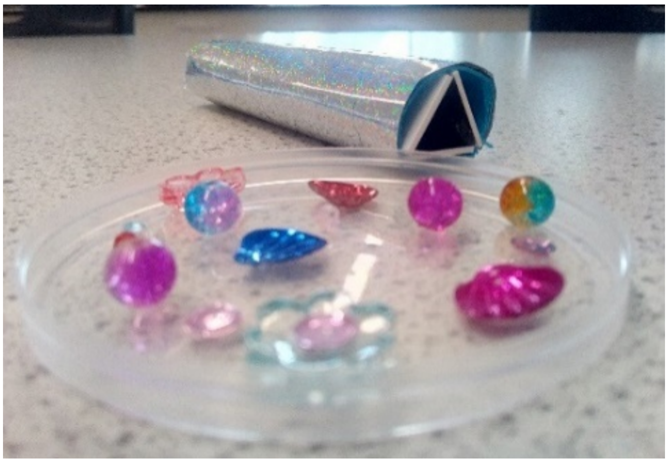

Figure 25. A 'diatom' kaleidoscope and the smart-phone kaleidoscope being used to observe an intricate pattern

The sessions and their relevance to existing curricula are summarised in **Table 1**.

Table 1. Summary of the activities' links to the UK physics curricula

Figure Number	Description	Physics curriculum links
1	Ocean in a bottle	Density; convection
2	Ocean thaumatrope and whale zoetrope	Persistence of vision
3	A painting of delicate corals made using thermochromic pigments, highlighting the damage of rising sea temperatures	Temperature and heat transfer
4	Ferrofluid sea urchins	Magnetic field patterns
5	Deep sea creature squishy circuits	Conductors and insulators; electrolytes; open and complete circuits; basic electrical circuit rules; short circuits; behaviour of LEDs
6	Origami otters, octopuses, dolphins, fish and lobsters	Spatial skills development
7	A paper circuit whose design was based upon bioluminescent sea turtles	Spatial skills development; open and complete circuits; basic electrical circuit rules; short circuits; behaviour of LEDs
8	A memory wire origami crane	Spatial skills development; open and complete circuits; basic electrical circuit rules; short circuits
9	Felt circuit jellyfish and seahorses	Open and complete circuits; basic electrical circuit rules; short circuits; behaviour of LEDs
10	Circuits involving magnets sewn into felt fish and magnetic switches sewn into felt narwhals, seals and penguins	Magnetism; open and complete circuits; basic electrical circuit rules; short circuits; behaviour of LEDs
11-13	Crocheted jellyfish, amigurumi seahorses and amigurumi sea urchins	Spatial skills development
14	Amigurumi porpoise, sea turtle, lobster and clam	Spatial skills development
15	Amigurumi boxing crabs with pompom sea anemones	Spatial skills development
16	Amigurumi animals affected by climate change	Spatial skills development
17	Amigurumi bioluminescent starfish formed using electroluminescent wire	Spatial skills development
18	Crocheted plankton: coccolithophore, bioluminescent dinoflagellate, radiolarian and a circular diatom	Spatial skills development and understanding of simple circuits
19	Hyperbolic crochet coral including hyperbolic plane, pseudosphere, seed-pod and double hyperbolic plane.	Spatial skills development and basic awareness of hyperbolic geometry
20	A woven basket fashioned to resemble the Venus' flower basket	Spatial skills development; refraction; total internal reflection and optical fibres
21	Pipe cleaner penguins inside a snow globe, surrounded by magic snow	Spatial skills development; covalent bonding in polymer
22	A jellyfish artwork constructed out of autoheal self-repairing polymer	Pressure; smart materials
23	3D shapes made using ultraviolet light to cure liquid resin	Ultraviolet light
24	Cyanotype seaweed and algae	Ultraviolet light
25	'Diatom' kaleidoscopes	Reflection

Analysis Methods

To assess the project's effects upon the students, they were asked to perform each of the following tests before they started attending the sessions and upon completion eight months later. A control group of thirty pupils (fifteen girls and fifteen boys) who did not take part in any of the activities was also tested at the starting point of the club, allowing a reference point and comparison to be made. However, a larger group was sampled (N=50) for the attitudinal questionnaire as it did not demand much time to complete and therefore did not necessitate non-STEAM club pupils deviating from their normal time tabled lessons. Again, there was an even gender divide for this control sample.

Each student's spatial ability was gauged using the paper folding test from Ekstrom, French and Harman (1976). This paper folding test required students to visualise where the holes would be situated after a piece of paper is folded and a hole is punched through it. The Purdue Pegboard Test (Tiffin and Asher, 1948) was employed to investigate dexterity.

Duckworth's 8-item grit scale was used to explore their passion and perseverance (Duckworth and Quinn, 2009) and Schnitkner's 3-factor patience scale was used to investigate their patience (Schnitkner, 2012).

Mohamed (2006) summed up scientific creativity as being:

> 'the uniqueness and appropriateness of the student's responses to questions related to science'.

The impact of the club upon students' creativity was measured using the 7-item scientific creativity test developed by Hu and Adey (2002) and marked according to their instructions.

Four attitude statements were adapted from the Student Questionnaire For PISA 2006 document (OECD, 2005), one exploring each of the domains of enjoyment, self-confidence, value and motivation. The selected statements were similar to those of Muller et al. (2013):

> *I find learning science interesting*
> *I think science is too hard*
> *I think science improves people's lives*
> *I want to become a scientist*

The responses used a 5-point Likert rating scale in the form of 1-strongly disagree to 5-strongly agree.

Inevitably any improvement in the students may in part be due to them having been eight months older between the initial testing to the time at which the project was completed and the final tests were administered. It is impossible to delineate exactly how much any improvement in a STEAM club member is due to them having aged a further eight months and naturally matured from how much it can be attributed to the effects of the club itself. The club started in August 2019 and reached its completion in March 2020. Obviously, it would have been better if the control group had also been retested at the same time, but this proved impossible with the sudden, unexpected and prolonged closure of all schools within the UK as a result of covid. Retesting all the students at the end of the extensive lockdown period would have led to even more potential variables clouding the results. So, instead the STEAM club member's data from August 2019, March 2020 and the control group's data from August 2019 could only be used.

RESULTS AND DISCUSSION

For the individuals taking part in the ocean-based STEAM activities, the attitudinal questionnaire revealed the results outlined in **Figure 26**. This suggests that the club served as a positive influence upon the students' inclination towards following STEM pathways. Presumably this was in part due to the participatory, humanistic (Hadzigeorgiou, 2005, 2016; Hadzigeorgiou and Konsolas, 2001), social and interactive nature of the activities.

Figure 27 shows the STEAM club members' scores in the paper folding spatial test, both before and after completion of the project. It can be seen that the STEAM club members started out with a higher spatial awareness than their peers (the control group) and that their spatial skills strengthened whilst taking part in the club. Therefore, similar to studies discussed earlier, this data suggests that spatial skills can be improved through carefully devised intervention. This is key as it has been previously shown they can act as a potential barrier to STEM disciplines.

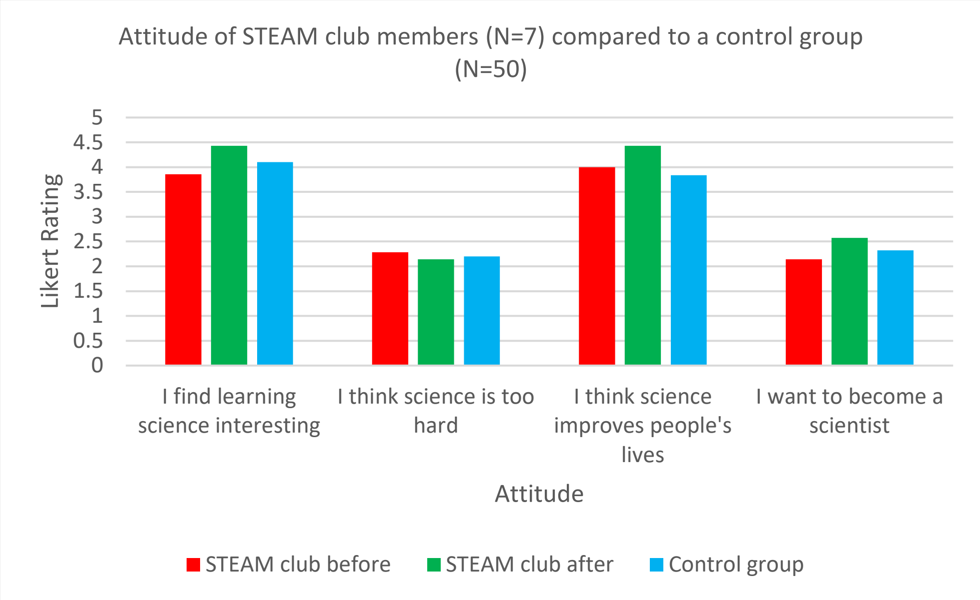

Figure 26. Students' responses to an attitudinal questionnaire before and after the ocean-based STEAM club in comparison to a control group who did not take part in the ocean-based STEAM club

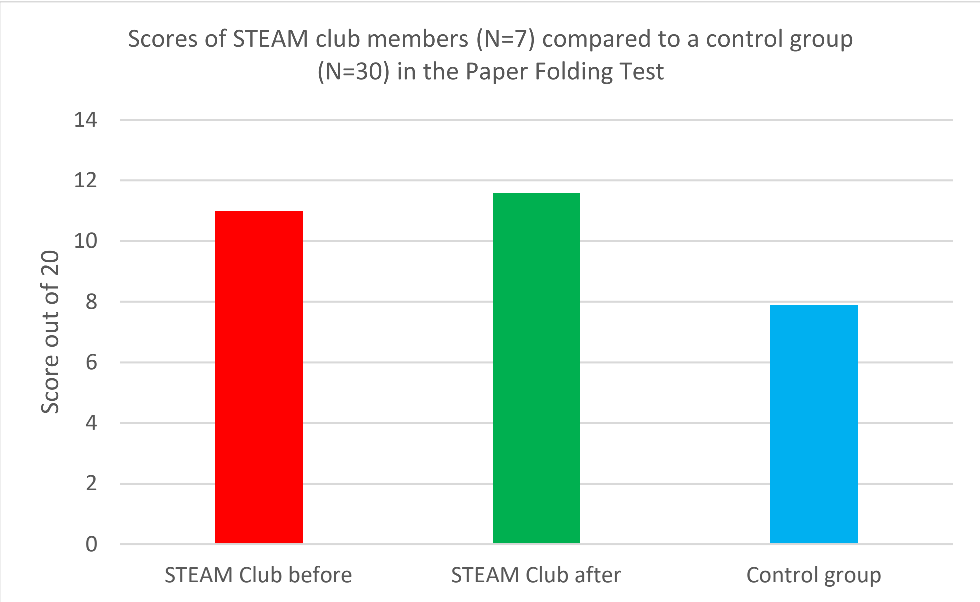

Figure 27. Ocean-based STEAM club students' paper folding test scores in comparison to their peers

The Purdue Pegboard Test involves placing as many pins as possible into slots on the board, using each hand individually over thirty second time periods. Then, over a further thirty seconds, they insert pins using both hands simultaneously. Finally, over a one minute time interval, they construct 'assemblies' comprising of a pin, a collar and two washers. The overall score for each element is the total number of pieces placed into the board. Figure 28 highlights the effect of the STEAM club activities upon the students' dexterity. It should again be noted that the club members were eight months older at the time of their second dexterity test and one may therefore initially ponder whether the gains could be attributed to them simply maturing with age, as opposed to any effect from the actual club itself. However, research from Gardner and Broman (1979) suggests that, when an eleven-year-old ages eight months, it should ordinarily have minimal impact upon this battery of tests. They found that 'assemblies' scores improve on average by less than two over this age range and that individual and bilateral hand scores show a variation of 0.1 or less between the ages of 11 and 12, with an actual decrease over this time in some elements. This finding presumably reflects typical variations between the same individual sitting a test at different times, something which could also be argued may have come in to play in our study. However, Buddenberg and Davis (2000) when exploring test-retest variability found a mean gain in one-trial administration of only 0.7 in each hand, 0.5 for both hands and 3.8 for assembly. The gains in our study compare favourably, with a gain of 1.3 for the preferred hand, 2.9 for the non-preferred hand, 2.3 for both hands and 6.0 for assembly.

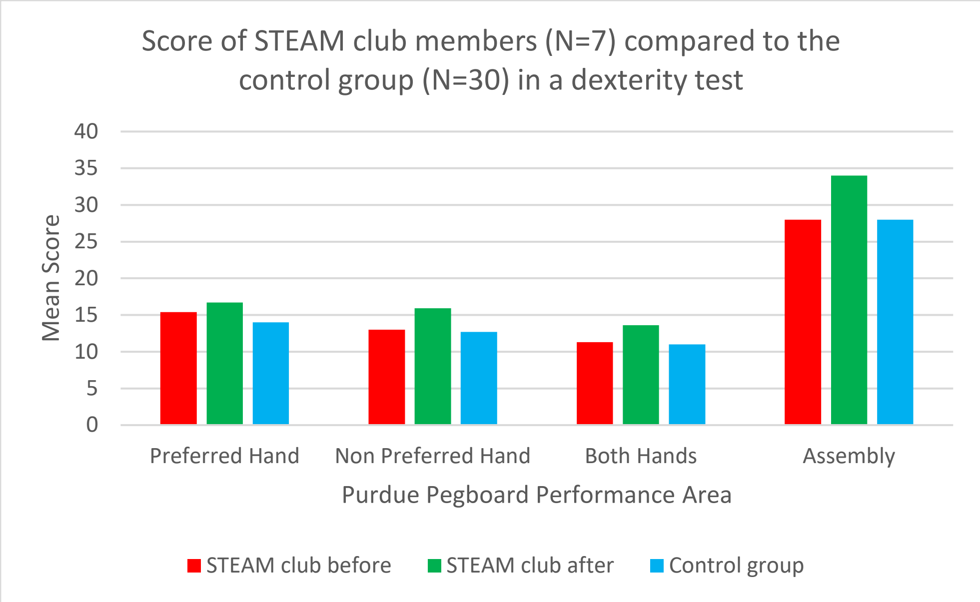

Figure 28. The effect of the ocean-based STEAM club upon students' dexterity

Figures 29 to **30** show a comparison of the STEAM club participants' grit and patience before and after completion of the project, with a control group's results displayed for comparison. On the 8 item grit scale (Duckworth and Quinn, 2009), all items were measured on a 5-point Likert scale and an overall score was assigned, with 5 being the most gritty. When using Schnitkner's 3 factor patience scale (Schnitkner, 2012), all items were measured on a 5-point Likert scale and an overall score was assigned, with 5 being the most patient. The pupils were all made fully aware that the club would require time and commitment to learn to crochet. Therefore, one may have anticipated that only those who were more gritty and patient than the norm would be inclined to join such a club in the first place. However, this does not actually appear to have been the case and this self-selecting group was found to have improved in these areas throughout the duration of the project. One may anticipate this should be the case anyway with the children having aged, but perhaps surprisingly Peña and Duckworth's (2018) longitudinal sample of students in 9th and 12th grades actually found 'absolute age has a positive effect of 0.09σ on perseverance of effort and a negative effect of -0.13σ on consistency of interest'. Therefore, the changes in the STEAM club's level of grit does seem to indicate a positive effect from the club. Bettinger and Slonim's data (2007) matches common intuition to show 'older children are more patient', but as their study involved experiments based around delayed economical gratification, it could not be determined how responses to self-report questionnaires on patience would ordinarily change over an eight month duration. Therefore, the extent of the impact of the club in this regard cannot be fully assessed.

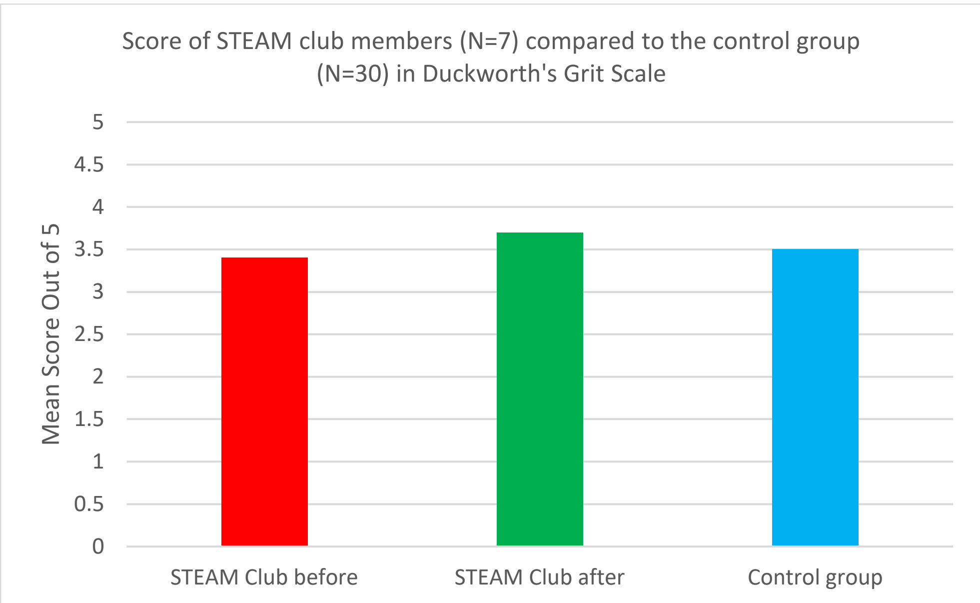

Figure 29. The effect of the ocean-based STEAM club upon students' grit

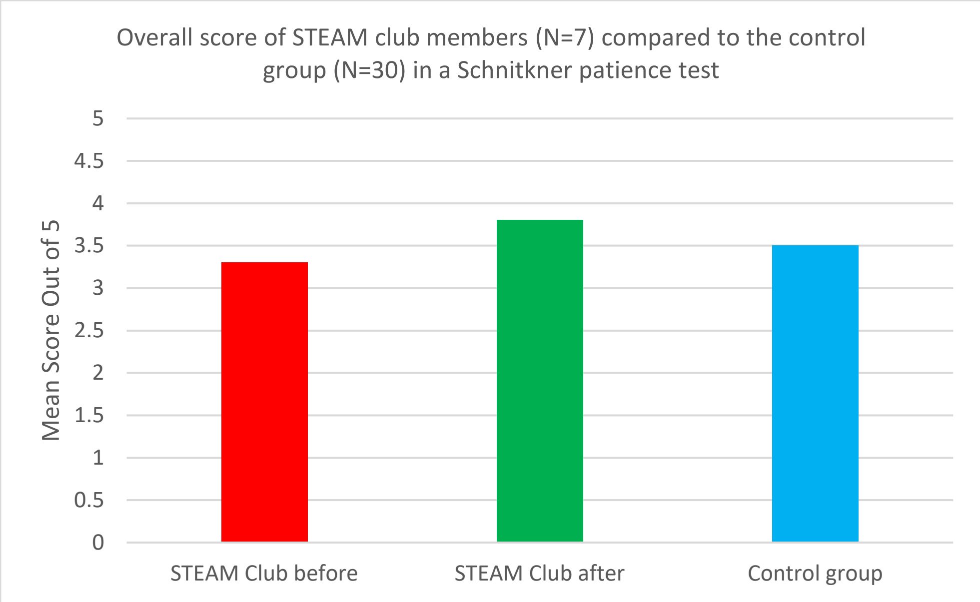

Figure 30. The effect of the ocean-based STEAM club upon students' patience

Figure 31 shows a comparison of the STEAM club participants' scientific creativity before and after completion of the project, with a control group's results displayed for comparison. It should be acknowledged that there are many different views on how best to assess creativity in general (Hocevar, 1981; Plucker and Makel, 2010; Lucas, 2016). Indeed, as noted by Hadzigeorgiou, Fokialis and Kabouropoulou (2012), any attempt to assess creativity poses inherent difficulties. They observed:

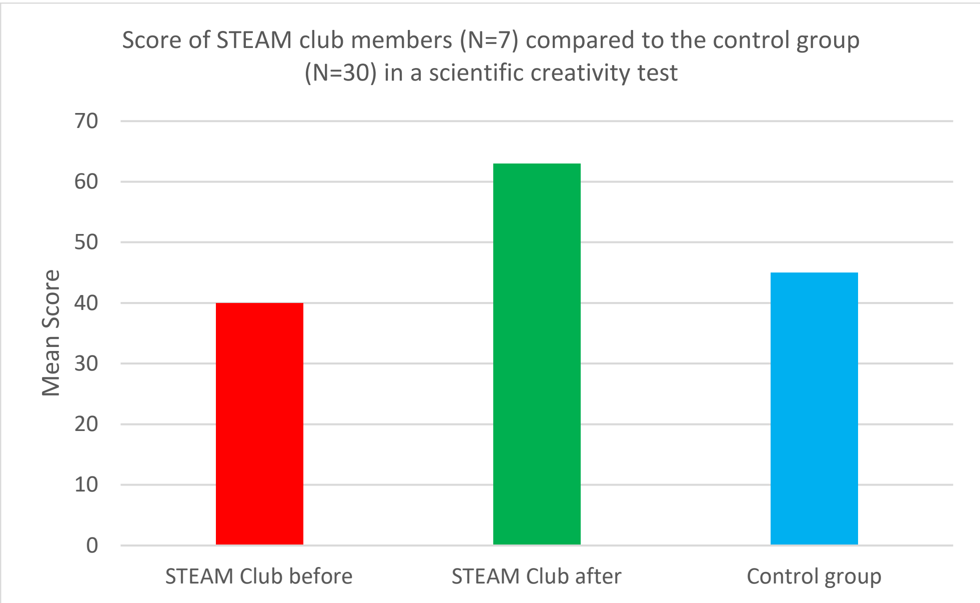

Figure 31. The effect of the ocean-based STEAM club upon students' creativity

"The problem is that, even if one teaches deliberately for creative thinking, one cannot expect to assess it when one wants to assess it, as a result or consequence of his/her teaching. The problem becomes more complicated if one considers the fact that, regardless of the opportunities students have for creative thinking, the testing situation may not provide a reliable means to assess creativity. For the test itself may be felt as a constraint on a student's freedom."

