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Trinity Walton Club: What is its Potential for Promoting Interest in STEM?

Mark Prendergast [1]*, Colette Murphy [1], Arlene O'Neill [1], Joseph Roche [1]

[1] *The University of Dublin, Trinity College, Arts Building, School of Education,* Dublin, IRELAND

***Corresponding Author:** mark.prendergast@tcd.ie

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ABSTRACT

Concerns are growing in many countries, including Ireland, regarding an inadequate number of graduates to meet workforce needs in science, technology, engineering and mathematics (STEM) fields. These graduate deficiencies are the result of low student uptake of STEM subjects and courses at post-primary and tertiary level education. Low uptake is partly a consequence of negative student attitudes towards STEM. Many students are losing interest in STEM at an early age due to an inability to see any relevance in their everyday lives. In light of such concerns, a Saturday afternoon club entitled "Trinity Walton Club" (TWC) was established in Trinity College Dublin with the purpose of uniting like-minded students to express, shape, inform and grow their interest in STEM. This club attempted to 'bring STEM to life' through thought provoking content, real world problems, contextualised analogies and projects. This paper describes the background to the TWC, reviews the literature around promoting student interest in STEM and examines initial feedback from participants in the pilot year of the club. The findings of this preliminary study indicate that the TWC has the potential to promote interest in STEM. Many of the recommendations from the literature review about promoting interest in STEM were referred to by participants in their responses.

Keywords: promoting interest, STEM club, STEM retention

BACKGROUND TO THE TRINITY WALTON CLUB

Trinity Walton Club (TWC) is a science, technology, engineering and mathematics (STEM) club which was established in September 2014 and piloted for thirty weeks through to June 2015. The club is based in Trinity College Dublin, Ireland and is a partnership between the College's School of Physics, School of Mathematics and School of Education. The pilot programme was open to young people in their second year (eight grade) of post-primary education, typically aged 13/14 years old. Its intention was to offer members an opportunity to "*unravel the wonders of STEM through thought provoking and appropriately challenging STEM lessons, hands on workshops and laboratory sessions"* (www.tcd.ie/waltonclub/). The club was named after Ireland's only Nobel laureate for Science, Ernest Walton (1903-1995), who was awarded the 1951 Nobel Prize in Physics, with John Cockcroft for 'splitting the atom'. It met Saturday afternoons from 2pm – 5pm and ran for three terms, with each term lasting ten weeks between October and June. The members were called 'alphas', after the helium particles that were critical to Ernest Walton's Nobel Prize winning experiments.

The overarching aim of the initiative was to promote interest in STEM amongst young people and to further enhance their STEM knowledge and skills (Roche et al., 2016). TWC provided additional academic stimulus in three main areas namely physics, mathematics, and a combined stream called technology-engineering. Typically the alphas were split into three groups with twenty participants per session. These sessions were facilitated by PhD students termed 'educators' and were generally fifty minutes each in duration. They offered structured activities that had unique learning objectives and attempted to demonstrate the interconnectedness of STEM in a real world context. The syllabus was developed by a core advisory committee, compromising of academics and the educators of the club. The sessions and activities focused on two main areas of skill development, namely, problem solving and higher order thinking skills. A range of suitable pedagogic approaches, guided the sessions and informed the delivery of the content. The content also complimented the national curriculum and was intended to nurture alphas ability and diligence in mathematics and science. Alphas were also encouraged and supported to partake in national STEM events and competitions.

Throughout the pilot programme, alphas worked collaboratively solving problems, experimenting, designing and building STEM projects, discussing concepts and reflecting on their learning. A range of social activities were organised for the alphas including informal meetings with scientists, technologists, engineers and mathematicians from both academia and industry, who shared their interest and pathway into STEM. After the thirty week programme, the alphas showcased their STEM projects to their families, school representatives and the public. They also received a certificate, acknowledging their commitment to their STEM education and were invited back to continue their involvement in the STEM club in the following school year. It is anticipated that TWC will expand in the future by offering new members the opportunity to take part. The intention is to increase the number of alphas to eighty per year starting from September 2015, and by 2018, to have four parallel programmes running for four different age groups.