It is also worth noting that in this ocean STEAM club study, the pupils were only afforded half an hour to complete the scientific creativity paper and not the full hour as assigned by Hu and Adey (2002). This surely would have caused some suppression in the mean scores, both before and after and in the control group. Again, part of the improvement in the students' scientific creativity could potentially be attributed to them having matured by eight months. However, Hu and Adey's scientific creativity study, which was carried out with students aged 12 to 15 years old, found the mean score to be 45.36 for 12-year-olds, 56.92 for 13-year-olds and 62.52 for 15-year-olds.

Therefore, assuming a linear progression between the ages of 11 and 13, one would have anticipated a change of 23% between the ages of 11 and 11 and 8 months, whereas the club showed a gain of 58% during this time.

CONCLUSION

We have endeavoured to exemplify the connectivity between the domains of physics and art through the use of an ocean-based STEAM club which can targeted at those within either the upper primary or lower secondary. Such an arts-infused extracurricular science club option proved particularly appealing to girls, with the majority opting to attend being female. This is in contrast to other STEM clubs that have previously run in the school that have attracted mainly boys. It would be interesting to explore whether such activities have an effect upon students' views on environmentalism and sustainability. The project certainly was shown to have a positive effect upon their attitude, spatial ability, dexterity, creativity, grit and patience, albeit more pronounced in some areas than in others.

One may question whether the same gains would have been achieved had the students taken part in a more traditional STEM club without the artistic element. One would assume that a more traditional STEM club would have had minimal impact upon spatial ability and dexterity as there would be no reason for it to do so. However, the added benefit of integrating arts into STEM-projects in terms of attitude, grit, patience and creativity is less clear and cannot really be quantified from this study alone, since this STEAM-group can't be compared with a STEM-group as there was not one running concurrently in the same school with the same age group. That is to say, there is no concrete proof from this research that the integration of arts has led to more of a gain in terms of spatial ability, dexterity, attitude, grit, patience and creativity. Presumably, it would be almost impossible to prove this anyway as different children may respond more positively and in different ways to certain activities. Nevertheless, this research has provided evidence that STEAM wins over STEM in terms of attracting more girls than usual into science-based clubs and that a STEAM club can bolster students' attitudes towards science and improve the abilities that they need for success within science.

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European Journal of STEM Education,
2021, 6(1), 16
ISSN: 2468-4368

Underrepresentation of Women STEM Leaders: Twelve Women on Different Journeys Using Their Voices to Shape the World through Science

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Citation: Stewart, C. A. (2021). Underrepresentation of Women STEM Leaders: Twelve Women on Different Journeys Using Their Voices to Shape the World through Science. *European Journal of STEM Education*, 6(1), 16. https://doi.org/10.20897/ejsteme/11387

Published: November 27, 2021

ABSTRACT

This study examined the conditions contributing to the underrepresentation of women leaders in science, technology, engineering, and mathematics (STEM) education. It was a qualitative phenomenological study of twelve women with twelve unique journeys. The women included secondary educators, postsecondary university professors, and professional STEM field careerists. This study examined the experiences of women in STEM through storytelling and identified four common themes shared by the twelve participants: a) *shaping of mental exploration*; b) *math efficacy*; c) *self-discovery through problem-solving regarding why and how things work;* and d) *connection to an encouraging learning community*.

While numerous studies have uncovered systemic causes of underrepresentation, this qualitative inquiry sought to learn about the experiences of women in STEM through their own voices and therefore advance qualitative studies in this area. The study participants were limited to women in the fields of science, technology, engineering, and mathematics identified through convenience and snowball sampling in the geographical study area. This study aims to reveal how self-efficacy takes shape during adolescence and, in turn, influences the persistence of women leaders in STEM education and careers.

Keywords: STEM, self-efficacy, adolescents, underrepresentation

INTRODUCTION

The underrepresentation of women leaders in science, technology, engineering, and mathematics (STEM) education provides meaning to the journey of those seeking to understand why, after decades of informed research, published literature, and policy implementation, the representation of women leaders in STEM education and careers does not equal that of their male counterparts. Noonan (2017) acknowledged the significance of the underrepresentation of women in STEM compared to the ratio of men and women in the college-educated workforce. To understand better the complexity of this underrepresentation, this research study sought to highlight the voices of twelve accomplished women in STEM with a total of well over 300 years of combined field experience. It was important for this study to examine self-efficacy through the voices of women in STEM, thereby capturing meaningful experiences and perspectives that no other research has previously captured. If self-efficacy is the belief in one's own ability and persistence is the continuation of goal-directed actions despite obstacles, can the reminiscence of adolescence by women in STEM aid in uncovering important details about the relationship between girls' self-efficacy and women's adult lives? To further advance qualitative studies in this area through the lens of women in STEM, this study explored why underrepresentation has occurred by examining two constructs: self-efficacy during adolescence and the persistence of women in the fields of STEM guided by two research questions: a) *How does self-efficacy shape during adolescence among women leaders in STEM?* and b) *What qualities and/or experiences during adolescence are considered to shape self-efficacy and therefore influence persistence among women leaders in STEM?*

The qualitative impact of this study lies in its links to the literature using *a priori* codes to aid in the investigation of STEM-driven interests by examining the connection between self-efficacy during adolescence and the persistence of accomplished women leaders in STEM. Twelve women with unique journeys and voices provided important knowledge about why women are underrepresented in STEM.

EXPLORING STEM THROUGH THE LENS OF SELF-EFFICACY

For the past 50 years, the literature has acknowledged that policies have improved women's persistence in the fields of science, technology, engineering, and mathematics (Carpenter and Acosta, 2005; Robelen, 2010; Rolison, 2003) but have not increased their representation in these fields (Beede et al., 2011). The underrepresentation of women leaders in STEM has been explored and leveraged in literature through the lens of professional development, role-modeling, science literacy, and career choices. For example, in "Looking through the Glass Ceiling," Amon (2017) acknowledges, that efforts have been made toward the advancement of women in science, technology, engineering, and mathematics STEM positions but there is little research directly examining women's perspectives and strategies for advancing in male stereotyped disciplines.

Research has quantified the outcomes contributing to the systemic underrepresentation of women, yet fails to understand from where this phenomenon stems. The relationship of self-efficacy during adolescence and persistence among women in STEM can shoulder an important meaning for those seeking to understand why underrepresentation continues to exist. The relationship supports strong objectivity and the assertion of Bandura's social cognitive theory and acknowledges that a higher sense of self-efficacy reflects an increased effort of persistence (Pajares, 2002). "Research supports the hypothesized relation of self-efficacy to academic motivation [effort, persistence] and achievement" (Bandura, 1977). Self-efficacy—the belief in one's own ability—can shape achievement outcomes, impact ability, and influence competency. A large body of literature is related to self-efficacy, but it does not indicate how self-efficacy is shaped among girls and how it can positively influence the lives of women and, in turn, increase representation among women in STEM. Bandura (1986) acknowledges that sources of self-efficacy are not natural and can be developed through different experiences. In developing girls' interest in STEM education and in sustaining their STEM careers once they graduate, we must recognize the impact of self-efficacy (Rubiano-Matulevich et al., 2019).

WHAT IS THE MEANING OF SELF-EFFICACY FOR GIRLS? AND HOW IS IT ATTRIBUTED TO STEM IDENTITY?

Self-efficacy among adolescent girls is an underexplored factor in the underrepresentation of women in STEM education (Zeldin et al., 2007). In terms of a girl's identity, according to Janice, Polnick, and Irby (2014), "gender identity and STEM identity do not come together for many girls and researchers have begun to explore how to address identity as a critical pathway to the STEM pipeline for girls" (pp. 142-143). The literature has recognized that self-efficacy is attributed to choices, persistence, and achievement. As Carlone (2003), notes, "Girls are often fighting against the powerful sociocultural legacy of science, which is often enacted in the classroom without the teacher realizing it." (p. 308)

According to Bandura (2010), "unless people believe they can produce desired effects by their actions, they have little incentive to undertake activities or to persevere in the face of difficulties." (p. 1). Grossman and Porsche (2013) state, "little research explores supports and barriers to STEM success for girls from the perspective of those students who are poised to contribute to STEM fields" (p. 699). The relationship between self-efficacy shaped during adolescence and the persistence of women in STEM has a strong potential to moderate systemic underrepresentation, which guided the present inquiry exploring whether Bandura's social cognitive theory could explain this connection. Bandura's social cognitive theory creates a space to examine how self-efficacy is shaped among girls and influences persistence as adults.

Bandura's Social Cognitive Theory

Bandura's social cognitive theory is based on sound research, but does the explanatory literature apply to girls and women? Given the underrepresentation of women in STEM, Bandura's social cognitive theory guided the inquiry to answer "why" in this research, with the goal of helping to reveal a) what self-efficacy means for girls; b) how is it shaped; and c) how it influences persistence among women in STEM. Bandura's social cognitive theory represents a triad of exchanges and/or reciprocal causations among personal, environmental, and behavioral factors. The term *reciprocal*—defined as something common or shared—explains Bandura's interpretation of how

Figure 1. Girls' Self-efficacy and STEM Persistence Model

each variable influences the others. His framework emphasizes an interaction among behavior, environment, and person/cognition. The inquiry into Bandura's social cognitive theory has created numerous questions. It should be noted, however, that his literature does not explicitly define self-efficacy among girls or its influence on the lives of adult women.

FRAGMENTED STEM CAREER PATTERNS AND EXPERIENCES

Women's self-efficacy and persistence have created a space to acknowledge why the majority struggle to persist, despite their instrumentation and entry into sciences. Rosser (2005) highlighted that the "postmodern feminist argues that there is no common experience for women." Feminists also stated, "women['s] experiences in STEM are fragmented and situation dependent" (p. 50). Situation-dependent experiences among women in STEM raise awareness but do not generate a substantial amount of information to educate society on why women are underrepresented in STEM fields. Maltese and Tai (2011) acknowledged that engagement in math and science is critical for developing the preparation and persistence necessary for college careers in STEM. Pajares and Urdan (2006) acknowledged that personality differences that are often perceived between men and women have varying effects on occupational efficacy, career choices, and preparatory development. Hartman and Hartman (2007) suggest perceptions of negative gender stereotypes related to science, engineering, and math are able to predicted poor retention and advancement for women at university.

Bandura has contributed insightful and meaningful research that added immensely to the framework of the current research encompassing three separate variables: adolescence, self-efficacy, and persistence. The conceptual framework for this study, shown in **Figure 1**, provides a visual representation of self-efficacy among all groups, self-efficacy among girls, and self-efficacy and its influence on persistence among women in STEM. In this manner, three constructs are derived: the exchange of messages, the process of self-discovery, and the process of self-actualization.

CONCEPTUAL FRAMEWORK

Exchange of Messages

The first construct in the conceptual framework represents the fundamental exchange among school, family, and environment. It visually represents the introduction to awareness and the significant importance of how each influence and/or cause changes when it encounters other variables throughout preparatory development. The literature describes self-efficacy as a belief in one's own ability. In the closer examination of self-efficacy among girls, Grossman and Porche (2013) concluded that surrounding social systems (i.e., family, teachers, peers, and school) communicate messages that shape science engagement. Self-efficacy and engagement in science among adolescent girls "[are] shaped by individual agency as well as messages surrounding social systems, such as family, peers, teachers, and school systems" (Grossman and Porche, 2013, p. 3). How a girl identifies with and interprets science creates identifiable engagement and a belief in her own ability (Wang et al., 2016).

Girls are inadvertently exposed to a wide array of beliefs and messages that resonate with gender expectations and identity. "Girls and women face systemic messages that STEM success is incompatible with female gender roles and may perceive science as alienating and inconsistent with girls' gender image expectations" (Hill et al., 2010; Brickhouse et al., 2000). Bandura (1986) acknowledged the existence of "self-beliefs that enable humans to exercise a measure of control over their thoughts, feelings, and actions; that what people think, believe, and feel affects how they behave" (p. 25). The question then remains, *what are those messages, and how do they impact and/or shape self-efficacy among girls?*

Process of Self-Discovery

The second construct visually represents how each element (i.e., self-belief, ability, and mentality) forms a connection of influence through the exploration of self-discovery. The variables illustrate her developmental awareness of how self-belief can influence her overall perception of her abilities, therefore visually explaining how each variable impacts the other throughout preparatory development. Self-discovery throughout adolescence is vital for development. The implications of this shaping and/or connecting of self-efficacy influence the mindset of a girl when she faces challenges. According to Dweck (2002, p. 132), "[A girl's performance in math and science] should also reinforce a growth mindset in girls to increase their understanding that math ability is cultivated through effort and persistence and is not a static or immovable trait. How a girl connects with math or science influences her behavior and potential outcomes. Shaping self-efficacy and nurturing interests in math and science among adolescent girls aid in their overall self-discovery. According to Bandura (1977), "Although self-efficacy is a type of cognition, theory and research support the idea that it can affect other facets of development (e.g., social, emotional, behavioral) and that it is influenced by various personal, social, and contextual variables." The search for meaning and/or self-discovery must shape an internal connection with efficacy to persuade and/or acknowledge intrinsic beliefs that support self-confidence.

Process of Self-Actualization

The third construct represents self-efficacy and its influence on persistence among women in STEM; namely, this construct reflects a woman's belief in her own ability despite the varied challenges she may endure. It visually demonstrates the transition from recognizing her abilities to acknowledging how self-belief attribute to self-confidence. As Capodilupo and Nadal (2009) said, "Micro-assaults are often conscious explicit derogatory remarks or behaviors; micro-insults may infer ascriptions of intelligence or second-class citizenship, and micro-invalidations infer assumptions of traditional gender roles or denial of sexism." Research paradigms have indicated that self-doubt and a lack of confidence appear to deter women from participating in STEM overall. Pajares and Urdan (2006, p. 13) stated, "The differences usually follow the stereotypic courses, with boys judging themselves more efficacious for careers in science and technology and girls reporting a higher sense of efficacy for social, educational, and health services."

RESEARCH BACKGROUND

This research study involved the analysis of reflective narratives through the lens of women in STEM and was guided by two questions: a) *How does self-efficacy shape during adolescence among women leaders in STEM?* and b) *What qualities and/or experiences during adolescence are considered to shape self-efficacy and therefore influence persistence among women leaders in STEM?* Twelve women were selected based on the following criteria: 1) being recognized as a leader in the field of science, technology, engineering, or mathematics; 2) currently holding or having previously held a leadership position in secondary or postsecondary STEM education or STEM professions; 3) collectively representing diverse fields of science; and 4) currently living and working full-time in a field of science in the U.S. or having retired from work in a field of science in the U.S.

Participants

The study consisted of twelve inspiring women with diverse career paths and unique journeys, namely, two STEM teachers (both former industry professionals), two university professors, and eight STEM professionals. The participants' various fields of science, career paths, and experiences brought value to the research study by capturing relevant and unique experiences that created a genuine understanding of how their self-efficacy had taken shape during adolescence and the qualities and/or experiences that they believed shaped their self-efficacy and thereby influenced their persistence in STEM fields.

Data Collection

Interviews were conducted with each of the twelve women in person and in a private setting between May 14, 2019, and September 18, 2019. During a formal 90-minute interview, the twelve women were asked to recall experiences related to their adolescent self-efficacy and persistence. The interviews were conducted using the Women STEM Leaders Interview Protocol, as shown in **Appendix A**. Throughout the interviews, I had become highly familiar with the interview protocol questions, which shaped the interviews as natural conversations, thus eliminating redundancy to previously discussed mentions throughout the interview. After the completion of manual transcription, member checking was performed for each interview to establish both accuracy and credibility (Lincoln and Guba, 1986). Following each audio-recorded and transcribed interview, member checking consisted of four steps: a) a complete transcript was emailed to each participant; b) time was allocated for each participant to review the transcript for accuracy and credibility; c) a second audio-recorded interview was conducted if inaccuracies were discovered by either the interviewer or interviewee; and d) the final transcript was provided to each participant, including notification that the interview protocol was complete. (**Note:** If inaccuracies, i.e., misspelled words or names or incorrect descriptive experiences, were found or if the participants requested corrections, the interview protocol was repeated for accuracy and credibility.)

Data Analysis

The data analysis was conducted using Dedoose software. *A priori* codes were used for initial coding, and constant comparison analysis was performed to identify emergent codes (Glaser and Strauss, 2017). The eleven *a priori* codes in **Table 2** used for the initial analysis were selected based on their descriptive meanings; these meanings were derived from the literature and can be found in **Appendix B**. Deductive coding, as described by Yi (2018), was also conducted by pre-establishing a set of codes from the literature (Trochim, 2006). To ensure reliability and validity, repeated data coding was conducted in two different periods (Time 1: May 14, 2019 - September 18, 2019; Time 2: September 23, 2019 - October 18, 2019). Further analysis and triangulation included analysis of the code frequency and application charts produced by Dedoose software to help identify themes. This three-year research study revealed four significant findings based on the examination of 155 pages of transcriptions; the analysis of 669 excerpts; countless hours of interviewing, coding, and member-checking over a six-month period; and the creation of visual representations specific to the research study.

Approaches to Ensure Validity

The research study referred to four specific criteria for trustworthiness: credibility, transferability, dependability, and confirmability. Shenton (2004) acknowledged the difficulty of the dependability of qualitative work and further concluded that comparative models should be used for trustworthiness. *Transferability*, as described by Shenton (2004, p. 63), is intended to "provide sufficient detail of the content of the fieldwork for a researcher to be able to decide whether the prevailing environment is similar to another situation." This research study included an ample sample of participants and diverse experiences to provide multiple perspectives for transmitting the results of the fieldwork to the reader, as a means of addressing transferability. Therefore, it was important for this study to provide a degree of contextual information from a broad group given the wide range of STEM-related professions.

According to Denzin and Lincoln (1994), *dependability* is the "stability of findings over time and confirmability to the internal coherence of the data in relation to the findings, interpretations, and recommendations." Examples of dependability include the establishment of an audit trail, coding-recoding, triangulation, and peer examination (Anfara et al., 2002). The research study ensured *dependability* through the process of coding and recoding and established an audit trail that was frequently examined by experts in the field throughout the coding and recoding process. The dependability of the study relied on in-depth interviews outlining descriptive experiences in a variety of fields of science.

Confirmability refers to the "internal coherence of the data in relation to the findings, interpretations, and recommendations" (Denzin and Lincoln, 1994). The experiences and ideas of the participants reflected the confirmability of the study data. The documented data indicated findings based on reflective narratives gathered without a biased agenda. In the effort to build trustworthiness and confidence, a few key points were emphasized in each interview: 1) *the participants were encouraged to be frank,* 2) *iterative questioning was employed*, 3) *frequent debriefing sessions were held,* and 4) *member checks were utilized to ensure accuracy* (Shenton, 2004).

Ethical Considerations

Given the positions and organizations that the research participants represented, confidentiality and protection of their identities were significant ethical considerations. It was important to create rapport with the twelve STEM professionals by welcoming their expression of their experiences during the interview protocol and process. No psychological harm or risk to those involved was anticipated or presented during the study, and the participants' perceived discomfort during the interview was taken into consideration. The research study met all ethical considerations by a) *creating a safe space* for each participant; b) developing a sense of *rapport*; and c) *supporting* the participant through the interview protocol. As a result, each participant was willing to candidly reveal her experiences. This building of trust created a level of comfort that allowed for honesty and provided a supportive interview space.

Table 1. Respondent Characteristics

Code name	Age	Field(s)	Level of education	Years in the field	Professional experience
Marie	57	Aerospace engineering	PhD	32+ years	Senior executive, NASA
Silvia	62	Aerospace engineering	MA	30+ years	Analyst, United Launch Alliance
Helena	46	Hydrogeology	MA	20+ years	Geologist, Leonard Rice Engineers
Kim	62	Chemical engineering	BA	35+ years	Chemical engineer, Phillips Petroleum
Heidi	48	Mathematics education	PhD	19+ years	University professor
Pam	34	Technology	BA	16+ years	CEO, technology company
Julie	59	Engineering	MA	30+ years	Municipal utility engineer
Heather	66	Neuroscience	PhD	40+ years	Neuroscientist, NIH and NSF
Carissa	40	Structural engineering	MA	18+ years	Martin/Matin, STEM teacher
Daisy	83	Physics	BA	20+ years	Botanist
Milli	52	Zoology	PhD	25+ years	University professor
Sarah	41	Technology	MA	18+ years	IBM, STEM teacher

Descriptive Analysis: Participant Backgrounds

Through their journeys, the twelve participants had well over 300 combined years of field experience. The women's field experiences ranged from secondary and postsecondary education to industry. Among the women, there were two STEM teachers (both former industry professionals), two university professors, and eight professionals in STEM fields. **Table 1** shows the descriptive characteristics and brief overviews of the respondents by *code name*, *age*, *field of science*, *level of education*, *years in the field,* and *professional experience*.

Of the twelve participants, only two had been raised in households in which the parents had earned a four-year degree. For these two participants, only one of their parents worked in a STEM field. Heather stated, "Dad graduated from Cornell University with a degree in civil engineering. Mom graduated from Duke University Phi Beta Kappa in the 1940s. I think her major was English." The other ten women mentioned that their parents' levels of education varied, e.g., coursework toward a high school diploma, GED or equivalent, and some college. Sarah mentioned, "Both of my parents are in India; they live in New Delhi. My mom finished her bachelor's in Sanskrit, and my dad, he is not that educated. My dad finished eighth grade."

Regardless of parental education level, there was a focus on the importance of education and an overall strong work ethic. Although the way in which the responsibility to pursue education and have a strong work ethic was expressed and taught varied among the participants, it prefaced their persistence in their academic journeys. Heidi explained as follows:

> In terms of education and occupation, [I] don't really feel like there was a ton of expectations for me. I mean, they expected that I'd graduate from high school, but I never really was encouraged beyond that. Grades in school, if I passed, did well enough, and didn't cause any trouble, that was generally the expectation for me. Like work ethic, I mean work hard. So, I had to balance…like the work ethic was more about being a human who was responsible and respectful, and you take care of other people, and you try to think of other people more so than yourself.

Importantly, these women were not only highly educated but also did not follow traditional STEM pathways; rather, they forged their own paths.

RESULTS

Math Efficacy

The first research question—*How does self-efficacy shape during adolescence among women leaders in STEM* —revealed the themes of math efficacy and shaping of mental exploration, which were shared by ten of the twelve participants. The literature emphasizes that more research is needed to explore pathways of the development of girls' overall STEM identities. As claimed by Koch et al. (2014, pp. 142-143), "gender identity and STEM identity do not come together for many girls, and researchers have begun to explore how to address identity as a critical pathway to the STEM pipeline for girls." According to the research participants, STEM identity is shaped through practical learning and exploratory experiences.

The *a priori* code "self-efficacy beliefs" captured the participants' own knowledge about their abilities and capacities, as opposed to other people's judgments of their capabilities. The excerpts support a continuum of comfort levels with problem-solving and how their degrees of comfort shaped their worlds. Bandura (1986, p. 391) stated that self-efficacy beliefs refer to "people's judgments of their capabilities to organize and execute courses of action required to attain designated types of performances." Bandura's definition of self-efficacy beliefs does not fully support the comments provided by the participants. Some of the participants emphasized that their families affirmed their math ability. Again, ten of the twelve participants described their ability as natural, innate, and/or something unexplainable. The term *efficacy* is defined by Merriam-Webster as a "capacity for producing a desired result"; efficacy fully supported the participants' experiences and beliefs. While the aim of the *a priori* coding was to capture all aspects of self-efficacy, when the excerpts were later examined, it was clear that the driving force for these women was *math* efficacy, not *self*-efficacy.

Math efficacy (which refers to how one sees the world through patterns, shapes, and numbers to shape a desirable outcome) was mentioned by ten of the twelve participants. In answering the first research question (*How does self-efficacy shape during adolescence among women leaders in STEM?*), determining the shaping of self-efficacy required tracing the participants' awareness of their capacity for math, referred to as *math efficacy*. The participants consistently emphasized their overall ability and capacity for math. Interestingly, the participants did not attribute their math ability to any direct influence from their environment, family, or school. Additionally, while some of the participants noted that parents and teachers had affirmed their abilities, others indicated that their abilities were challenged. Heidi revealed, "My algebra teacher, maybe in the eighth grade, would tell me that I did stuff weird; that I should do it the right way." The participants' propensity for math was eventually unpacked through their provision of multiple examples, such as examples of what began to shape their interests in STEM.

The research participants indicated that their *math efficacy* as adolescents introduced them to the experience of seeing the world from a mathematical perspective (e.g., in terms of patterns, shapes, and/or numbers) and of seeing how their ability could lead to a desirable outcome. The participants distinctively communicated their capacity for math through its distinct forms and association (e.g., patterns, shapes, and/or numbers) as a natural phenomenon. The participants specifically commented on how their capacity for math began with a distinct liking of an individual type of math (e.g., shapes, patterns, and/or numbers).

The participants' reflections reiterated that their experiences in math were shaped by a distinct form of math that captured their interest and that they understood better than other forms. For example, Marie explained as follows:

> Even my dad showing me how to take a motor apart and inner stuff, and whether they call it science or technology, whether you call it hands-on skills, all that stuff. He only had an eighth-grade education, but he taught me trigonometry and geometry. We did it by looking at trees and shadows and things like that. He was very practical; [quoting her dad] 'You can find this distance by this; you can see the sun, and you measure in the shadows of space,' and it was a good way to learn.

Marie's comment demonstrated and explained her connection to shapes and geometric forms. Marie's father illustrated a practical application of trigonometry and geometry. Her understanding of math took shape through her father's practical introduction of trigonometry and geometry by referring to trees and shadows. The experience she recounted became a segue in further advancing her curiosity and science literacy. Transformative learning, interest, and curiosity regarding shapes, patterns, and/or numbers were consistent topics across the participants' reflections. Helena provided the following reflection:

> So, my geometry class was transformative for me. I ended up in that class with 100 percent, you know, at the end. And that is when I realized that I could really, that I understood complicated shapes and complicated depths. And I think those concepts—I mean, calculus and DiffEq—that just helped affirm it. But geometry, really, I could see in my mind the angles and see how it related to each angle, each deformation fitted together.

Helena's experience of understanding how patterns and shapes fit together affirmed her math ability by revealing her connection to shapes. Her reflection explained how her interest in shapes created and further developed her capacity to sustain interest.

It was interesting to hear how the participants explained math logically through the practical connection of patterns, shapes, and/or numbers. For example, Carissa noted, "Mine isn't so much science as much as numbers. Like, I just loved numbers and problem-solving. I would do logic problems, those logic puzzle books—I would get one every year, and that would be something I would enjoy doing." Carissa's love for numbers prefaced her interest in patterns, as it affirmed her interest and curiosity about how things connect through problem-solving.

The word "natural" was associated with math ability in the reflections of ten of the twelve participants. Each experience illustrated how the participant's understanding of specific forms of math (e.g., patterns, shapes, and/or numbers) had taken shape throughout adolescence. These findings indicated that the participants' understanding of math was shaped by a distinct form of math (e.g., patterns, shapes, and/or numbers), which nurtured their capacity for interest in math. The participants' reflections on math efficacy determined how each viewed the world through patterns, shapes, and numbers in ways that shaped desirable outcomes.

Shaping of Mental Exploration

The *a priori* code *shaping* referred to excerpts that reflected the development and cultivation of participant STEM-driven interests, thus *shaping* their STEM identities. According to Bandura (2005, p. 12), "choices made during formative periods of development shape the course of lives. Such choices determine which aspects of their potentialities people cultivate and which they leave undeveloped." His explanation describes the causal meaning of shaping and is consistent with the participants' experiences. The excerpts supported Bandura's definition and brought meaning and awareness to the formative periods in girls' lives by detailing the experiences of women in STEM. The participants' formative periods of development began with exploration—that is, their development started when they began to wonder how the world works.

The theme of *shaping of mental exploration* consisted of a variety of exploratory experiences that might be expected, including music and experimentation, as well as others that were somewhat surprising, such as cooking, ranching, and even rock collecting. These experiences provided the participants with an explorative sense of wonder that framed their STEM-driven interests and enjoyment. Marie, an aerospace engineer, reflected as follows:

> I would say that the most formative moment was watching Apollo 11. And I still remember being seven years old; that made me want to work for NASA. Being seven years old, watching Neil Armstrong and Buzz Aldrin walk on the moon, and I can still remember telling my mom and dad that's what I wanted to do. And then, from there it became aviation and science and space and astronomy and all those things—it became my focus from then on.

Heather, a retired neuroscientist, was raised around animals and noted that she translated practical applications into scientific practices. She stated,

> And the training for the horses and making sure that everyone is behaving properly…I realized that there's a real scientific way to do this properly. And yet I kind of learned some of it in an ad hoc way.

Heather's experience of having responsibility for taking care of animals to meet a need—and/or gain impromptu practice—shaped her capacity to translate common practice into scientific understanding; in other words, it shaped her science literacy. She further described,

> The biology combined with the psychology [class] gave me the basic biological control of behavior of thought. World events or behavior is not random—there are causes. There's a stimulus and a response type of activity that goes on for people, for animals, and in nature generally. And that kind of gave me a concept of putting order onto my worldview.

Heather's experience of taking care of animals shaped her curiosity into a scientific understanding of how people and animals respond to stimuli. The shaping of mental exploration, as explained by Heather, is not necessarily associated with a physical location. Instead, the experience is intellectual and involves scientific exploration.

Mental exploration takes the shape of exposure, imagination, and curiosity, but more importantly, it allows the imagination to ask questions, formulate answers, and discover possibilities. Mental exploration, as explained by the participants, served as a contextual framework for development that hastened their eagerness to learn, explore, and develop the humility to wonder and consider extensive possibilities.

Self-Discovery through Problem-Solving Regarding Why and How Things Work

The second research question—*What qualities and/or experiences are considered to shape self-efficacy and therefore influence persistence among women leaders in STEM?*—revealed the common theme of self-discovery through problem-solving to determine why and how things work and through connection to an encouraging learning community, which were experiences shared by eleven of the twelve participants.

The participants' responses described self-discovery and its importance in influencing persistence throughout their academic and/or professional experiences. Each participant noted that she understood and preferred the logic of math and science courses over courses in the liberal arts. The participants' general curiosity about why and how things worked created a platform for navigating their academic journeys. Specifically, persistence was influenced and/or developed by establishing self-awareness and by approaching problem-solving through logic and measurable outcomes.

Of the twelve participants, eleven shared the theme of *self-discovery through problem-solving to determine why and how things work*. The women's capability to understand "why and how" and not just "what and when" influenced their academic journeys. Among the participants, problem-solving took the form of realizing that through their STEM-driven interests, they were drawn to efforts that required or developed a logical outcome (e.g., problem-solving applications, math, logic books, puzzles, and science experiments). Self-discovery supported their STEM-driven interests and framed their STEM identities. Self-discovery regarding the desire to solve problems in order to understand why and how things work provided the women with explanations, reasons, and purpose and encouraged them to continue in their efforts. They shared similar reflections of experiences that opened the door to inquiry, problem-solving, and the questioning of why and how things worked. Helena provided the following reflection:

> I think that my first was curiosity and then just the overall driving need to understand how it worked. And then once I figured out how it worked, having the sense of satisfaction and well-being and say[ing], 'Okay, now the next problem' [laughed]. And I think, too, the need to fix things, you know, and problem-solving that…How do I…Here is the need and the want; what are the solutions to fix it? You know, like the need to figure out how to cook macaroni and cheese [laughed]. My sisters and I were hungry [laughed], and we wanted mac and cheese, but we weren't allowed to use the stove [laughed]. So, was there another way [laughed]? There was not at the time [laughed].

Helena's comment demonstrated her driving need to know "how," emphasizing how problem-solving had a practical connection to science through the mundane process of cooking macaroni and cheese. Helena recognized that this drive began with curiosity and then developed into practical problem-solving. Learning how to cook macaroni and cheese was a practical task born from a sense of curiosity and developed into an internal need to continue solving problems. For Helena, "having the sense of satisfaction and well-being to say, 'Okay, now the next problem'" indicated her desire and ability to negotiate a task and her instinctive willingness to persist to the next problem.

Milli acknowledged that problem-solving was associated with determination, learning how to navigate, and seeking the necessary resources to obtain the answer:

> So I was still operating like, 'Oh, I'm great' and all that, and slowly, like, we had a physics teacher, he'[d] just come and do stuff; I just couldn't keep up with it. And I could see, but I could see the boys, especially the boys were able to. So, I would, like, ask them, 'How did you do that?' And then they would just show me, and I was like, 'But the teacher didn't show that step that you did.' So I didn't know where they were learning. And so I struggled with, especially with physics, I think, in the eleventh grade.

Milli realized that during her adolescent experience, she required more than just basic classroom instruction to grasp the necessary information to excel academically:

> And I…I just went, and there was a place in Delhi called Nai Sarak, which is where you get, like, supplementary books. And so I told my mom I needed to buy some books because the schoolbooks are not explaining. And so I got some extra books, and I started to read a little bit, like learn a little bit more on my own and to see what was going on.

Milli's experience demonstrated her rigid determination to further her learning by any means necessary. She acknowledged her difficulty in the classroom and sought out the necessary reading materials outside the classroom, but most importantly, she proved that she was willing to continue despite the challenges she faced.

This shared theme explicitly indicated the similar ways in which the participants navigated their academic journeys. The participants' reminiscences consistently showed that their problem-solving stemmed from their curiosity and desire to question why and how things worked. Their self-discovery of problem-solving to understand why and how things work created a favorable pathway for academic and professional choices, which resulted in their willingness to continue solving problems. This self-discovery created an internal eagerness to question, query, wonder, and uncover why and how things worked. The participants had one factor in common: the shared desire to solve problems by applying logic and reason. Their eagerness to question and problem-solve cemented an internal logic that provided order and explanation. Silvia affirmed, "It's just seeing all kind[s] of things in your world and having that background to understand what you see, right…not everybody cares about that [laughed], right?…But I do; I want to understand why."

Connection to an Encouraging Learning Community

Based on the women's reflections, connection to an encouraging learning community was important. Eleven of the participants noted a connection to an encouraging learning community consisting of, e.g., family, school, or environmental influences. In the participants' responses, the *a priori* code 'connection' was applied to human interaction with family, teachers, and the environment. Pajares and Urdan (2006, p. 359) stated, "For instance, if a young person can be helped to realize that increased effort and perseverance will result in academic progress and greater understanding in mathematics, connections will be made to achieving success in other academic areas." In line with Pajares and Urdan (2006), Marie stated, "I think if I had not had a family that told me I could do anything, that would have made a major difference." The human connections expressed by the participants influenced their personal journeys, professional careers, and academic pursuits. DePaulo (2010) stated, "Relationship, though, is a great big word. It covers all sorts of human connections, including ties to friends, parents, children, siblings, other family members, coworkers, neighbors, mentors, and more." For the participants, "connection" included influences from both inside and outside the home (e.g., teachers, parents, extended family, coaches, supervisors, and professors) that significantly impacted their own personal journeys. The connection emphasized by the participants gave meaning to their learning and provided encouragement, thereby influencing their journeys. Daisy emphasized, "You know, I was always…as I said, my mother was incredibly supportive, and she wanted me to succeed."

The adolescent experiences that the participants shared in their reflections supported their willingness to pursue academic interests and make life-changing decisions, while messages from their family, friends, and/or communities gave meaning to their journeys. Kim recalled the following:

> Yeah, so, that particular teacher and my math teacher suggested I go into mechanical engineering. The fact that it was a woman, maybe [it] was helpful that she was interested specifically in what I was doing. I do not know…I had no idea she made a habit of that whole semester, just going around chatting with each student [and] finding out where they were going forward. I had absolutely no idea. But I know I sort of appreciated that.

The participants' reflections and connection to an encouraging learning community put into perspective the importance of an educative foundation, including where and how it begins.

Helena said that the messages she received provided her with real meaning:

> So I think middle school, and I think it was a specific science teacher and their influence on me. But my seventh-grade science teacher, he was a male. My eighth-grade science teacher was female; I can't remember their names right now. But they, I think they specifically fostered me and said, 'Here, you can do better.' And I think that really honed my interest, and then I made sure all through high school [that] I had science classes. I didn't *not* take science. And I think, too, just those conversations with my grandparents, and my grandfather was a general contractor. And he said, 'Don't be the general contractor; be the "-ist."' Whatever, you know, the biologist, the geologist, the engineer…be that person.

The participants' reflections revealed how the connection to an encouraging learning community can make a difference. Each of the women emphasized what an encouraging learning community meant to her personally and how it came to influence her journey. The comments shared by the participants emphasized that intentional acts of support from professors, parents, and teachers who advocated for their success helped guide their decisions by helping them realize that anything and everything was possible if they just believed. Marie recalled, "I always thought I could, and I did well, the teachers always said that I did well. So that gave me the belief."

Visual Explanation of Findings

The research study comprised the analysis of two research questions: a) *How does self-efficacy shape during adolescence among women leaders in STEM?* and b) *What qualities and/or experiences during adolescence are considered to shape self-efficacy and therefore influence persistence among women leaders in STEM?* The analysis of these two research questions led to the identification of four themes shared by the twelve participants, demonstrating that significant journeys can and do align.

The model visually represents the participants' narratives of how their innate ability for math was influenced during their formative periods of development. The participants emphasized that their distinct liking for a particular form of math was nurtured through real-world exploratory experiences derived into interests and shaped by family, school, and environment, inevitably empowering them to explore, dream, and question how the world works. The concentric images surrounding math efficacy indicate three important factors that shaped their STEM-driven interests: a) introduction to problem-solving, thus creating a distinct liking and curiosity through self-discovery; b) connection to family and community, which nurtured STEM interests and influenced their confidence in solving complex problem-solving applications; c) mental exploration, which developed a sustainable desire to question, query, and wonder how the world works, thus shaping their STEM identity.

Figure 2 provides a visual analysis of the findings, accompanied by contextual constructs that give meaning to the information that the participants expressed throughout their reflections. The visual model below presents three concentric images central to math efficacy that frame how the participants' adolescent self-efficacy took shape and, in turn, what qualities and/or experiences in adolescence influenced the participants' persistence throughout their journeys.