All students wishing to participate in TWC had to first pass an entrance assessment and demonstrate an appropriate aptitude before they were offered a place in the STEM club. Although it is a not-for-profit club that is subsidised by Trinity College Dublin and external supporters, a fee of €250 per term was charged per student to ensure the programme was self-sufficient. TWC also offered full scholarships to twenty per cent of members who came from socio economic backgrounds that are underrepresented at university. The 2014-2015 pilot cohort comprised of sixty students, thirty male and thirty female, from thirty different schools in the greater Dublin area.

REVIEW OF LITERATURE

The next section of the paper will review existing literature in the area of STEM education. It will begin by investigating some of the current concerns regarding STEM education, before focusing on students' attitudes and interest toward STEM and how these can be promoted.

Concerns regarding STEM Education

Research shows that despite their importance, the disciplines of STEM have experienced problems in producing adequate numbers of graduates to meet workforce needs in these fields (Hall et al., 2011; Frazer et al., 2010). This has serious repercussions for the Irish economy, particularly in relation to the technology and industrial sectors (Expert Group on Future Skills and Needs (EGFSN), 2008). Although entrance into the STEM fields has grown, this growth is not keeping pace with the overall needs of the labour market (Hall et al., 2011; Hunt, 2011). Concern has also been expressed about students entering higher education without the necessary skills and knowledge to engage effectively with learning in the disciplines of STEM (Hunt, 2011; Treacy and Faulkner, 2015; Treacy et al., 2016).

Recent international comparisons show that Irish fifteen year old students are performing above the Organisation for Economic Co-operation and Development (OECD) average in mathematics and science. In the 2015 Programme for International Student Assessment (PISA), the data for students in Ireland indicated a mean mathematics score of 504, which is significantly above the average across OECD countries (490). The mean mathematics score for Ireland was ranked 13th out of 35 OECD countries and 18th out of all participating countries (Shiel et al., 2016). For science, the mean score of Irish students in PISA 2015 was 503, which was ranked 13th among 35 OECD countries and 19th among all participating countries (Shiel et al., 2016).

However despite such encouraging performances by Irish students in mathematics and science on international comparison tests, concern has been expressed about the declining uptake of these subjects both in the later stages of post-primary education and at tertiary level (Smyth and Hannan, 2006). Such concern can be linked to a number of continuing failures within the Irish education system. For example, at primary level in Ireland, the science curriculum aims to develop both conceptual and procedural understanding among students through an allocation of forty-five minutes per week for infant classes and one hour per week for all other primary classes (Department of Education and Skills (DES), 2012). While these aims are impractical in terms of the time allocated, of more concern is that 16% of students participating in a National Council of Curriculum and Assessment (NCCA) study claimed that they had done no science at primary school (Varley et al., 2008a). After completing eight years of primary education, all students progress to post-primary education in Ireland. This is typically of six years and during this time students complete two State examinations namely the Junior Certificate (lower post-primary) and the Leaving Certificate (upper post-primary). These examinations can be taken at different levels with the most challenging level referred to as Higher and the next level referred to as Ordinary.

Despite the subject's importance, it is not compulsory to study science at lower post-primary level in Ireland. At upper post-primary level, the proportion of young people taking physics and chemistry is low and has shown a decline since the 1990's (Smyth and Hannan, 2006). In 2016, only 17% of Leaving Certificate students took chemistry, and only 14% took physics (State Examinations Commission [SEC], www.examinations.ie). One possible reason for this is that in contrast with many other European countries, not all Irish schools provide opportunities for students to study the sciences at upper post-primary level, with a "significant minority" failing to offer physical sciences at Leaving Certificate (Smyth and Hannan, 2006).