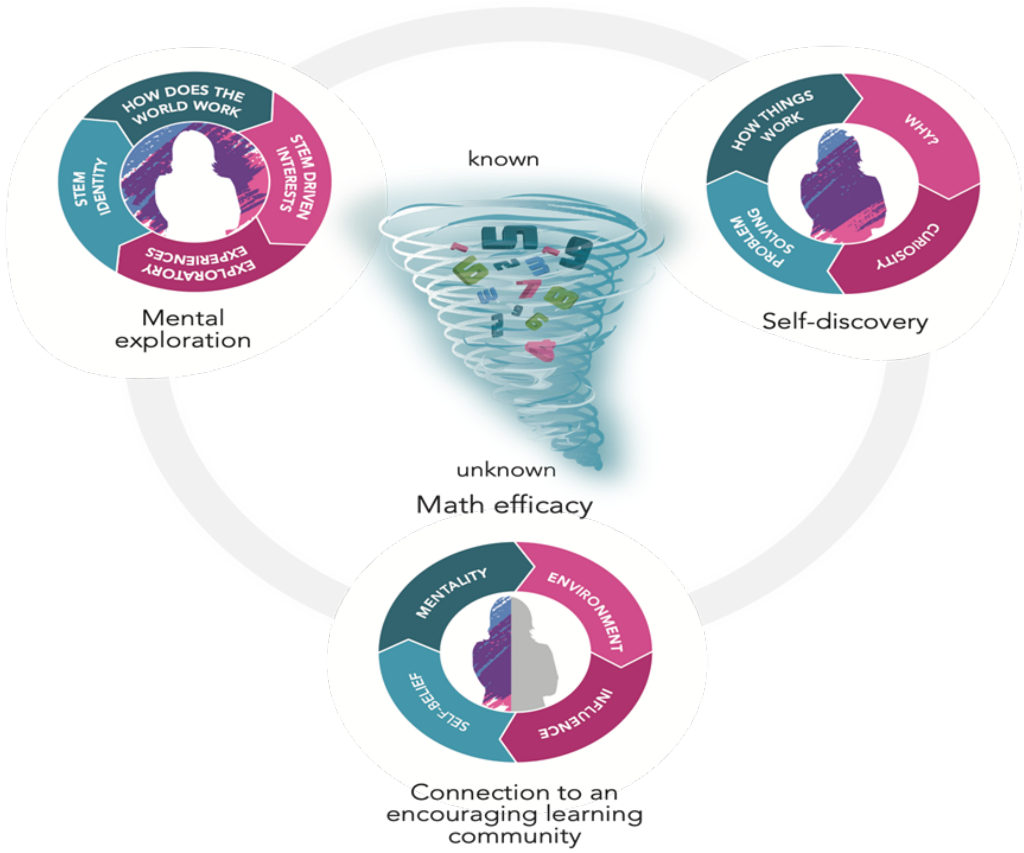

Figure 2. STEM Efficacy and Persistence Model

Visual Description: STEM Efficacy and Persistence Model

The STEM efficacy and persistence model provides a visual analysis of the four themes shared by the twelve participants. The model shows how the shaping of mental exploration, self-discovery of problem-solving to understand why and how things work, and connection to an encouraging learning community often work in concert with math efficacy. All four themes were relevant and vitally important to shaping adolescent self-efficacy and its influence on persistence among women in STEM. The first theme, *math efficacy*, reflected how the participants' views of the world, through patterns, shapes, and numbers, shaped their desired outcomes and appeared to begin during their formative periods of development. As Heather said, "That kind of gave me a concept of putting order to my worldview." Her reflection was consistent with the other participants' emphasis that patterns, shapes, and numbers brought order to chaos, helping to shape the world around them. Examples of math efficacy shared by the participants included their preference for math and science, logic games, puzzles, and problem-solving over the liberal arts.

The second theme, *shaping of mental exploration,* showed how the participants' sense of logic took shape through exploratory experiences (e.g., music, rock collections, ranching, cooking, and experimentation). The exploratory experiences through which the participants sharpened their STEM identities through STEM-driven interests were prompted by the question, "How does the world work?" The third theme, *self-discovery through problem-solving to understand why and how things work,* was central to the formative development of the participants' curiosity. Their curiosity led them to ask questions and seek answers through problem-solving. Carissa stressed,

> Even though I really wasn't very good in English, they all were amazed at my problem-solving abilities and my math abilities. And it just came easy for me, like I didn't have to try hard to…so I didn't really learn how to apply myself either in school at a young age…or it wasn't really until grad school that I really had to figure out how to work hard at school.

Furthermore, the fourth theme, *connection to an encouraging learning community*, consisted of significant influence and/or support from, e.g., parents, extended family, teachers, professors, and coaches. The participants emphasized that an encouraging learning community provided a positive influence and an environment in which to learn, excel, and explore education. This support provided meaningful guidance that they attributed to their academic fulfillment in school, college, and/or the workforce. For example, Sarah described the influence of a woman role model as follows:

> I had the best boss ever when I started, and she was a woman. So she was my role model. And when I say role model, I think that helped for me as well, just seeing her, the way she worked, the way she handled stuff, multitasking, time management. I think I have learned a lot from my first boss just by the way she was working. And that is when I made my own way from there.

DISCUSSION

This study emerged from a "why" question, specifically, why women are underrepresented in STEM? I purposefully sought to represent the voices of women from various fields of science and organizations. In doing so, I wanted the study to be relatable; benefit a broader population; provide sustainable findings; and significantly impact all girls and women regardless of their journeys, ethnicities, levels of education, etc.

To do so, it was important for the study to include a descriptive model, e.g., the *STEM efficacy and persistence model*. The purpose of the *STEM efficacy and persistence model* was to provide a visual representation and framework of the detailed, specific adolescent memories of twelve accomplished women in STEM. The model illustrates how three important constructs work in concert with *math efficacy*, with each element having equal importance. The model was specifically designed to be used as a tool and/or guide and to visually describe how self-efficacy was shaped among twelve women in STEM and, in turn, influenced their persistence by detailing vital aspects of their formative periods of development, e.g., curiosity, interests, and STEM identities.

As the sole investigator in this study, I believe that there is a need for further qualitative studies to continue unpacking the role of self-efficacy during adolescence and thereby to help provide meaning to practicing professionals, educational settings, and potential future STEM professionals. Additional qualitative studies of women in STEM with larger samples would provide an extensive causal, in-depth understanding of the association between *mental exploration*, *self-discovery*, *math efficacy*, and the *connection to an encouraging learning community*.

The implications of this study contributed to increased awareness. It is important to note that the theme of *math efficacy* was shared among the participants even though none of the direct interview questions in the protocol pertained to math. *Math efficacy* has been explored in terms of how women connect to distinct forms of math, e.g., patterns, shapes, and/or numbers, therefore supporting their worldview rather than limiting it. The concept is consistent with the participants' reflections regarding experiences that prefaced their math ability and, more importantly, how their natural connection to math allowed them to see and shape their world. The connection between a person's math ability and judgments has been explored through the lens of math self-efficacy. Betz and Hackett (1983) acknowledge assessments in terms of individual judgments regarding how to solve mathematical problems. Each of the participants honed in on her math ability as central and significant during her formative periods of development. The participants referred to their math abilities as natural, innate, and/or unexplainable. It was understood that their capacity for math was formed through their interest in distinct forms of math, e.g., patterns, shapes, and/or numbers.

It is also important to recognize certain significant aspects of math efficacy: a) when the connection to math occurred; b) how the connection was influenced; c) why the interest emerged; and d) who affirmed the interest. In the women's narratives, all four components of math efficacy were equally important during their formative periods of development. The findings of this research study showed that math efficacy was not demonstrated by a behavior or measure but, rather, by a relative understanding of how each participant connected to math and sustained her interest in distinct mathematical forms, e.g., patterns, shapes, and/or numbers.

Math efficacy was included in this research study to explain how women allow their innate math ability to influence how they see and shape their world. It was introduced as a new concept in this study to provide insight into how relevant forms of math, e.g., patterns, shapes, and numbers, were present during the participants' adolescence and, in turn, shaped the participants' views of the world. This concept was not introduced to de-emphasize the importance of past and present studies of math self-efficacy, mathematics-related behaviors, or the definition of math as the ability to perform mathematical equations. Rather, it was intended to reveal how the participants' connections with math were shaped during adolescence.

Another implication that has the potential to benefit the broader population relates to self-discovery and awareness of innate abilities during formative periods of development. Throughout the research study, multiple women shared their early preference for math and science over liberal arts coursework, e.g., English, literature, and spelling. Carissa indicated, "I think the biggest challenges I had were reading and writing and not enjoying it…and spelling; I am still a horrible speller." After the analysis of similar reflections, academic journeys, and professional career choices, it was apparent that some, if not all, of the participants became aware of their innate abilities early on through self-discovery, which shaped the trajectories of their lives.

Marie shared an experience that she considered to be a life-changing event, as it sparked curiosity and led her to what she eventually considered a possible career pathway. This experience allowed her to dream, connect, and impact her academic trajectory. One moment, one experience, and one event can shape the life of an adolescent forever. During the interview, the questioning was paused as Marie listened to a broadcast over the radio commemorating Apollo's 50th anniversary—an indescribable moment. It was easy to see the excitement in her eyes and to understand how this event had shaped her personal journey and passion.

Self-discovery among the participants was demonstrated in their realization that math and science courses stoked their curiosity and eagerness to know why. Their reflections also emphasized distinct boredom in non-math and science courses (e.g., geography, spelling, and English). Self-discovery, according to Summer (2017, p. 391), "requires a process of conjecture and refutation, a willingness to question and criticize received views and to welcome challenges and criticism to views that one holds dear and that may seem to be part of one's identity." For the participants, self-discovery was thought of as the curiosity to ask "why?", which led to problem-solving in search of a logical explanation for how things work. The participants' curiosity increased their eagerness and desire to solve problems. Many of the women shared interesting experiences they had in the classroom based on their awareness of abilities, advanced understanding of math and/or science coursework, and interest and curiosity.

Other participant endeavors (e.g., science projects, tactile problem-solving, music, board games, trips to the library, vacations, and rock collections) supported the participants' adolescent interests and later STEM identities. These experiences shaped their development through pragmatic opportunities to wonder, dream, observe, ask questions, and explore beyond the present day. Each of their experiences provided an opportunity to dream. Milli indicated, "We never had a lot of money, we never had luxuries, but we had dreams." To increase awareness, it is imperative to a) advance curricula that respond to and focus on the intellectual development of advanced learners in math and science; b) increase awareness of the differentiation between science and non-science coursework across educational settings; and c) develop educational practices to assist in understanding how science-literate students respond to both science and non-science coursework.

Based on the research study, the analyzed reflections offered additional insight that could benefit STEM education at all levels, including insight on a) the benefits of hands-on tactile learning; b) innate ability (sense of knowing) and its association with science literacy; and c) the positive influence of women, e.g., teachers, mothers, and professors, during formative periods of development. Hands-on tactile learning was mentioned in several reflections. The mention of hands-on learning stemmed the participants' interest early on and, in turn, helped them develop a sense of self-confidence. Pam mentioned,

> So, from building and tweaking and learning how to change light fixtures and things like that, I had this kind of hands-on…and I think science and that allowed for you to be hands-on and allowed for you to be kind of a tactical learner and that was something that helped me and until this day still helps me, I think.

The reference to science and its relation to hands-on tactile learning increases awareness of a) the shaping of science; and b) science literacy behavior early on.

The participants' awareness of their innate abilities during their formative periods of development, which were expressed through likes and dislikes, and the association of this awareness with science literacy were paramount. Pam mentioned,

> For me, when I likely could have been exploring and doing more with science and math, I think I spent time not trying to fail at English and writing and literature in those areas. So, I think there was an internal inside academia and outside academia of not letting that fall. Ultimately, the energy that could have been put into exploring and doing more of what I was good at and what I *liked* was shifted back into putting way more time and energy and effort into something just so I could, again, have good grades and [not] disappoint.

Helena shared a similar reflection,

> I think it was [an] *innate* feeling. It made me, and maybe that was developed by my mom giving me books and my constant questioning. And her taking me seriously and not saying oh…figure it out. But helping to foster my curiosity and my drive.

The reflections that the participants shared provide insight into a) how likes and dislikes were expressed and demonstrated through words, academic pathways, and career choices; b) when likes and dislikes were expressed during formative periods of development; and c) the academic outcomes and career pathways chosen based on the participants' senses of their likes and dislikes early on.

Several of the participants mentioned the last implication, the positive influence of a woman role model and/or mentor, e.g., a teacher, mother, coach, or professor. In their reflections, several participants concluded that the influence of a woman shaped their journeys as young adolescents. Milli mentioned, "So, yes, teachers and then, of course, my mother being a huge influence. In the sense that she herself, she just created a space in the house where it was encouraged to excel in school." The benefit of having a positive influence from a woman was consistent across many memories that detailed the significant contributions of such an influence on development, academic pathways, and career choices. The findings regarding the positive influence of a woman indicate how significant such an influence can be to academic success for girls during their formative periods of development.

Limitations

The findings in this study were generated from interviews with twelve women in various fields of science with various career paths and experiences. The participants were limited to women in the fields of science, technology, engineering, and mathematics who were identified through convenience and snowball sampling in the geographical study area. The participant sample was limited based on women in STEM who agreed to participate and who were recruited from my personal and professional networks as feasible candidates based on the research criteria.

CONCLUSIONS

The voices of twelve women, each with a unique journey, illustrate four themes significant to increasing awareness of how self-efficacy is shaped during adolescence and, in turn, influences persistence among women. The study a) provides insight to help increase the representation of women in STEM by welcoming narratives of women that would advance qualitative studies in this research area; and b) increases awareness of science literacy based on the reflective narratives of women in STEM to help shape educational settings and professional learning communities. This research study is dedicated to girls who may question their abilities, young women questioning whether to begin careers in STEM, and practicing professionals seeking support in sustaining a career. I would like girls and women to realize that their persistence does matter and that when girls persist, women will thrive.

LIST OF ABBREVIATIONS

STEM-Science, technology, engineering, and mathematics

DECLARATIONS

Availability of Data and Materials

The datasets, e.g., the interview protocols generated and/or analyzed during this qualitative phenomenological study and personal identifying information, are not publicly available due to the confidentiality of the interviewed participants but are available from the corresponding author upon reasonable request with consenting approval from the participant.

Competing Interests

The authors declare that they have no competing interests.

Funding

The research study did not require any sort of budget or funding.

Authors' Contributions

As the sole researcher and author of this study, I recruited participants from my personal and professional networks and among those whom members of my network identified as feasible candidates with regard to the research criteria.

ACKNOWLEDGMENTS

This work was possible due to various sources of support and expertise, e.g., my advisor, committee members, and thought partner. Thank you for your guidance and mentorship and for undertaking this journey with me. This study would not have been possible without the shared journeys and voices of twelve accomplished women. Thank you for your patience, willingness to share your experiences, and especially, your trust in me. Finally, I want to thank my family for their encouragement and loving support throughout this journey. I hope this work benefits STEM communities and professional and educational settings and contributes to the increased representation of girls and women among those pursuing STEM education and careers.

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APPENDIX A: INTERVIEW PROTOCOL

Table 1. Women STEM Leaders Interview Protocol

Family Background	• What were your parents' levels of education and their occupations?
	• What were some of the messages you received from your parents regarding your work ethics, aspirations, and/or education?
	• Were there any family traditions that impacted you during your adolescence?
	• What type of responsibilities (i.e., chores) were required of you as an adolescent in and outside the home?
	• What types of activities and/or programs did you participate in (i.e., sports, school clubs, and/or afterschool programs)?
	  o How did you enjoy them?
	  o What did you enjoy about them?
	  o How did the activities make you feel?

Adolescent Self-discovery	• How did you perceive yourself as an adolescent girl? • How were you perceived as an adolescent girl? o by others? in school? at home? in the community? • Please explain your journey of self-discovery as an adolescent girl. What specific experiences do you attribute to your self-discovery?

STEM Interests & Connection	• Please reflect on your initial connection to science and explain that experience?
	• How did the connection and experience make you feel?
	• What about science prompted your initial interest as an adolescent?
	• When and how did you realize you enjoyed science?
	• Explain what triggered your curiosity about science.
	  o What was your initial takeaway from the experience?
	  o How did it make you feel?

Middle School, High School, & Academic Performance	• What positive academic influences inspired you as an adolescent girl?
	  o How did they influence your performance? Why?
	• Please share an experience you had as an adolescent in school when your academic achievement was praised in the classroom?
	  o How did it make you feel?
	• What environmental influences (teachers, peers, family) could have contradicted your interest in science?
	• What environmental influences (teachers, peers, family) supported your interest in science?
	• Did you have any immediate family members and/or close relatives in science fields?
	  o If so, how did it impact or influence your interest in science?
	• What environmental influences (teachers, peers, family) supported your interest in science?
	• How did you perceive your academic ability in science compared to that of other students?

Adolescent Experiences / Journey	• What were some of the adolescent experiences that helped shape your academic journey? • What experiences specifically shaped your effort to persist academically in and outside the classroom? • Please explain a situation during adolescence in which you experienced self-doubt that caused you to question your abilities and impacted your academic performance? o What contributed to your self-doubt?

Challenges & Influences	• What challenges did you experience as an adolescent?
	  o in the classroom? outside the classroom?
	  o What contributed to these challenges?
	• What environmental factors influenced your academic journey?
	• How did negative academic influences impact you as an adolescent girl in and outside the classroom?

Aspirations	• What career fields inspired you as an adolescent? • As an adolescent, what aided and/or nurtured your interest to pursue a career in science?

Reflection	• During your academic journey, did you persist by choice or circumstance?
	• Please explain your definition of academic persistence.
	  o What or who influenced your academic persistence? How?
	• What were some of the experiences during adolescence that helped shape your academic persistence?
	• At what point during your academic journey did you achieve self-mastery?
	  o What experiences do you attribute to your self-mastery?
	• If you had the opportunity to speak to an adolescent girl with self-doubt about her ability to persist in science, what would you say?

Probes to encourage respondents to further explain their responses and/or provide additional elucidatory information were administered as needed and consisted of "Please explain", "Why?" and "How?"

APPENDIX B: A PRIORI CODES

Code	Definition
Persistence	• "Voluntary continuation of goal-directed action in spite of obstacles, difficulties, or discouragement" (Peterson and Seligman, 2004, p. 229).
Performance	• "Refers to both behavior and results. Behaviors are emanating from the performer and turn the performance of an abstract concept into a concrete action" (Brumbach, 1988).
Self-efficacy beliefs	• "People's judgments of their capabilities to organize and execute courses of action required to attain designated types of performances" (Bandura, 1986, p. 391).
Self-discovery	• "Requires a process of conjecture and refutation, a willingness to question and criticize received views and to welcome challenges and criticism to views that one holds dear and that may seem to be part of one's identity" (Summer, 2017, p. 391).
Self-belief	• "People with self-beliefs of confidence have been shown to attribute failure to lack of effort; people with low self-beliefs of confidence ascribe their failures to lack of ability (Collins, 1982).
Self-mastery	• "The ability to take control of one's life without being blown off course by feelings, urges, circumstances" (Collins English Dictionary).
Success	• "That young people can fulfill individual goals and have the agency and competencies to influence the world around them" (Wallace Editorial Team, 2017).
Academic Achievement	• "Represents performance outcomes that indicate the extent to which a person has accomplished specific goals that were the focus of activities in instructional environments, specifically in school, college, and university" (Crede et al., 2015).
Connection	• "Relationship, though, is a great big word. It covers all sorts of human connections, including those structured across activities. For instance, if a young person can be helped to realize that increased effort and perseverance will result in academic progress and greater understanding in mathematics, connections will be made to achieving success in other academic areas" (Pajares and Urdan, 2006, p. 359).
Nurture	• "It is more likely that behavior is due to an interaction between nature (biology) and nurture (environment)" (Bandura, 1977).
Shape	• "Choices made during formative periods of development shape the course of lives. Such choices determine which aspects of their potentialities people cultivate and which they leave undeveloped" (Bandura, 2005, p. 12).

EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 17
ISSN: 2468-4368

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Simulating Professional Practice in STEAM Education: A Case Study

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Citation: Lugthart, S. and van Dartel, M. (2021). Simulating Professional Practice in STEAM Education: A Case Study. *European Journal of STEM Education*, 6(1), 17. https://doi.org/10.20897/ejsteme/11393

Published: December 1, 2021

ABSTRACT

Situated learning could benefit STEAM education because both aim to develop skills that can deal with complex real-life situations. Although ample research has been conducted into situated learning within higher vocational education in general, there exists little research on the implementation of the educational approach in STEAM education specifically. To gain insight into what is needed for this implementation, a case study of a situational simulation was conducted within a STEAM education context, in which we observed students in simulating media design studios. We observed the setup, working and evaluation phases of the simulation and analyze the data this yielded - setup surveys, studio agreements, feedback forms, individual reflections and concluding surveys - based on three core features of situated learning: community of practice, participation and authentic context. Based on this analysis, we conclude that our study confirms the potential of situated learning for STEAM education. Our case study also suggests four guidelines for, as well as one challenge in, the implementation of situated learning in STEAM education. These guidelines and challenge are 1.) to actively facilitate quality feedback between students within a situational simulation; 2.) to promote taking various professional roles within the simulation, 3.) to provide situational-specific scaffolding based on the determination of which skills and information should be offered by tutors and which skills and information students already possess or are best left to develop and find by themselves; and 4.) to gain insight into individual learning goals for the benefit of the cognitive realism of the simulation; while 5.) the absence of real financial or commercial consequences compromises the authenticity of a situational simulation and, consequently, challenges the implementation of situated learning in STEAM education.

Keywords: situated learning, media design education, authentic learning, learning environments, situational simulation

INTRODUCTION

Situated learning has been advocated as a valuable educational approach for STEM education (Asunda, 2014). The approach might arguably also benefit STEAM education, as both STEAM education and situated learning aim to develop skills that can deal with complex real-life situations and collaborative environments (Daugherty, 2013; Guyotte et al., 2015). Similar to educational approaches like constructivism (Kafai, 2006), connectivism (Griffiths and Guile, 2003), problem-based learning (Barrett, 2010) and authentic learning (Roach, 2018), situated learning is focused on providing learning experiences that occur through the social interaction and kinesthetic activity of real-life activities in the context of a prospective practice or related tasks (Northern Illinois University Center for Innovative Teaching and Learning, 2012). STEAM education does not only typically focus on design thinking and fostering imagination and creativity to approach real-world problems in an innovative way (Cruz et al., 2021;

Daugherty, 2013), but can also be characterized as incorporating "studio habits of mind as an experience-based technique for problem solving, learning, investigation, and discovery" (Daugherty, 2013, p.12). Additionally, Guyotte et al. (2015) question the notion of the 'lone artist' working in their studio, stressing the collaborative aspect of STEAM within inter- or transdisciplinary practices. Just as the above-mentioned situated learning approach does, the design challenges that are common within STEAM education aim for the learning of skills by working on real-world problems in a collaborative setting.

Given this kinship between situated learning and STEAM it is surprising that there exists little research on the implementation of the educational approach in STEAM education specifically, while ample research has been conducted into situated learning within higher vocational education in general (see, e.g., Choi and Hannafin, 1995; Herrington and Oliver, 2000; or Shaltry et al., 2013). The domain of media design consists of the creative interdisciplinary practices typical of STEAM, even though it "involves the physical, functional, and operational manifestation of human-factors design" (Garson and Khosrowpour, 2007, p. 661) that are often associated with STEM. Within STEAM, media design is typical for its use of studios as a common organizational form, in which so-called soft skills (i.e., artistic, design, communication and collaborating skills) are just as important as so-called hard skills (i.e., knowledge of hardware and production pipelines) (Vyas et al., 2012). As a result, media design education offers an ideal context to come to a better understanding of how situated learning, i.e., learning by participating in activities that replicate actual work settings (Northern Illinois University Center for Innovative Teaching and Learning, 2012), should be implemented within STEAM education.

Therefore, we formulated the following research question: How could situated learning be implemented within STEAM education? To answer this research question, we conducted a case study in which students were monitored during the setup, working and evaluation phases of a situational simulation in STEAM education and surveyed after completing the simulation to evaluate their experiences.

In the below, we will first briefly discuss how the principles of situated learning relate to STEAM education, before we present our case study in more detail. We will subsequently present our results and discuss them, to then conclude on that discussion by offering guidelines for the implementation of situated learning within STEAM education and identifying a challenge to this implementation.

BACKGROUND

Since researchers have become aware of the limitations of traditional classroom instructions, educational approaches which promote learning that connects to real-life experiences have gained more and more attention. Situated learning is such an approach and is based on the view that "meaningful learning will only take place if it is embedded in the social and physical context within which it will be used" (Herrington and Oliver, 1995, p. 254). According to Donaldson and Barany (2019) situated learning has three core features: communities of practice, participation, and authentic context.

The first core feature of situated learning, *communities of practice,* refers to the sociocultural specificity of a community of practitioners, i.e., groups that form around shared patterns of behavior. In the domain of media design, such shared patterns of behavior can for instance be observed in a design studio: since the work is collaborative in nature, the studio space offers typical ways in which material artefacts, inspiration, storyboards and sketches are shared, as well as in which discussion and critique are facilitated. Communication with clients, including the typical practice of 'pitching' projects to clients, also is a typical facet of design studio practice. Hence, the shared patterns of behavior typical for a community of practice are not only related to 'hard skills' (i.e., technical skills); they also form around 'soft skills' (i.e., the interpersonal skills required to perform a role) that are typical for a practice. To learn the patterns of behavior within a community of design practitioners, learners require access to real-world practices within design studios. This access requires that the school invests in building a network of partners in the field, to ensure a strong connection with the practice (Wesselink et al., 2010).

The second core feature of situated learning, *participation*, refers to if and how students are encouraged to explore which roles or activities inside a community of practice fit their talents and skills best. Within media design schools, students are introduced to the complete process of design, from idea generation and concept to producing a project; but also to specific roles, like being a director, storyboard artist, concept artist or producer. In the practice of media design, it is important to have clear overview of the whole production process, yet it is also common to specialize in a certain area of expertise or in one or more roles within the practice. Therefore, providing experience with these areas of expertise and roles is vital to prepare students for a professional career in media design. Scaffolding may be required to support a learner in the transition from newcomer to full participant through participation in a community (Donaldson and Barany, 2019). Where and when to provide this scaffolding is particularly challenging within situated learning environments, since "any preplanning in this context makes a mockery out of the learning outcomes" (Roach et al., 2018, p. 498). According to Herrington and Oliver (1995), the role of the teacher should be integral in situated learning environments, and the coaching and scaffolding they provide should always be timely and situation-specific.

The third core feature of situated learning is *authentic context*, i.e., "robust, complex, social environments made up of actors, actions, and situations" (Stein, 1998, p. 2). As "learning context and the activities within that context are meaningful [in providing] the opportunities necessary to solve problems practically so they can transfer those competencies to real-world experiences" (DiSchiavi, 2019), authentic contexts may help bridge the gap between (studying in) a school environment and (working in) a real-life practice. Such learning environments should also be *cooperative* in nature, to add to the authenticity of the (learning) environment by enhancing social interaction and enabling learners to build on experiences together (NIU-CITL, 2012).

Typical examples of situated learning experiences usually take place outside of the school environment, i.e., field trips or internships. However, the possibilities to benefit from situated learning principles within the school context, e.g., in the form of educational simulations, have extensively been explored since the 80s (Lunce, 2006; Herrington, 2015; Roach et al., 2018). Within educational simulations, the student buy-in is vital. To achieve this, the cognitive realism of the simulation is more important than its physical realism and the assignments should be of value for the student as much as for the community of practice (Roach et al, 2018).

Because of its open-ended design and the complexity of modelling real-life situations inside a school environment, Lunce (2006) argues that a situational simulation "is the most difficult type of simulation to design and to utilize effectively." Referring to scientific and engineering simulations, designing simulations arguably are particularly complex for simulations that involve computer programming. In the context of media design, creating a realistic framework that does justice to the complexity of real-life practice is arguably even made more difficult by the 'wicked problems' that many such designers work on (Donaldson and Barany, 2019).

The above suggests that four factors need to be taken into account in the implementation of the three core features of situated learning in a school environment: 1.) the implementation requires a strong partner-network that can provide access to a community of practice; 2.) the student collaboration in the (simulated) real-world practice should allow for freedom to explore different roles and identities; 3.) coaches should provide situation-specific scaffolding; and 4.) a high level of cognitive realism can be achieved when the (simulated) assignments are of value to the learner and the community of practice.

In the next section, we will introduce a case study titled *Project Soho* that was conducted to provide more insight into how these four factors influence the implementation of the three features of situated learning in the creative interdisciplinary practices typical of STEAM education.

CASE STUDY: PROJECT SOHO

Every year, students of the Master Animation of the Master Institute of Visual Cultures (MIVC, The Netherlands) participate in a situational simulation called *Project Soho*. In *Project Soho*, groups of students simulate media design studios modelled after the animation studios that are situated in close proximity to each other in the neighborhood of Soho, the bustling creative heart of London. The aim of the simulation is to familiarize students with the hard and soft skills that an animation studio requires and to discover what their preferred role in the creative practice of animation might be. Potential clients in the network of the school are contacted with the request to participate and provide a realistic briefing. Before determining their realistic assignments, clients receive information about the aims of *Project Soho* and what is expected of clients in the process. They are for instance expected to provide a contact person for questions by students and to be available to meet with the students for the brief (setup phase), pitch (working phase) and final presentation (evaluation phase) of the project.

Method

At the start of the simulation, four or five students are grouped together to form a design studio: tutors form groups on the basis of the roles that students prefer and make sure that the soft and hard skills required to operate an animation studio are represented within each group. The studios themselves can still decide on how they will divide the roles per assignment. The studios then start their work on realistic assignments for real clients. Although students do not receive financial compensation for their work, their studios are required to provide clients with a realistic budget for the assignments and discuss these budgets with their clients. The assignments are diverse in the level of creative freedom they allow as well as in their envisioned results: they may range from creating the title sequence for a festival or short (online) idents to celebrate the anniversary of a national film institute, to creating 3D characters for an immersive experience or a commercial to promote a smartphone app. The realistic design briefs describing the assignments are sent to the main contact of each studio in varying intervals throughout the simulation. In response to receiving a briefing, studios can either accept or reject an assignment, based on their studio profile, planning and learning goals.

Scaffolding is provided by tutors on a weekly basis and upon request also by experts in the field. In such scaffolding, tutors and coaches typically discuss aspects and issues related to the organization of their work (e.g., how to streamline the production pipeline) and to the interpretation of roles (e.g., what the tasks and responsibilities of a certain professional role are).

Participants and Duration

The case study involved 22 master students (participants), with backgrounds ranging from communication and media design to graphic design and animation backgrounds. Some of them had more training within the visual arts, like illustration, while others had experience with programming and interaction design. The study was conducted over a period of eight weeks, in which three phases of simulation occurred: setup, working, and evaluation.

Data Collection

During the *setup phase*, a setup survey was distributed amongst the participants to assess their expectations of *Project Soho* for the purpose of our study. The survey also served to make an inventory of their preferences for a professional role within the simulation, the skills and experience they would bring into the studio and their personal learning goals. Participants could opt for multiple roles, since they would work on multiple projects and could redivide roles within each of them. After grouping the students into studios on the basis of this data, each studio was requested to set up an agreement on how they would work together: including a description of the studio's identity and working hours, the frequency of internal meetings, the division of roles within the studio and how potential internal disputes would be settled should they occur. For the purpose of our study, copies of all studio agreements were also collected during the *setup phase*.

In the *working phase* of the simulation, feedback forms were collected that were modeled after the 360 degrees feedback method (Kaya et al., 2016), in which studio members were asked to provide each other with feedback regarding their individual performance within the studio. Participants were asked to fill in these forms once halfway the simulation and once at its end.

In the *evaluation phase*, copies of individual reflections were collected. Participants were asked to reflect on what they learned during the simulation, based on the feedback given in the feedback forms and including any actions that were taken in response. Furthermore, an online concluding survey was held under participants after the simulation finished. This survey provided data on the experiences of participants with the 'community of practice' (questions 1 to 5); of their 'participation' in that community (question 6 and 7); and of the 'authentic context' in which they participated (question 8). Question 1, 2, 5 and 6 were multiple choice questions, while questions 3, 4, 7 and 8 provided open ended questions.

In the next section, we will present the data yielded by our case study and analyze it based on the three core features of situated learning: community of practice, participation and authentic context.

RESULTS & DISCUSSION

During the *setup phase*, 21 participants filled in a setup survey: one participant failed to submit a survey. In the survey, five participants expressed a desire to explore the role of 'producer'. However, the most popular role according to our survey, was that of '(art) director': exploring this role in the simulation was desired by 15 participants. Other roles that were mentioned were 2D animator (twelve times), character designer (eight times), storyboard artist (six times), and 3D animator (four times). Subsequently, tutors compiled five groups of participants to form simulated animation design studios, based on the skills that students indicated they possessed in the survey, by for instance equally dividing 2D and 3D skills over the groups. It is important to note here that more participants expressed a desire to explore the role of director than the number of groups that were formed.

In the *setup phase*, students attended presentations by media design industry professionals, in which they were introduced to the various roles and responsibilities within a media design studio (e.g., storyboard artist, lead animator, technical director, creative director and producer). Afterwards, the groups (studios) were asked to develop their studio identity, work on a studio agreement and provide contact information for clients. This resulted in five studio identities (*Anymate* (five members), *Beehive* (four members), *Mixmax* (four members), *Multiki* (five members) and *MXR* (four members)) and yielded five copies of studio agreements. Each of the five studios were provided with a designated workspace in the school. Based on the studio agreements they developed, studio members both worked at school and from their homes during the *working phase*. During this phase, five client briefings were distributed amongst all five studios. All studios excepted at least three of these assignments. The *working phase* of our study yielded 22 feedback forms.

Finally, the *evaluation phase* yielded 21 individual reflections and 16 concluding surveys.

The next subsections will analyze the setup surveys, studio agreements, feedback forms, individual reflections and concluding surveys based on the three core features of situated learning: community of practice, participation and authentic context.

Community of Practice

In section 2, we introduced the importance of a strong partner-network for access to typical patterns of behavior of a community of practice.

In the concluding survey all of the respondents answered 'yes' to question 1: 'Did project Soho provide you with insights into the practice of animation studios?' Most of them (87.5%) responded positive to question 2: 'Did you learn about typical ways of working and collaborating that take place within such animation studios?' One respondent answered: 'not more than I already knew'. Another respondent was 'not sure'. When asked to mention any 'hard skills' (i.e., technical skills, like using software) that they learned (question 3), nine respondents mentioned specific software (*Toon Boom*, *C4D* and *AE*) and five mentioned folder structure/pipeline organization (i.e., how to organize a production). Storytelling skills were only mentioned once ('how to work with a storyboard and animatic'). When asked about 'soft skills' (question 4), answers ranged from learning about how to pitch and communicate with clients, to more personal skills such as giving feedback and gaining confidence. One respondent said: "I learned more about meetings with clients (debriefing, listening, pitching) and I also learned the importance of good communication within the studio, setting realistic expectations for everyone and how to plan better."

In their individual reflections, three participants explicitly mentioned that they normally work by themselves. Resultantly, the soft skills that are important to collaborate effectively were often mentioned in the individual reflections. A member of *Beehive* for instance wrote: "The period overall demonstrated the value of working as a team to me. I am used to working by myself, but hearing different ideas from other members and combining them into one resulted in concepts that positively surprised me." The lack of experience in working together as a team also shows in the discomfort that participants experienced with respect to providing feedback to fellow members, which eight participants reported in the individual reflections. A member of *Anymate* for instance wrote: "Quite often I felt a bit bad to share an opinion. I was scared to come across pushy and bossy. Now, in the feedback forms, I see everyone appreciated my feedback, on the basis of which I conclude that I did show respect towards them and [giving feedback is part of having] a good conversation about the work." Similarly, a member of *Beehive* mentioned: "We initially experienced uncertainties about the concept and unclarity about who was taking the lead. At this time, I was afraid to say what I was thinking as it could hurt the feelings of other members. Now I would behave differently in that situation."

When asked 'Did the experience provide you with access to the professional field? E.g., did you develop your professional network?' 50% of the respondents answered this question positively. The other 50% were 'not sure' if the course resulted in better access to the professional field and was beneficial to their development of a professional network (question 5). This outcome may have been influenced by the effect that the COVID19-pandemic had on the balance between working on- and offline.

Participation

Besides the importance of a strong partner-network for access to typical patterns of behavior of a community of practice, in section 2, we also introduced the importance of exploring roles and identities for the implementation of participation in a community of practice and emphasized the need for timely and situation-specific scaffolding as part of it.

The individual reflections that our case study yielded in particular demonstrated the value of the exploration of professional roles within the simulations. A member of *Anymate* for instance commented: "Being an art director really opened my eyes. In my mind, the role of art director was so much smaller than I experienced it to be. There is so much one needs to take into account as a director!" Another perspective on the value of the explorations of different roles is expressed by a member of *MXR*: "Because I switched roles, I now understand better what art directors and animators expect from each other."

The individual reflections also showed that the exploration of various roles only confirmed the expectations of some participants, while for others it did the opposite. A member of *MXR* for instance wrote: "I am a natural leader and like to keep an overview of everything, so I was interested in taking up the role of producer. [Project] Soho was perfect for me to try it and I learned that the role indeed suits me." A member of *Beehive* experienced the opposite: "Working on three projects at the same time has taught me that the role of producer is not for me. It has been valuable [to experience this role] nonetheless, as I gained insight into what it means to perform this role."

Besides demonstrating the value of exploring various professional roles within an educational simulation, our data also shows that in the development of professional careers, from novice to expert, it is important that participants learn by doing: by performing a professional role in the context of a (simulated) practice it becomes apparent what is expected from that role without explicit instruction (i.e., situated learning). The concluding survey showed that 93,8 % of the respondents reported a better understanding of the profession: i.e., 'yes' to question 6 'Do you better understand what is expected from a professional in the field of animation after project Soho? For instance, how to communicate, work/produce and apply technical skills.' This is also supported by quotes from the individual reflections. A member of *Mixmax* commented: "I wanted to step out of my comfort zone, so I chose to be the art director […]. This also meant pitching the idea to the client. This was very scary for me, yet in the end I started to like it more and more. I am a generalist and I look at the big picture of how different people and pieces fit together and what my place within that picture is. I noticed that this personality trait really helped me in directing."

At the same time however, the need for scaffolding in exploring professional roles was also expressed in the responses to the question (7) 'Looking back, were there specific moments during Project Soho in which you felt the need for more / better instructions by tutors or experts?' Some needs that were expressed in response to this question are related to planning skills. For instance, two respondents reported a need for more help in planning their work and two participants reported needs related to soft skills, such as giving constructive feedback. Five respondents expressed the need for more support in setting up and running their studios, by providing examples of studio agreements and budgets for instance. Also, seven participants mentioned the need for more clarity on how to engage with clients within the simulation (especially with respect to the financial agreements) and on what would happen with their design output.

Authentic Context

With respect to the authenticity of contexts in situational simulations, in section 2 we argued that a high level of cognitive realism can be achieved when (simulated) assignments are of value to both the learner *as well as* the community of practice as a whole.

The setup survey provided insights into the different roles that participants wanted to perform as part of the simulation, to make sure the roles they would be performing within it would be of value to them. Participants opting for the role of 'producer' were divided over the five studios, but most of the other roles required to complete an assignment were determined by the members when the client brief was received and accepted by the studio. In line with actual professional media design practice, the producer decided which team member was assigned which professional role and in many cases members were asked to fulfill multiple roles. In this sense, the simulation was authentic. However, since 15 participants expressed the desire to perform the role of (art) director, and there were not enough positions for art director available, it was not possible for all of those participants to perform this role. Even so, all participants with a desire to experience this role that could not perform it in the simulation, could perform another role they had expressed an interest in, resulting in the same or a similar value of their participation in the simulation.

The value for the community of practice is embodied in the design outcomes: with the exception of one outcome, all assignments resulted in products of which the client indicated that they could actually use them.

The concluding survey data suggests that a high level of cognitive realism was achieved: 10 out of 16 respondents answered question 8 positively: 'Was project Soho in your opinion authentic to the professional field of animation? I.e., did you experience its (physical) environment/setting, clients (type of clients/ contact with clients), working in team/ collaboration as studio as genuine?