While mathematics is studied by the vast majority of post-primary students, there are also many concerns with the domain such as the low numbers opting to study the subject at Higher level (Prendergast and O'Donoghue, 2014). For example in 2011, figures show that only 45% of the Junior Certificate cohort took the Higher level mathematics' examination. More worryingly only 16% opted for the Higher level Leaving Certificate examination (SEC- www.examinations.ie). While these figures have increased since a reform of the curriculum, there are still many concerns regarding the mathematical ability of incoming university students (Treacy et al., 2016; Prendergast and Treacy, 2017).

There are many reasons cited throughout the literature for such poor uptake in STEM subjects and subsequent graduate deficiencies in mathematics and science. Some of these may be a result of structural problems in our education system such as subjects not being offered in some schools (Smyth and Hannan, 2006) and insufficient class time (Prendergast and O'Meara, 2016). However there is also evidence to suggest that many of these problems may be a result of negative student attitudes towards STEM subjects (Osborne et al., 2003; Papanastasiou, 2000).

Student Attitudes towards STEM

As signalled by the Trends in International Mathematics and Science Study (TIMSS) (1999), student attitudes have an enormous impact on student achievement in a particular subject area (Mullis et al., 2000). Attitudes largely determine what students learn and their willingness to learn. Lindgren (1980) supports this view by stressing the importance of students holding favourable attitudes if learning experiences are to be successful. With reference to mathematics, there is much negativity surrounding the current public image of the subject. In contrast to the *"shame associated with illiteracy, innumeracy is almost a matter of pride amongst educated people"* (Ernest, 1995, p.449). The widespread public image is largely a negative and inaccessible one. This dates back to the age old image of mathematics as difficult, cold, abstract, theoretical and largely masculine (Ernest, 2004). Such negativity consequently has an off-putting effect on the uptake and performance in school mathematics. Statistics released by PISA (2012) showed that just under half (49.6%) of Irish students agreed that they were interested in the things they learn in mathematics (Perkins et al., 2013). In addition, only 40% of Irish students declared that they look forward to their mathematics lessons, while only 37% responded that they do mathematics for the enjoyment (Perkins et al., 2013). Students are reluctant and unwilling to engage in a subject in which they can see little relevance (Prendergast and O'Donoghue, 2014). This is confirmed by the results of an Irish study carried out by Smyth, Dunne, McCoy and Darmody (2006) where 25% of Irish 15 year olds nominated mathematics as one of their least favourite subjects in school.

In contrast interest in science amongst students is generally high, with over 75% expressing enthusiasm for the subject in a study carried out by Smyth, McCoy and Darmody (2004). This finding resonates with that of Varley et al. (2008b) who determined that many students find the science content at post-primary level to be interesting and informative, though difficult at times. The ROSE (Relevance of Science Education) survey conducted in Ireland in 2003/4 found that a majority of 15/16 year old students expressed positive attitudes towards Junior Certificate science and claimed that school science was interesting (Matthews, 2007). However overall attitudes towards learning about biology and chemistry were more positive than attitudes towards physics (Matthews, 2007). Such findings confirm those of other studies where students' attitudes towards physics are not very positive (Varley et al., 2008b). Another finding from the ROSE study was that 55% of Irish students chose the 'extremely disagree' option for wanting to 'become a scientist' (Matthews, 2007). This has implications for Ireland's future social and economic growth (EGFSN, 2008). To combat this problem, studies have identified that stimulating and maintaining students' personal interest is a key issue to address (Beggs et al., 2008; Kuechler et al., 2009; Prendergast and O'Donoghue, 2014). Too many students lose interest in science and mathematics at an early age, and thus make an early exit from possible STEM careers (Sanders, 2009). In a U.S. survey of college students, Beggs et al. (2008) identified various influential factors in their choice of subject and found that student interest was rated as the most important influence. This is supported by another US study carried out by Hall et al. (2011) who found that the top influence on career choice reported by students was their personal interest.