Six out of 16 respondents answered 'almost' to question 8. Although one participant reported a lack of time spent inside the studio workspace ("Due to the pandemic we did not get to experience the [studio] environment that much.") this did not seem to hinder the authenticity of the simulation. As one participant mentioned: "My experience was similar to the real studio experiences that I had before, although those were not in animation. So, in my opinion it was quite realistic […]. Of course, [on the basis of this experience] I still do not know how it is to work in a big studio for a long time."

Four out of the 16 respondents mentioned that working with 'mock' budgets affected the authenticity of the simulation. One respondent for instance mentioned: "It is almost real. But in terms of choosing which client we wanted to work with, we always chose the one we were interested in working with instead of the one who would pay [the most for our work]. If there would have been real money involved, we would have made different choices." The individual reflections also pointed this out: four participants reported to have learned what taking on or declining work means for the income of a studio, but without the pressure of actually having to financially survive as a studio. A member of *MXR* commented: "Another thing I learned is to choose the project wisely and be realistic. For example, a project that pays well or offers a chance to promote the studio often provides lesser creative freedom." This participant also indicated that the studio always opted for projects with the most creative freedom ("passion projects") as this decision would not have any (real) financial or commercial consequences.

CONCLUSIONS

From the findings above, five conclusions can be drawn that answer to our research question: How could situated learning be implemented within STEAM education?

Our first conclusion is that access to a community of practice in a situational simulation should be implemented in STEAM education by actively facilitating quality feedback between students and that clients can play a role in providing insight into behavior typical for their community of practice. The patterns of behavior surrounding feedback between studio members in particular (both how it is received and ought to be processed) are crucial to learn how to become part of the community of practice. Being able to offer and receive quality feedback are vital skills within the media design practice (Evans, 2020; McDonald, 2020). Within our case study, participants mainly learned from each other's feedback. Yet, based on the reported experienced value of such feedback, it might be beneficial to also include client feedback as a way to learn to give or receive quality feedback. Clients should perhaps also be involved in providing access to what is typical behavior with respect to giving and receiving quality feedback.

Secondly, we conclude that the implementation of participation in STEAM education requires that participants can take up various roles within the situational simulation.

Our third conclusion is that the implementation of situated learning in STEAM education requires situation-specific scaffolding, which in turn requires the determination of which skills and information should be offered by tutors and which skills and information students already possess or are best left to develop and find by themselves. Providing scaffolding in the right place at the right time is difficult. Partly, because the needs for scaffolding can differ between students. Although additional scaffolding, such as providing examples of documents like studio agreement and budgets could make for better scaffolding, at least in this particular simulation, adding to the scaffolding always begs the question which skills and knowledge should be offered by tutors and which of them students already possess or best find out for themselves.

Fourthly, we conclude that the level of cognitive realism of a situational simulation in STEAM education may benefit from gaining insight into the individual learning goals of participants.

Finally, our fifth conclusion is that the implementation of authentic contexts in STEAM education may be compromised by the absence of real financial or commercial consequences in situational simulations. 'Mock' budgets may be in the way of making realistic decisions. These insights reveal an important clash between the aim to facilitate a high level of cognitive realism and the practical restrictions of the school context: a situational simulation should provide an authentic context by connecting to real clients, but that authenticity is compromised by the absence of real financial or commercial consequences.

As our case study focused on the creative interdisciplinary aspects of media design practices that are typical of STEAM education, it remains to be seen if these five conclusions also hold for STEM education, with which media design shares "the physical, functional, and operational manifestation of human-factors design" (Garson and Khosrowpour, 2007, p. 661).

Besides confirming the potential of situated learning for STEAM education, these five conclusions to our case study suggest four guidelines to the implementation of situated learning in STEAM education, as well as one challenge. These four guidelines and challenge are to 1.) actively facilitate quality feedback between students within a situational simulation; 2.) promote taking various roles within the simulation; 3.) provide situational-specific scaffolding based on the determination of which skills and information should be offered by tutors and which skills and information students already possess or best develop and find for themselves; and 4.) gain insight into individual learning goals for the benefit of the cognitive realism of the simulation; while 5.) the absence of real financial or commercial consequences may compromise the authenticity of a situational simulation and, consequently, forms a challenge to the implementation of situated learning in STEAM education.

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EUROPEAN JOURNAL OF STEM EDUCATION

European Journal of STEM Education,
2021, 6(1), 18
ISSN: 2468-4368

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Delta Studies: 7 Propositions for Arts/Sciences Education

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Citation: van den Akker, R., Noordegraaf-Eelens, L., van Eekelen, B. F. and Teeuwen, R. (2021). Delta Studies: 7 Propositions for Arts/Sciences Education. *European Journal of STEM Education*, 6(1), 18. https://doi.org/10.20897/ejsteme/11394

Published: December 2, 2021

ABSTRACT

Living in a Delta, amidst water, land and air, means living and engaging with complex concerns. To address these concerns the Rotterdam Arts and Sciences Lab (RASL) has developed an education- and research program for Higher Education in which the (alpha-, beta-, and gamma-) sciences and the arts are combined to engage with with all of the scales, entanglements and complex societal concerns of this Delta-multiple: Delta Studies. Delta Studies can therefore be understood as a companion to the alpha, beta and gamma sciences, as it sets out from and blurs, 'composes' (Latour, 2010) and 'composts' (Haraway, 2016) with, the sciences and the arts. Delta Studies exists through combining and composing with the skills and knowledges of the arts and the sciences as well as the situated knowledges of societal partners. In this manner, it questions existing hierarchies of ways of knowing and making public(s) in order to create new ways to engage with complex concerns and reimagine our collective futures. This article presents the guiding propositions of Delta Studies.

Keywords: Delta Studies, Rotterdam Arts and Sciences Lab, Arts and Sciences Education

'What if we could hear the Higgs boson?'

Eldred, S. (2016). Art–Science Collaborations: Change of perspective. *Nature*, 537, 125-126.

INTRODUCTION: WHAT IF

Living in a Delta, amidst water, land and air, means living and engaging with complex concerns. It means cohabiting with humans, animals, objects, technologies, and infrastructures as well as with their collective histories and, especially, their entangled futures.

On the occasion of the 100th question asked to the Dutch Climate Helpdesk, which is staffed by a group of scientists and answers questions from the general public, one of its initiators, an oceanographer, was invited on national radio. This milestone had been reached in under three months and he illustrated the wide variety of questions he and his colleagues responded to in this period, relating to anything from solar panels and e-bikes to plastic soup and global warming. The relatively high demand for such a thing as the Climate Helpdesk illustrates both the widely shared need to act in response to what is often labelled as the Climate Crisis and the multiple scales, levels and entanglements that constitute the very situation in which we need to respond—that is: be able to respond, be response-able (see Haraway, 1992, 1997, 2016; Despret, 2004, 2016; and Barad, 2007).

Yet our oceanographer—perhaps unwittingly—also illustrated that, while scientific knowledge is a necessary component of being response-able, in itself it is not and cannot be sufficient to imagine modes of existence that enable living and engaging with complex concerns, their collective histories and their entangled futures. Reflecting on a question about the plastic soup in our oceans, which spoke to his own discipline, he gave an academically sound lecture. He connected the plastic in our oceans to the plastic in our backyards, to the fossil fuels that go into producing plastic, to burning fossil fuels in general, to rising CO2 levels, to global warming, to rising sea levels, etc.

What is response-ablity in the face of such a complex societal concern? Where and when is a response enabled? What would be its scope? At a loss, and with a sigh of resignation, our oceanographer asked: '*What if*… what if we could see CO2 as a purple cloud? Perhaps we would do more…'

The Rotterdam Arts and Sciences Lab, a collaboration of Erasmus University Rotterdam, Codarts Rotterdam and the Willem de Kooning Academy/Hogeschool Rotterdam, argues that it is precisely the 'What if...'-questions that can help us overcome the very same resignation experienced by our Oceanographer. For 'What if' is the first proposition of all possible worlds; it is the question that enables a re-imagining of the present and alternative ways of doing, thinking, and making with and beyond the disciplinary practices of the sciences and the arts. In the Dutch language we speak of the alpha-, beta-, and gamma sciences. Over the past few years the *Rotterdam Arts and Sciences Lab* (RASL) has developed an education- and research program for Higher Education in which the (alpha-, beta-, and gamma-) sciences *and* the arts are combined to engage with the Delta multiple, with all of its scales, entanglements and complex societal concerns: Delta Studies. Delta Studies can therefore be understood as a companion to the alpha, beta and gamma sciences, as it sets out from and blurs, 'composes' (Latour, 2010) and 'composts' (Haraway, 2016) with, the sciences and the arts. For us, Delta Studies exists through combining and composing with the skills and knowledges of the arts and the sciences as well as the situated knowledges of societal partners. In this manner, it questions existing hierarchies of ways of knowing and making public(s) in order to create new ways to engage with complex concerns and reimagine our collective futures.

We outline seven propositions for Delta Studies, i.e., an approach towards education (and research) with the sciences and the arts developed in the context of the Rotterdam Arts and Sciences Lab. This approach has emerged from our dual degree programme in which students obtain a degree from an arts institution (the performance arts at Codarts or the visual arts at WdKA) *and* can graduate in a wide variety of academic disciplines at Erasmus University Rotterdam (Arts and Culture Studies and the Humanities, Social and Behavioral Sciences and Economics and Busines, as well as Life Sciences). Whereas students follow parallel tracks in the dual degree programme, we developed, too, the Minor *Re-Imagining Tomorrow through the Arts and Sciences* (30 EC) (De Groot, 2020) and various extra-curricular Studios in which students and particpants with disciplinary backgrounds in the arts and/or sciences can collaborate and compose together with societal partners in order to engage with complex societal concerns. The Minor was recently awarded the first Dutch Education Premium ('Nederlandse Onderwijspremie') by the Dutch Ministry of Education.[1] Currently, we are designing a transdisciplinary Bachelor- and Master Programme and setting up a transdisciplinary research programme. Rooted in Science and Technology Studies and New Materialist thought, these seven propositions are our points of departure when it comes to *doing* education and research with, and beyond, the arts and sciences.

DELTA STUDIES IS SITUATED AS A DELTA

A delta is as much comprised of land, water, and air as it consists of the entanglements between human and non-human creatures, subjects and objects, techniques and technologies, infrastructures and circulations across various scales. Delta *is* scale; and like all scales, the Delta is imagined and requires (imaginative) work (Tsing, 2000). Therefore, scaling the delta is a verb. The delta does not stop at man-made boundaries (nation-states, provinces, water/land distinctions). Delta Studies incorporates their making and their effects in its enquiries. The Mannheim convention (1858) for instance enables the life, traffic and trade along the Rhine. In Delta Studies, the boundaries between water, land, and air dissolve. The delta is a delta because of its entangled becomings.

Methodologically, we approach the delta intentionally as localized and local—it is comprised of cables, electricity, fishery, windmills, roads, waterways, neighborhoods and social institutions. But "local" means it is also always already tied up with hinterlands and with specific international flows, such as outsourced labor and containers that come and go (and some that stay as student housing). Delta Studies also connects to other deltas, and actively fosters exchanges with other delta areas.

[1] https://www.rijksoverheid.nl/actueel/nieuws/2021/01/14/eerste-nederlandse-hogeronderwijspremie-voor-zes-onderwijsteams.

Time-wise, Delta Studies takes a long view. A delta concern cannot be solved in 100 days (a design challenge) or 2-4 years (a standard period for research projects). Delta Studies dares us to ask for longitudinal studies that don't follow education and funding rhythms. A delta concern, moreover, has its own rhythms, and these rhythms are part of what needs to be investigated. Living in a delta means cohabiting with humans, animals, objects, technologies, and infrastructures, each with its own (known and unknown) histories and possible futures. Since we are in it for the long run, Delta Studies engages and seeks to create room for the unknown, disturbances, indeterminacies, failures, and changing visions. Multiple futures are in fact made and imagined in the Delta. Delta Studies examines what histories of the future the Delta has already metabolized (e.g., Maasvlaktes, Rhine futures), while defuturing (taking away futures of humans and non-humans) takes place on a large scale.

The Delta may be thought of as layered (loosely following the Annales school), but we don't work in the layers but through the layers. We look for instance at how infrastructures change culture, and how culture reworks infrastructures. Deltas are sustained by multiple entanglements and enfold many circulations across scales – from the local to the planetary. Deltas are always already multiple.

DELTA STUDIES ENGAGES WITH COMPLEX CONCERNS

The Delta is a living system. Students and researchers can learn to design with the tide while engaging with complex societal concerns. Complex societal concerns are not problems to be solved, fixed or tackled in the short term. They are are societal issues that impact us (in the broadest possible sense), while bringing together human- and non-human creatures, living things and '(hyper-)objects', like class or climate (Morton, 2013), in an entangled, multi-layered manner and across times, spaces and scales. Such concerns are too complicated to handle as a problem and to be 'tackled' with solutionism – so, instead, we *engage* ourselves with it, by e.g., working on fostering long-term coalitions. In this manner, Delta Studies moves back and forth between 'matters of fact' (decontextualized scientific findings) and 'matters of concern' (the complex networks that make and sustain something or someone in its particular situatedness) (Latour, 2004; but see also Barad, 2007, 2010, 2015; Haraway 1992, 1997, 2016; Blaise et al., 2017). This is not to say 'everything [is] connected, without adequately addressing the complex structure of connectivity' (de Frietas, 2016, p.2, as cited in Blaise et al., 2017). The Delta Studies approach takes the ontological irreduceability of a complex concern as a starting point, yet demands epistemological reduction, while mapping the relations, connections, links, threads, ties, etc. of a *specific* issue (see also Latour, 1993, p.158). 'Why? Because to explain is to reduce' (Bryant, 2013).

While mapping the concern, we assemble coalitions with relevant knowledge, imagination, expertise, and skills. We ask ourselves, for which lines of inquiry do we need others? And, how can we reciprocally be of benefit to one another? The goal is not to create scalable one-size-fits all solutions. Some concerns need to be on the agenda for a longer period than design challenges or research grants allow for. Some concerns are too complicated to handle as a problem and be 'tackled' with solutionism – so, instead, we *engage* ourselves with it, by e.g., working on fostering long-term coalitions. Delta Studies makes students – artists, scientists – astute problem (re-)framers, and capable of identifying and exploring different presents and alternative futures with and through situation-specific compositions.

DELTA STUDIES IS PREMISED ON EQUALITY OF KNOWLEDGES

The premise of Delta Studies is that compositions of artists, scientists, and societal actors can only work when the composing itself takes place without hierarchies across its components. It is important to avoid that one discipline orders or structures the other components and therefore reduces *a priori* the complexity and outcome of the composition. To engage with complex societal concerns we need a multisensory approach and an equality of knowledges.

This equality of knowledges is an ongoing practice, something to strife for, and most surely not a given. It needs constant work and reflection, and hence adaptation. In her outline of the 'provisional pedagogies' that inform the education in the RASL Minor *Re-Imagining Tomorrow through the Arts and Sciences*, Tamara de Groot (2020) writes (and its worth citing her at length):

> To enable this, we make explicit and work with the frictions, conflicts and paradoxes inherent to transdisciplinary practice across and beyond the arts and sciences. These tensions emerge as a result from the coming together of people with different disciplinary backgrounds, world views, ways of knowing, dispositions and practices. In so doing we aim not to gloss over such differences and tensions, but to make them productive. While there are differences between participating members in any collaborative setting, in transdisciplinary collaborations the acknowledgement of, and working with

> difference is essential because it makes visible disciplinary logics and paradigms. Difference in transdisciplinary collaboration manifests itself in zones of tension, where discipline-informed ways of doing clash with each other and with certain core aspects of transdisciplinary practice.

These 'zones of tension', she argues, arise not simply from collaborating between and across different disciplines. They arise because, in a situation where the equality of knowledges is presumed, teachers and students (1) are 'challenged to not only "bring in" knowledges and practices, but to critically reflect on the knowledges and practices they are already working in (and which they might not be very aware of)' and (2) they need to cultivate an 'attitude of attention and curiosity with regards to other ways of knowing and acting' (De Groot, 2020).

DELTA STUDIES REIMAGINES TOMORROW THROUGH COMPOSITIONS

Engaging with complex concerns requires situation-specific compositions of, and composing with, artists, scientists, and societal partners. Arts, sciences, society. Each territory comes with its own form of knowledge production (epistemologies), way of speaking (languages), and modes of making publics (valorisation). Each territory comes, in sum, with its own dominant logics. Such logics are not encompassing all practices in these territories, but rather are the dominant modes of engaging with the world. Within its zones of tension, RASL brings together these three logics; three logics that each are necessary to formulate a response to complex concerns, but that—each on their own, individually—are not sufficiently able to do so:

- The 'what is'-logic of the sciences through which objective truth claims are constructed and facts are assembled (Latour and Woolgar, 1986);
- The 'as if'-logic of the arts, and especially contemporary arts (Vermeulen and Van den Akker, 2010, 2015), through which speculative embodied knowledges, involving all the senses, are developed;
- The 'if, then'-logic of current risk societies (Beck, 1992), in which future risks are managed through protocols, scenarios, algorithms, war games, and dilemmas: IF [Event], THEN [Consequences].

By bringing the distinctive logics of these realms together in a composition of equals, we can mobilise transdisciplinary ways of doing and thinking (while preventing evermore disciplinary ways of acting in, and seeing, the world). For we contend that it is only through composing with scientific-, artistic- and situated (of societal partners and students with diverse backgrounds) societal knowledges, imaginations, skills, and expertise that we can enable transformative response-ability, enable Δ. Delta Studies bring together these three different ways of thinking and doing, making, creating, performing, seeing and feeling, unpacking and interpreting, speculating and representing so as to be able to pose "What if"-questions. Such questions re-imagine the present in order to make public(s) for future modes of being, for alternative tomorrows.

DELTA STUDIES AIMS FOR TRANSFORMATIVE RESPONSE-ABILITY

Delta Studies makes explicit and works with and through the frictions, conflicts and paradoxes inherent to (transdisciplinary) practices across and beyond the arts and sciences. Tensions emerge as a result of the coming together of different disciplinary paradigms, world views, ways of knowing, dispositions and practices. Yet Delta Studies does not gloss over these zones of tensions. It 'stays with the trouble' (Haraway, 2016). It responds to them by making them productive in the process of becoming response-able—that is: discovering what it is that one can and cannot contribute while composing for societal transformation (Haraway, 1992, 1997, 2016; Despret, 2004, 2016; Barad, 2007)

In their insightful article 'Towards a Response-able Pedagogy Across Higher Education Institutions in Post-Apartheid South Africa: An Ethico-Political Analysis', Bozalek and Zembylas (2017) rightly argue:

> Response-able pedagogies are also ethico-political practices which incorporate a relational ontology into teaching and learning activities and thus extend their transformative potential. In other words, response-able pedagogies constitute relational processes through which social, political, and material entanglements in higher education (i.e., students, facilitators, discourses, texts, performances, drawings, face-to-face and online comings-together) are rendered capable through each other to bring about social transformation. […] The turn to matter within new materialist thought foregrounds the productive qualities of the co-implication of bodies, power, ethics and subjectivities within pedagogical processes. Bodies, power and subjectivities, of course, have been explored previously in education research (e.g., see Youdell 2006), however, the conceptual shift of new materialism that is pedagogically significant is the incorporation of a relational ontology where bodies and matter are entangled and are endowed with

agency and complexity and resist being posited as inferior to language or discourse (Hickey-Moody, Palmer and Sayers 2016).

In Delta Studies, transdisciplinary compositions (i.e., 'entanglements of bodies and matter') collaboratively compose for social transformation. This implies agency. The key questions, however, which one is forced to answer when living and working in deltas, always pertain to scale and scope. This requires constant reflexivity, constant scaling and scoping: Where do we compose? And with whom and for whom? Do we do difference? Do we make difference? Do we add matter? Do we matter?

DELTA STUDIES DOES NOT MAKE A DIVISION BETWEEN EDUCATION AND RESEARCH

Delta Studies does not separate learning from knowing; education is research and research is education. Academics, artists, students and staff involved in Delta Studies act as researchers together, compose together.

In this context, 'staying with the trouble' (Haraway, 2016) also requires a focus, and reflection, on the very process of composing within zones of tension (De Groot, 2020). On a meta-level, education therefore is considered to be a complex concern within Delta Studies. It is object of study itself. Students and lecturers are repositioned towards one another in a composition—and this process requires that particpants stay with trouble, explore the zones of tension, and adapt their pedagogies (hence: provisional pedagogies) on the go.