Student Interest

Many definitions are offered throughout the literature regarding interest. Boekaerts and Boscolo (2002) propose that interest is conceptualised as the affect that relates individuals to the activities that provide the type of novelty and challenge that they desires. Hidi and Harackiewicz (2000) describe interest as an interactive relation between an individual and certain aspects of his or her environment (e.g. objects, events, ideas). It can be viewed both as a state and as an outlook of a person, and it has a cognitive as well as an affective component. Hidi (2006) considers interest to be a unique motivational variable, as well as a psychological condition that is characterised by increased attention, concentration and affect. Regardless of definition, the importance of interest was recognized in the late 19th century and not just for career and subject choice. Psychologists and philosophers such as Ebbinghaus (1885) and James (1890) acknowledged that interest made a significant contribution to what people paid attention to and remembered (as cited in Prendergast and O'Donoghue, 2011). Even before that, the philosopher Thomas Reid (1788) suggested that emotional engagement is required for a learner to maintain attention, and therefore to learn anything. In the early part of the 20th century there was a continued understanding of the important role interest played in learning and development. Dewey (1913) maintained that interest facilitated learning, improved understanding and stimulated effort as well as personal involvement.

Dewey's work is supported by more recent research conducted by Hidi and Harackiewicz (2000) who found that interest has a powerful influence on students' academic performance. Del Favero et al. (2007) acknowledge the many studies that have shown the energising function of interest in fostering students remembering and understanding material, and stimulating students' positive attitude towards a topic (e.g. Hidi, 1990; Mason and Boscolo, 2004; Schiefele, 1991, 1998). Hidi and Anderson's (1999) work supports this view by concluding that interest has a profound effect on students' recollection and retrieval processes, their acquisition of knowledge, and their effort expenditure. On top of this, theorists have suggested that interest may be the key to early stages of learning, as well as to differences between expert and moderately skilled performers (Alexander, 1997). When interested in a topic or domain, students are more likely to use higher-order learning thus improving their knowledge (Murphy and Alexander, 2002). This is supported by the findings of Krapp (2002, p. 384) who concluded that "*an interest triggered learning activity leads to better learning results*".

Promoting Student Interest in STEM

Given such importance, it is essential that teachers and educators alike make a conscious effort to promote interest at every available opportunity. However, a study carried out by Weiss (1990) in the U.S. found that only 31% of mathematics teachers declared that they give a heavy emphasis to getting students more interested in the subject. One reason for this lack of emphasis from teachers may be a lack of knowledge about how to systematically develop interest in their classrooms. There are many recommendations on how to do this offered throughout the literature. Firstly, it is important that educators always demonstrate their own interest in the subject matter (Bergin, 1999). The next task is to engage their students in the topic. This can be done using certain aspects of the learning environment, such as modification of teaching materials and strategies, and how tasks are presented (Hidi and Harackiewicz, 2000). Hidi (2006) suggests other means to achieve interest such as selecting resources that trigger interest. These may include games, puzzles, and hands-on activities, depending on the particular topic. However, while such resources trigger student interest, many of them fail to maintain the students' interest over time (Mitchell, 1993).

A study carried out by Mitchell (1993) in the US found that the two main factors in maintaining student interest over time were meaningfulness of task and student involvement. Meaningfulness refers to students' perception of topics as meaningful to their own lives. For example presenting content in more relevant contexts illustrates the value of the subject and makes it more personally relevant for the student. Meaningfulness is effective because content that is perceived as being personally meaningful to students, empowers them and holds their interest (Mitchell, 1993). Involvement refers to the degree to which students feel they are active participants in the learning process. Students are more interested when they learn by doing as opposed to sitting and listening (Prendergast and O'Donoghue, 2014).