In more traditional higher education settings, research and education are related but separate activities. They are separated by their actions (what is done) and by the publics that are formed and addressed (who is involved and communicated to). Higher Education workers address and are assessed by students in an education context and address and are judged by peers within research environments. Teachers are experts that transfer knowledge and skills. During their trajectory through Higher Education, students get more and more involved in (scientific or artistic) research as they increasingly master the skills of their expert teachers. Education and research are, in other words, based on the 'master-apprentice' relationship.

Within Delta Studies, the relationship between student and teacher can be described as co-researchers and, on a meta-level, this relationship is in itself subject of research. In this manner, research and education are not only intertwined, but also co-constitutive of each other. In this 'education as research'-model, students and lecturers set out from a concern within the environment of the former (so the issue is not given by the latter), a concern the student wants to be able to respond to. This repositions the student-lecturer relationship, since the expertise of the lecturer is necessary (in terms of process), but, in all likelihood, not sufficient (in terms of content). So, the teacher becomes a participant, too, in the research. Then, the mapping of entanglements results in a need to mobilise, and collaborate with, other forms of knowledges, skills, expertise, and imaginations. This repositions the student away from individual response-ability towards collective response-ability, in a transformative composition. Education becomes research in reciprocity. In this manner, response-ability implies the shift in education from the individual and the matter of fact (to be transferred from lecturer to student) to teamwork and matter of concern (to be discovered by co-researchers).[2] Education is not the place where knowledge is transferred, it is the place where 'what if'-questions are formulated, knowledges are created, and response-ability is composed.

DELTA STUDIES REIMAGINES MAKING PUBLIC(S)

Delta Studies reimagines making publics by avoiding extractive approaches to research, teaching and learning. By composing inclusive and equitable processes, Delta Studies does not draw a line between academics, artists and their publics. It does not identify publics as 'stakeholders', but as participants with relevant situated knowledges, skills, and expertise that can contribute to 'composing' (Latour, 2010) and 'composting' (Haraway, 2016) transformative compositions.

Delta Studies reimagines making public, too. Its transformative compositions can be valorised in as many ways as there are situations (and situation- specific needs, possibilities and limitations); its 'output' can have many different manifestations (practico-material, sensorial, aesthetic, scientific, etc.) and forms (interventions, contributions, publications, performances, gatherings, etc.) – as long as making public makes publics, response-ability, and Δ.

[2] This evidently results in forms of assessment that move away from individual assessment (but this is a topic for another article).

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European Journal of STEM Education,
2021, 6(1), 19
ISSN: 2468-4368

Uncertain Matters: Material to Form Curricula for Digital Design and Fabrication

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Citation: Knochel A. D. and Meeken L. (2021). Uncertain Matters: Material to Form Curricula for Digital Design and Fabrication. *European Journal of STEM Education*, 6(1), 19. https://doi.org/10.20897/ejsteme/11530

Published: January 11, 2022

ABSTRACT

We review the development of a mobile makerspace platform focused on digital fabrication in particular additive manufacturing (AM) or what is more commonly referred to as 3D printing. We engage in a reflexive analysis of our curriculum development as a part of the iterative process of this design-based research project. We review the component parts of our Material to Form curriculum, reflecting on the events of the makerspace platform as they symbiotically informed and catalyzed the iterative development of the curricular component. Our analysis is focused on thematic curricular ideas stemming from the uncertain material and disciplinary possibilities of digital fabrication. Our reflexive method draws from our own identity as arts education researchers working within STEAM frameworks to analyze researcher-participant knowledge of the mobile makerspace events. We also draw upon a mixed method dataset that offers insight into participant engagement to better understand iterative development of curriculum. In our analysis of this curriculum development, we highlight both implications for engaging interdisciplinarity and connecting across disciplines through culturally responsive teaching. The outcome is a unit of curriculum for using digital fabrication in classrooms that offers theoretical and practical considerations concerning design thinking and digital fabrication for STEAM practitioners.

Keywords: STEAM, making, makerspace, digital fabrication, kinaesthetic learning

INTRODUCTION

Digital design and fabrication create opportunities for new material expression and design innovation for artists and engineers alike. Combining the excitement from the maker movement and the novel creation of deployable makerspaces, we review the development of the Mobile Atelier for Kinaesthetic Education (MAKE) 3D and the Material to Form curriculum resource[1]. MAKE 3D is a mobile makerspace platform that can be deployed anywhere there is electricity to create a curricular spectacle of digital fabrication, in particular additive manufacturing (AM) or what is more commonly referred to as 3D printing. Curricular spectacle is any pedagogical approach involving activities, resources, and instruction common to curricular endeavors that maximizes visibility through highly innovative approaches and nuanced presentations of content (Sinha et al., 2020). Our interdisciplinary design-based research project combines this notion of curricular spectacle and a mobile makerspace platform to develop

[1] The Material to Form curricular resource can be downloaded for free at https://sites.psu.edu/mobilemakerspace/make-with-us/

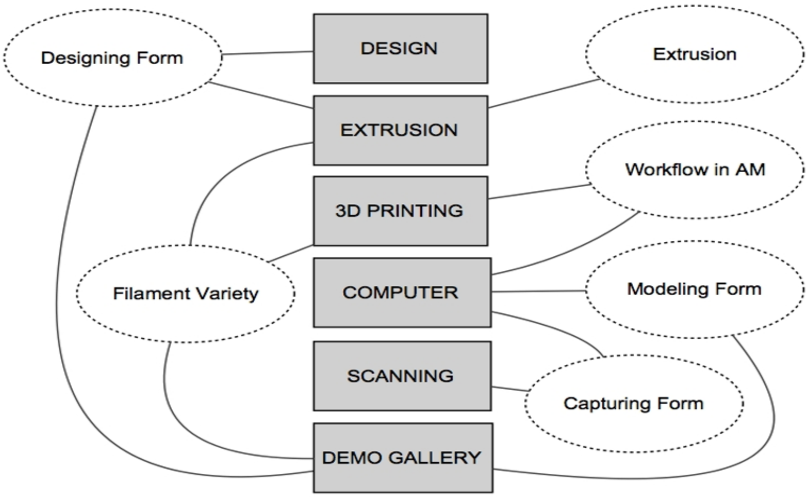

Figure 1. A diagram that connects the physical mobile stations that were housed in the MAKE 3D trailer (gray boxes) and the curriculum modules that utilized the activities at these stations (dotted line ovals)

strategies for how to meet the novice user almost anywhere and entice them into a series of hands-on activities providing a range of knowledge and aptitude for additive techniques in digital fabrication.

In the following, we engage in a reflexive analysis of our curriculum development as a part of the iterative process of this design-based research project (Barab and Squire, 2004; Design Based Research Collective, 2003). We review the component parts of our Material to Form curriculum exploring thematic connections between the maker movement, art education and arts-integrated approaches to curriculum such as science, technology, engineering, art, and math (STEAM) initiatives. Our review includes reflecting on the events of the MAKE 3D platform as they symbiotically informed and catalyzed the iterative development of the curricular component. The purpose of our analysis is to share and discuss the development of a free online instructional resource developed as part of a research study involving a mobile makerspace that introduces digital design and fabrication for interdisciplinary contexts of learning. Our analysis is focused on thematic curricular ideas that came from iteration and an exploration of the uncertain material and disciplinary possibilities of digital fabrication. Our reflexive method draws from our own identity as arts education researchers working within STEAM frameworks to analyze researcher-participant knowledge of the MAKE 3D events. We also draw upon a mixed method dataset that offers insight into participant engagement to better understand iterative development of curriculum. The outcome is a unit of curriculum for using digital fabrication in classrooms that offers theoretical and practical considerations concerning design thinking and digital fabrication to meaningfully inform an interdisciplinary teaching resource designed for STEAM practitioners.

Overview of the MAKE3D Project and Material to Form Curriculum

As a part of our funded research (NSF award #1623494), the research team of MAKE 3D developed a deployable makerspace exploring interdisciplinary making with a particular emphasis on 3D printing technologies. The focus on additive forms of digital fabrication, specifically 3D printing that uses fuse deposition modeling, came about due to its centrality within the research interests of the core research faculty involved in the project. Three core faculty comprised the research team including: Aaron D. Knochel, the principal investigator, an Associate Professor of Art Education whose research included a focus on makerspaces, informal learning, and digital fabrication; Tom Lauerman an Assistant Professor in the School of Visual Arts in sculpture and ceramics whose work in digital fabrication includes designing his own paste extrusion 3D printer that uses clay; and Nicolas Meisel, an Assistant Professor of Engineering in the School of Engineering Design, Technology and Professional Programs with a focus on engineering design and additive manufacturing. The team shared an interdisciplinary approach to design thinking and material science that inspired a curricular approach incorporating a comprehensive spectrum of concepts that we call the Material to Form curriculum. The Material to Form curriculum is structured in six modules. Initially these modules were organized in the following: Designing Form, Modeling Form, Capturing Form, Extrusion, Workflow in Additive Manufacturing (AM), and Filament Variety. The Material to Form curriculum and the MAKE 3D stations were co-constructed symbiotically to maximize informal learning in a deployable makerspace platform (**Figure 1**).

The essence of a mobile makerspace lies in its nature of being accessible, both physically and intellectually (Moorefield-Lang, 2015). The entirety of the deployable MAKE 3D platform is contained within a trailer and different equipment, consumables, and support systems necessary to operate the makerspace were custom designed for mobile deployment. When the MAKE 3D trailer arrives at the desired location, all contents can be

Figure 2. An example of the flexibility of the mobile makerspace installation. We were able to set up in this courtyard using an electrical outlet on a streetlamp post

deployed in a flexible configuration allowing the learning space to cater to the needs of the students and environment (**Figure 2**).

The curriculum for MAKE 3D was developed with the intention of introducing 3D printing in a makerspace platform to evaluate informal learning events. The curriculum was originally conceived as a project with a clear start-to-finish trajectory. However, given the nature of the makerspace as an informal learning space for voluntary learners and the project's mobile platform, it became apparent that the materials and curriculum would need to be accessible from multiple entry points allowing a range of durations of engagement. As such, each learning module required flexibility to address varying expertise, learning styles, time constraints, and levels of interest. Throughout the development of the MAKE 3D project, the Material to Form curriculum has gone through multiple iterations informed by ongoing pilot studies and changing membership within the research team (Jordan et al., 2020; Sinha et al., 2017).

The structure of the curriculum utilizes a backward design approach inspired by the Understanding by Design (UbD) framework (Wiggins and McTighe, 2011). UbD approaches the curricular process first by identifying desired results, that then determine assessment evidence, leading to planning the learning experiences and instruction. Each Material to Form module is organized around this framework by providing module goals, essential questions, and meaning and acquisition statements of learning objectives; followed by formative and summative assessment standards that are based upon the National Core Arts Standards (National Core Arts Standards State Education Agency Directors of Arts Education, 2014); and then a suggested learning activity which includes a material list, key terms, and proposed project. Modules also include additional teaching resources providing case studies and instructional resources in the form of hand-outs and graphic organizers that can be used to assist in guided instruction. Case studies focus on a particular artist or group, offer examples of their work, provide a project description, reflection questions, and references that lead to further resources. As a design-based research project, the research team focused contextual and formative analyses to iterate both the MAKE 3D platform and the Material to Form curriculum throughout the project duration. These modules and the MAKE 3D events that influenced their development will be discussed in more detail in the following.

Designing form

Designing Form focuses on creative prototyping based on the process of design thinking (Doorley et al., 2018; IDEO, 2012). The conceptual foundation for this module is based on the understanding that design is an iterative process, which is cyclical and manifests through multiple modalities of problem posing and solving. Although there are many manifestations of design thinking stages and it has encountered various critiques as a potentially meaningless umbrella term or management fad (Micheli et al., 2019), we focus on its iterative nature and cyclical orientation organized around stages generally identified as: empathize, define, ideate, prototype, test, and implement.

To support participant engagement within this station, nontechnical materials such as cardboard, scissors, and tape are provided for the prototyping process. Printed support materials that indicate the stages of design thinking are also on offer. Facilitating the Designing Form station in MAKE 3D events, it was clear that student engagement was uneven. Due to the open-ended nature of the station, there was little to engage students within a set of challenges or parameters that often motivate problem posing within design thinking initial stages of empathize, define, and ideate. Instead, the station became an entry way to engage with materials through forms of sculptural doodling: a playful practice of manipulating 3D materials without defined purpose that takes on emergent intention. Students would utilize this space to socialize and become more comfortable within the makerspace. After some time, this may or may not have led to experimentation with other stations. The low technical barriers also may have influenced why students chose to start or remain at the Designing Form station.

The written curriculum reflects our experiences with the Designing Form station within MAKE 3D events in that essential questions and the activity are focused on iterative design processes, understanding stages within the design thinking framework, and finding problems through play, free association, and personal interest. The two case studies also reflect some of these foci, but in reviewing all case studies one could easily rearrange certain cases as they exemplify multiple concepts within the curriculum. The first case, Rebecca Strzelec is an artist, designer, and educator whose practice includes the creation of wearable art objects created using computer-aided design (CAD) programs and 3D printing. Rebecca's work combines utilitarian, political, and whimsical themes exemplifying how everyday life can impact product design in unexpected ways. The second case, artist Jonathan Keep works in synthesizing traditional techniques in ceramics with digital fabrication processes. Keep's works are often inspired by patterns and forms from the environment such as icebergs or petrified wood, and his practice reflects upon the aesthetics of the natural world while simultaneously experimenting with process and materiality (Han, 2014). His iterative form creation utilizing parametric design and 3D printing in clay highlights the cyclical nature of design thinking and prototyping processes and is key to why he is included in the Designing Form module.

Modeling form

This module focuses on CAD 3D modeling, available through programs such as Fusion 360 (https://www.autodesk.com/), Tinkercad (https://www.tinkercad.com/), and SketchUp (http://www.sketchup.com/), as an important part of digital fabrication. Understanding and utilizing software resources are often the most intensive aspects of learning to use digital fabrication tools. Like graphic design and 2D printing, the printing process requires an understanding of the basics of the printer and materials that allow it to function, but ultimately it is the use of software to create that differentiates the outcome. Understanding the basics of 3D printing file types and material properties are important, but the ability for software to push the modeling process into formations that are impossible to achieve through handwork are what drives design innovation in this space. An extreme example of this is the innovation taking place in automation and prototyping where artificial intelligence and generative 3D modeling are pushing boundaries of CAD to maximize parametric design possibilities and increase predictive capabilities.

The MAKE 3D platform was always a project space that focused on the novice, introducing additive processes such as 3D printing through short, accessible, high-impact engagements. We knew from the beginning that our mobile platform and emphasis on curricular spectacle would be best applied to opening learners' interests in these technologies and our emphasis was on giving them enough exposure to entice their further exploration. For these reasons, Tinkercad was ultimately chosen for the makerspace because it is free to the public and can be learned quickly. Modeling Form relied heavily on the computer station that was in the MAKE 3D platform, which hosted six desktop computers and several small posters that prompted learners to get started in Tinkercad. Research assistants were also stationed nearby as there was constant need to monitor internet connections and answer questions. The Modeling Form module was setup along with the Workflow module as a grouped station since both required a computer for modeling activities.

The written curriculum extended the in-person events by not only focusing on modes of CAD, but also by providing information and processes that introduced modes of remix into learners' modeling repertoire. In this module, students explore using Tinkercad to both build new digital forms and to employ strategies of remixing pre-existing digital models to create new objects. The role of remix was never a part of the conversation or support material developed for MAKE 3D events, but it became clear that learners were familiar with navigating creative communities online where sharing projects and modifying other users' works is the norm: examples include code blocks in Scratch, fan art in DeviantArt, and 3D models in Thingiverse. Therefore, the curriculum extends focus of CAD modeling to also learn how appropriation and remix as creative strategies can play a part in 3D modeling. The first case study in this module focuses on artist Matthew Plummer-Fernandez's "artbot," developed in collaboration with Julien Deswoef, called Shiv Integer (Hern, 2016). Shiv lnteger randomly selects objects licensed for remixing on Thingiverse before assembling them into dysfunctional sculptures and uploading them once more onto the Internet as new designs (Newitz, 2016). The second case study focuses on developments in parametric design presenting researchers Eduardo Castro e Costa and Jose Duarte's project in mass customization of ceramic tableware using the program Grasshopper (Castro e Costa and Duarte, 2013). The objective of their project is to grant potential designers, businesses, and customers the opportunity to design and model custom products according to their practical needs and personal preferences.

Capturing form

Like Modeling Form, the scanning equipment provided in the Capturing Form module offers participants the opportunity to develop 3D models but using a very different approach through digital scanning. Initially, the MAKE 3D platform employed two 3D scanning set ups: An Occipital Structure Sensor mounted on a mini iPad and a Microsoft Kinect with Skanect software. Over the course of the events, the Occipital Structure Sensor proved to be more user friendly and intuitive for learners in the space. The hands-on engagement introduced participants to 3D scanning, but what was most exciting about the station was the high level of peer-to-peer interaction that the station inspired. Scanning usually involved two or more people as participants scanned each other, making scanning an inherently collaborative event. While both Modeling Form and Capturing Form required research assistant support, at the Capturing Form station there was usually a demo given periodically and then learners would pass on instruction to one another. By contrast, learners at the 3D modeling station tended to be more isolated while using the desktop computers.

The Capturing Form module in the written curriculum extends the possible tools at play by highlighting free-to-use apps that can run on iOS or Android smartphones. The research team was aware that equipment like the Occipital Structure Sensor or Kinect are not cheap or widely available, so the curriculum tries to expand access via the use of applications that employ photogrammetry. Remix is also discussed in this module introducing the idea of scanning the world around you as a course for creative modeling and design evolution. This brings into effect some dramatic outcomes that are highlighted by the case studies in considering acts of 3D modeling as appropriation and body customization. In the first case, Morehshin Allahyari's work Material Speculation: ISIS probes the illusory condition of the recurring copy that challenges concepts of memory, the past, and loss through historically significant sculpture (Karimi and Rabbat, 2016). Allahyari's work explores the complexity of cyber archeology and cultural appropriation through digital scanning, open source culture, and postcolonial theory. The second case focuses on BOOMcast as an example of how digital scanning and 3D printing can be used for customized medical applications. BOOMcast was initially created as a customized cast by Studio Fathom for T.V. personality Mike North of Prototype This! and Outrageous Acts of Science (Holterman, 2015). Despite the BOOMcast being a one-off project, it points to directions other innovators may take 3D printing and scanning to better serve the medical needs of individual bodies.

Extrusion

The Extrusion module and contributing stations within the MAKE 3D platform was another landing area for many participants as they entered the MAKE 3D environment, but one that was much more focused on material play without the underlying concept schema of design thinking present in the Designing Form station. Material extrusion systems in the form of 3D pens and handheld clay extrusion tools were leveraged alongside 3D printers using both clay and plastic filament. These materials and processes highlight additive processes of fabrication both from a computer-aided and hand-building perspective to allow participants to reflect on the complexities of design choices to the capabilities of the manufacturing system.

Within MAKE 3D events, the Extrusion module and the Filament Variety module were often set up together on a table along with the 3D pens and clay extruders. The 3D pens are simple devices that mimic the function of a 3D printer head by heating the filament at the point of contact while also feeding the filament through an extruding nozzle very similar to a glue gun. The 3D pens are good for demonstrating various filament properties, such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), but also provide an acute contrast to the precision of computer-aided fabrication that you would get from a 3D printer. Due to the varieties of material play and the contrast of low-tech and high-tech fabrication, this station was always lively and full of engaged students exploring material possibilities, mixing media, and generally keeping hands busy.

The Extrusion module in the written curriculum reflects these modalities of compare-and-contrast material exploration that was activated in MAKE 3D events. Essential questions and lesson content focus on analytic and creative processes where materials and processes are explored, tested for limits, and evaluated for their prospective applications. The first case study focuses on Tom Lauerman, a core faculty member of the research team, whose practice integrates traditional techniques such as sculpture, craft, and design, along with contemporary digital processes that aid creative ways of working (Lauerman, n.d.). Beginning in the Fall of 2015, Lauerman became interested in developing and exploring extrusion-based processes for 3-D printing in clay, and his innovations in the field include his progressive development of a dual-color clay 3D printer (Lauerman, 2019). The second case study, unusual in that it focuses on a project as opposed to an individual or group, provided information about filament making itself and its relationship with plastic waste cycles through the Felfil. The Felfil is an open-source desktop filament extruder that makes custom filament from recycled plastic pellets and failed print material (Nelli, 2016). The Felfil project focuses on open-source solutions for recovering and repurposing plastic waste to reduce its environmental impact. Both cases highlight the additive process as independent of the actual material used, but also ask learners to reflect on the implications of their material choices from a design perspective and as part of a material life cycle.

Workflow in AM>>>Process

The Workflow module originally focused on the preparation of 3D prints from importing the STL file to exporting the 3D print-ready file. Vocabulary and essential questions were focused narrowly on print preparation by reviewing the different parameters in the slicing software (*Cura*) that can be varied to create the desired output. Setting these parameters requires consideration of aspects such as designating support material, infill densities, layer thicknesses and object orientation to the print bed.

While this information is important to understanding the design and print aspects of 3D printing, ultimately the MAKE 3D events were not well suited for engaging learners in this production cycle. 3D printing is slow, so to take a participant from idea, to design, to print would take at a minimum several hours. The duration of our events averaged 2-4 hours, and individual participation averaged about an hour. These averages indicate that participants rarely experienced a full prototyping cycle. In actuality, the 3D printers functioning in the space were more for proof of concept as opposed to providing a production environment.

Renamed in the written Material to Form curriculum, the Process module focuses mostly on the design and print workflow, but also expands to examine the notion of process itself in creative practice. In this way, the preparation process becomes a location for experimentation and emergence even while negotiating fixed technical parameters that need to be understood to successfully 3D print. Again, the case study gives some insight into this expanded sense of process. The case study highlights the work of Sophie Kahn, a visual artist whose creative practice plays with digital fabrication processes, misusing advanced 3D laser scanners with the goal of generating glitchy outcomes. Kahn then prints the resulting defective files of failed 3D scans as sculptures.

Filament variety>>>Material variety

Finally, while not a formal curricular module, a Demonstration Gallery (see **Figure 3**) was conceived to add a collection of 3D printed items that would allow participants to see a wide variety of materials and objects constructed through additive processes. The gallery provides a curated collection of engineering and art objects in a range of printed materials that are meant to illustrate the wide variety of potential in 3D printing capabilities.

Originally called the Filament Variety module and later modified to the Material Variety module, the written curriculum reflects a wide array of additive processes, most not represented in the MAKE 3D platform. Due to issues of safety and cost, MAKE 3D presented fuse deposition and paste extrusion 3D printers. Other processes such as selective laser sintering and stereolithography are in the curriculum to present the full array of what is possible. The case study for this section focuses on Alex LeRoux, an engineer and designer who developed a 3D printer known as the Vesta that uses concrete. Le Roux successfully printed what is believed to be America's first livable 3-D-printed shelter (Scott, 2016).

Iterating Curricular Form and Modularity

Over the course of the development of the MAKE 3D curricular resources, we drew upon several conceptual frameworks informed by design thinking (Doorley et al., 2018; IDEO, 2012) and the process-oriented constructionism of Seymour Papert (Harel and Papert, 1991). The later development of the expanded mods drew from the art education concept of transdisciplinary 'big ideas' as conceptualized by Walker (2001) and subsequently elaborated upon by scholars including Bautista et al. (2016), Buffington (2007), and Parsons (2004). In this section,

Figure 3. The Demonstration Gallery at a MAKE 3D event

we will summarize the evolving forms the Material to Form curriculum has taken, the conceptual framings that shaped those forms, and their affordances and constraints.

The six modules of the Material to Form curriculum (Designing Form, Modeling Form, Capturing Form, Extrusion, Process, and Material Variety) are centered on material processes in 3D printing. In addition to its process-oriented framework, design thinking also places an emphasis on naming and solving problems (Schön, 1983), and visualizing and materializing potential solutions to them (DiSalvo and Lukens, 2009; Ejsing-Duun and Skovbjerg, 2019). By emphasizing experimentation with 3D printing, the Material to Form modules aimed to foster student capacity for materialization of solutions to challenging problems.

Reflecting on the conceptual strengths of the Material to Form modules, we also identified constraints they presented as a curricular tool. Despite our efforts to build the modules for freeform navigation, the focus on technical processes and materials do suggest an order, with more complex processes building on earlier concepts. This structure may, for instance, disinvite an educator without access to 3D scanning tools by implying that not only could they not make use of the Capturing Form module, but also subsequent modules. Centering the modules heavily on particular processes also meant that such a teacher, even if they were interested in the artists and concepts discussed in Capturing Form would not be able to use that resource. As the project evolved, we sought to develop resources that could leverage the process-based instruction from the earlier modules, while opening them up structurally and conceptually to invite educators with varied interests and facilities in their places of teaching.

As a result, we introduced two mods[2] to the curriculum structure: Forms and Bodies and Glitching Form. The mod was conceptualized as a different curricular form that could extend learning from the original six modules by introducing more thematic investigations of 'big ideas' (Walker, 2001). A big idea, similar to a key idea (Parsons, 2004) or organizing theme (Bautista et al., 2016), is a concept that extends beyond any single discipline (Walker, 2001). A big idea is a concept that

[2] We chose the term mod, as an abbreviation of modification, as an ode to video game culture when players introduce modifications to a game space that changes its action or appearance.

'does not belong to the art world, though it is something artists have made works about. It suggests many questions, is full of complexities, has many instantiations, and encourages different points of view' (Parsons, 2004, p.788).

Big ideas are transdisciplinary by nature and useful for building curricula that integrate disciplines such as the arts and sciences (Bautista, 2016). Big ideas invite multiple perspectives and ways of working and are useful for accommodating a population of educators with diverse interests and resources (Buffington, 2007).

The mods we built around the big ideas of human bodies and glitching systems could be readily used in spaces with different material affordances, as their conceptual aims could be accomplished via a variety of means. A setting without access to a 3D printer could still meaningfully engage with any of these units, focusing on creating solely digital work such as 3D models, or by eschewing digital media completely and challenging students to fabricate with physical materials like wood or clay. The flexibility afforded teachers is also extended to students, as the thematic framing of the mods aims to create an open-ended problem space for generating varied solutions. This open-endedness was developed to both foster design thinking's generative and iterative approaches to problem-solving (Doorley et al., 2018; Schön, 1983), and to reflect contemporary art practices, which are largely centered on solving material and conceptual problems rather than cleaving to a particular artistic process (Parsons, 2004). Centering a big idea in each mod, rather than centering a technical process, allowed for the inclusion of case studies in the teaching resources featuring artists who engage with the theme using a variety of processes, including entirely non-digital craft processes. STEM fields have historically been exclusionary to both women (Hill et al., 2010; Makarova et al., 2019) and populations of color (Riegle-Crumb et al., 2019), so expanding the case studies to include artists working outside of digital fabrication allowed us to curate a more equitable and representative canon of creators in these curricular mods. The mods are also not dependent on each other, and don't invite a particular order of completion, more overtly enabling teachers to select, omit, or reorder them however they choose.

The first mod developed for the curriculum, Forms and Bodies, challenges students to create an artifact to be worn by a particular body. Students need to collect data on a chosen person in their life, both through physical measurement and interview, to develop an object that is a "good fit" literally and metaphorically for their chosen person. The mod emphasizes the particularity of bodies, and questions ableist generalizations about human bodies and the shapes they take (Hamraie, 2013). The mod is also structured around three categories of body-object relationship: extending bodies (discussing artists such as Rebecca Horn and Stelarc), adorning bodies (discussing artists such as Danit Peleg and Rebecca Strzelec), and connecting bodies (discussing artist Sonya Clark's "Communicatools" series). This tripartite structure is intended to scaffold a variety of potential learner engagements and teacher coordinated emphases with the generative problem space of human bodies.

The Glitching Form mod has a similar tripartite structure, built around three common glitching practices: glitching at the point of capture by interfering with scanning processes, glitching with software by (mis)using 3D modeling tools, and glitching with code by manipulating the underlying data structures of digital forms. This mod examines how glitch artists experiment with technical systems that undergird ubiquitous digital artifacts, breaking rules and pushing boundaries of these systems and structures to make them more visible (Russell, 2020). Ultimately, students are challenged to conduct their own creative exploration, developing a digital or physical artifact that meaningfully explores the potential of glitching forms.

Having summarized the evolution of the Material to Form curriculum modules and the subsequent mods, we turn next to analyzing the implications of the changes made to the curriculum over time, and how they reflect on issues of interdisciplinarity. We will also examine how the above-described curricular choices interface with larger trends of research and practice exploring culturally-responsive teaching across disciplines. We will first discuss issues of interdisciplinarity as they impacted the research and development of the curriculum, and then discuss the culturally responsive teaching within education scholarship both within the arts and engineering, drawing connections between the two throughout.

Theorizing Interdisciplinarity

Over the arch of the MAKE 3D project and through the development of the Material to Form curriculum, there is a trajectory that moves from the technical to the thematic. The initial bond that allowed the core research team to come together was a shared interest in the emergence of digital design and fabrication technologies that were changing manufacturing and production for artists and engineers alike. The role that 3D printing played cannot be overstated in this process: it was a core technology that excited the research team from various disciplinary perspectives; it dovetailed nicely with maker education and informal learning due to its prevalence within the maker community both in makerspaces and online forums; it overlapped with advances in open source cultures through 3D printing initiatives such as RepRap (https://reprap.org/wiki/RepRap) which was important for leveling the playing field for those with limited access to more expensive or technically complex printing procedures; and it captured the high visibility computational event that was at the core of our theorized use of curricular spectacle to harness the potential of short exposure learning experiences that may provide lasting impact to learner's education. As Knochel (2018) has theorized, these high-visibility technologies can perform as curricular boundary shifters: entities that have a high incidence of disciplinary border crossing that transforms cultural, social, and institutional norms in learning spaces and beyond.

However, boundary shifting is not an easy process within radically transdisciplinary spaces of science, technology, engineering, art, and design. Malina et al. (2015) suggest that there is a 50-plus-year history of investigations in science, engineering, art and design that has generated over 40 reports suggesting that the community of interest and practice is healthy and well established while at the same time
'it is clear that many of the opportunities and obstacles now facing the SEAD community were identified and worked on in the past.' (p. 6).[3] Ultimately our project succumbed to many of the issues that are prevalent within the SEAD and STEAM educational communities. Such communities have ongoing challenges sustaining funding, ensuring a deep sense of epistemological variance in knowledge formation, and maintaining methodological rigor to meet the varied demands of very different academic communities. However, the opportunities to impact student learning though arts-integrative initiatives far outweigh these challenges. Integration of arts and humanities to STEM subjects have been associated with positive learning outcomes including increased critical thinking abilities, higher-order thinking and deeper learning, content mastery, problem solving, teamwork and communication skills, improved visuospatial reasoning, and general engagement and enjoyment of learning (National Academies of Sciences, Engineering, and Medicine, 2018). And while these impacts to student learning are important for advocating for STEAM initiatives, there are perhaps even more vital reasons that STEAM initiatives need to be pursued as they are situated within research concerning gender difference in learning and broadening participation for STEM fields. As Marín-Marín et al. (2021) in their bibliographic analysis of the term 'STEAM' within publications within the Web of Science (WoS) database, state

> the topics of study on STEAM-EDU [an abbreviation used by authors to refer to STEAM projects in the educational field] include aspects related to gender differences, the influence of STEAM-EDU on people of different races, the skills developed by students, and teacher training to implement teaching and learning processes with STEAM-EDU (p. 18).

The aligning of STEAM education with integrated knowledge and holistic learning toward equitable access, rather than focusing solely on technical overlaps between disciplines, is significant in our estimation. Our own curricular journey showcases this evolution from technique to theme as we made more careful and intentional shifts in the Material to Form curriculum that reflect efforts in broadening participation and engaging in culturally responsive forms of pedagogy in any discipline. We share more about this aspect in the next section.

Connecting Across Disciplines Through Culturally Responsive Teaching

In shifting our curricular design strategies from the process-oriented modules to the big idea-oriented mods, we drew upon culturally responsive pedagogies in both art and STEM education. We recognized that centering digital fabrication processes as the locus of critical and creative attention to some extent decentered the cultural contexts of digital fabrication as loci of critical attention. In the mods, we aimed for the curriculum to acknowledge that the often assumed-neutral cultural referents in both art and STEM education are neither neutral nor universal, but largely rooted in dominant disciplinary histories centered around White and European cultures and male cultural producers (Acuff et al., 2012; Martin et al., 2018). Ladson-Billings's (1992, 1995) work on culturally-responsive pedagogy critically addresses the implicit cultural norms imposed upon students by curricula and aims for educators to affirm and respond to the varied cultural referents students bring into the place of learning. Responding to the diverse cultural referents of students not only broadly contributes to a 'synergistic relationship between home/community culture and school culture' (Ladson-Billings, 1995, p. 467), but also can pointedly address the systemic exclusion and devaluing of marginalized students that contribute to educational inequity (Hanley and Noblit, 2009; Ladson-Billings, 1992, 1995). As such, culturally-responsive pedagogies have been explored by both art educators and STEM educators as strategies to address inequity in their respective disciplines. In this section, we will discuss applications and theorizations of culturally-responsive pedagogy in art and STEM education, and how our conceptualization of the Material to Form mods attempted to address the issues surfaced in each discipline.

Acuff et al. (2012) noted how, in culturally-responsive art education, critical curation of the canon of thinkers and artists included in curriculum is necessary to avoid perpetuating received (often white-male-centered) histories

[3] Discourses and scholarship in science, engineering, art and design (SEAD) are very similar to those in educational communities of science, technology, engineering, art and math (STEAM). The only difference in our estimation is that STEAM has been taken up more widely in pre-K-16 educational discourses.

of art. In the shift toward centering big ideas in the mods, we were afforded a wider array of potential exemplary artists to draw from, facilitating a critical and considered curation of exemplars. Not tethered to specific digital fabrication processes, the Forms and Bodies mod could bring in artists like Sonya Clark, who works with a wide variety of physical materials, including ones drawn from traditional craft practices of the Black diaspora. Lai (2012) argued that by meaningfully engaging with and affirming creative practices rooted in historically marginalized cultures, culturally-responsive art pedagogy 'resist[s] the cultural deficit paradigm and decontextualized learning that devalues or disconnects students from their ethnicity and culture' (p. 18). In developing the mods, we aimed to include non-digital modes of making, particularly those by women and BIPOC creators, not as an addendum or option for deficient settings without digital fabrication tools. Rather, we aimed to center and legitimize non-digital making practices as valid approaches to addressing the big ideas and critical questions at the center of each unit while still impacting understandings of material and technical processes. Likewise, in the Forms & Bodies mod, disabled bodies are not singled out as deficient and needing assistance, but rather as part of the diversity and particularity of human bodies that artists and designers must attend to when creating objects that interface with human bodies.

Several scholars of art education have noted that culturally responsive practice in the arts not only benefits the marginalized students who may see themselves reflected in the curriculum, but that it may confer benefits upon all participating students. Acuff et al. (2012) argued that culturally-responsive art practice ultimately benefits all students, as all students are impacted by the 'prescribed and oversimplified stories' (p. 10) imposed by the uncritical repetition of dominant norms. Drawing on the psychological research of Amodio and Lieberman (2009), Lee (2012) specifically asserts the necessity of critically-responsive art education for non-marginalized students, as arts practice elicits both embodied experiences and the cognitive creation of meaning which are 'critical to unlearning cultural bias… [which] is considered to be deeply rooted in the emotional processes of the brain' (p. 49). While the Material to Form mods reflect the attitudes of culturally-responsive arts pedagogy in their conceptualization and curated canons more so than the earlier modules, there are still areas for improvement. A minority (28%) of the artists discussed in the mods are white men, however the majority (84%) of artists discussed are white, and all of the included artists work and live in the global North. The shift to a big-idea-centered ethos creates the opportunity for these oversights to be addressed in future iterations or additional mods, which a focus specifically on digital fabrication processes may not.

Scholars in STEM education have likewise articulated the need for, and benefit of, culturally-responsive pedagogy in their discipline. Scott et al. (2015) noted that, while there are numerous technology programs

> 'currently offered to raced-gendered-ethnic minority students … the vast majority focuses exclusively on technical literacy (i.e., programming) and do not mention issues of diversity, community, culture, or identity' (p. 413).

The focus on technical literacy enacts a tacit imposition of the assumed-standard values of (majority white and male) STEM industries and communities onto the targeted students, marginalizing the values and modes of making and thinking these students bring into the learning environment (Scott et al., 2015). To invite the development of more equitable and comprehensive STEAM learning programs, Scott et al. (2015) recommended five tenets of culturally-responsive computing (CRC):

1. All students are capable of digital innovation.
2. The learning context supports transformational use of technology.
3. Learning about one's self along various intersecting sociocultural lines allows for technical innovation.
4. Technology should be a vehicle by which students reflect and demonstrate understanding of their intersectional identities.
5. Barometers for technological success should consider who creates, for whom, and to what ends rather than who endures socially and culturally irrelevant curriculum. (Scott et al., 2015, p. 420-421).

Some STEM education scholars have found maker contexts to be valuable settings for fostering CRC, and particularly for critically questioning what counts as *making* (Martin et al., 2018) and who counts as a *maker* (Fields et al., 2018). Martin et al. (2018) sought to expand what counts as making by affirming and incorporating the repertories of practice students brought into their maker space. A young Black woman with interest and experience in fashion design, for example, was able to bring her repertory of practice into the makerspace and extend it with the tools and skills made available to create attire with programmable lighting (Martin et al., 2018). Fields et al.'s (2018) expanded conception of who counts as a maker recognizes a need for diverse representations of making to affirm and serve all students. To accomplish these goals, Fields et al. (2018) developed an e-textile making project within the context of their equity-focused Exploring Computer Science curriculum. In examining the problem of culturally-responsive STEM pedagogy from a curriculum design perspective, Fields et al. (2018) noted how their design of the e-textiles project not only invited and affirmed diverse participation by students with varied relationships to digital technologies, but also invited and affirmed diverse *implementation* by *teachers* with varied relationships to digital technologies.

In approaching our development of the Material to Form mods, we likewise curated exemplar artists and centered big ideas with the aim of inviting and affirming both students and teachers who may not have the experience or material means to engage in 'making' when it is defined strictly as digital fabrication. The centering of interdisciplinary big ideas was chosen to invite students and teachers regardless of their relationship to the arts or technology. For example, the centering of human bodies in Forms and Bodies aims to connect to the fact that every student, teacher, and artist has a body, and the centering of glitches in Glitching Form aims to connect to the fact that every contemporary student, teacher, and artist daily interacts with digital systems which may be critically subverted. Within the mods, other interdisciplinary and endemic global issues are addressed, such as ableist design norms discussed and destabilized in the Forms and Bodies and Glitching Form mods. As discussed above, the curated canon of exemplar artists in the units is designed to de-center white-male-focused histories of art and technology by discussing and affirming the practices of makers using a variety of digital and non-digital media, who occupy a variety of identity positions, and who have varied relationships to established communities and industries around digital technology and art making.

CONCLUSIONS

In this reflexive analysis of our curriculum development, we've traced the evolving form of our Material to Form curriculum, exploring thematic connections between the maker movement, art education, and arts-integrated approaches to curriculum. Our review highlights a trajectory of revisions tuned to the MAKE 3D events and learner engagement, but also acknowledges the situated knowledge and researcher identity that informs highly interdisciplinary and design-based research. This reflexive analysis in curriculum design showcases the tenuous bonds of interdisciplinary work from shared intrigue by technological innovation to central pedagogical values commited to expanding access and broadening participation within these disciplines. Next phases of the research include continuing mod development finding intersections and thematic syntheses that can further extend the technical core of the Material to Form curriculum. Additionally, the research team is seeking opportunities for further fieldwork to gather data concerning curriculum effectiveness. Focus on thematic curricular ideas that came from iteration and an exploration of the uncertain material and disciplinary possibilities of digital fabrication offer meaningful and culturally responsive pedagogical strategies impacting interdisciplinary teaching contexts designed for STEAM practitioners.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the National Science Foundation Grant No. 1623494. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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