Similar to empowering students through meaningfulness and involvement, Del Favero et al. (2007) suggest that several forms of social interaction may also support the development of interest at various stages. This view was supported by Hidi and Harackiewicz (2000) who found that working in the presence of others resulted in increased interest for some individuals. This supports the case for the inclusion of group work and discussion in educational settings. Furthermore Del Favero et al. (2007) determine that problem-solving can often maintain interest by making students aware of gaps in their previous knowledge of a topic, thus encouraging further exploration of concepts and ideas.

THE STUDY

This study explores the potential of TWC for promoting and maintaining interest in STEM. The lessons, activities and resources were all designed and implemented with recommendations from the literature in mind. There was a constant effort to promote interest amongst its members through meaningful and contextualised learning experiences. The educators who facilitated the sessions and activities were encouraged to demonstrate their own interest in STEM. The activities were designed to be as interactive and hands on as possible. For example, the alphas were brought trampolining to explore the variables that control how high one can jump. This offered a conceptual and meaningful pathway to explore several physics and mathematics phenomena. Guided discovery and group work were promoted in each session to allow for students to construct their own meanings and learn from their peers. After activities, there was always time allocated for reflection, allowing opportunity for the alphas to develop their own understanding or discuss concepts further with the educators or their peers. In addition to providing stimulating STEM content through inquiry and project based learning, the sessions and activities often required alphas working in small groups to present and discuss their findings to the larger group. This necessitated the alphas to clarify their own understanding and further enhance their higher order thinking skills. Furthermore the educators employed assessment for learning (AFL) techniques that informed their teaching and offered feedback to the alphas. The educators also facilitated peer and self-assessments. Both of these methods were effective in supporting alphas to develop internal expectations for their work and take ownership of their learning, all of which have been shown to promote interest in the literature.

The design and development of individual lessons, activities and resources will be outlined in detail in a future paper. The purpose of this paper is to evaluate initial feedback from the pilot cohort of alphas to determine whether the TWC has the potential for promoting and sustaining student interest. This feedback was collected through a survey given to the alphas in April 2015. The survey was administered using Survey Monkey and all of the sixty students from the 2014-2015 pilot cohort were invited to respond. It was completed by forty-six participants, signalling a response rate of 77%.

The survey contained ten questions and was predominately qualitative in nature, although there were some quantitative aspects.

For example:

- What do you like most about the TWC?
- If you could change one thing about the TWC, what would that be?
- Please rate each of the three streams (Physics, Maths and Technology - Engineering) using the following 5 point Enjoyment Likert scale. Please tell us what your favourite stream is and why?

The findings of the survey were analysed with a view to answering the following research question: What is the potential of the TWC for promoting interest in STEM? It is important to note at this point that the participants of the study were all voluntary members of the TWC and thus were likely to have an existing interest in STEM. This must be considered when analysing and attempting to draw conclusions from the data.

FINDINGS

The qualitative data from the questionnaires was analysed using a thematic content analysis. Although this study did not involve a large amount of qualitative data, it was decided that two of the authors would carry out the analysis to increase comprehensibility and to provide sound interpretation of the data. A coding scheme was generated based on the main themes which were identified from participants' responses. The final coding scheme consisted of three main codes namely student enjoyment of TWC, knowledge and skill development, and confidence and interest in STEM. Each of these themes will now be discussed in more detail and the main points will be backed up by relevant quantitative data which was analysed using a Microsoft Excel spreadsheet.

Student Enjoyment of TWC

It is clear from the questionnaire data that the majority of participants enjoyed their TWC experience. As can be seen from **Figure 1**, 40 out of 46 respondents (87%) said that they enjoyed the Walton club. There were many reasons for this enjoyment offered throughout the data. Participants liked the *"interactive"*, *"engaging"* and *"fun"* nature of the TWC. The social aspect was very important ("*My favourite thing about TWC was the opportunity to socialise with people my age interested in the same subjects as I am"*), along with the opportunity to engage with '*weekly challenges*', "*experiments*" and "*guest speakers*". They also liked the relationship with the educators which was "*relaxed*" and "*friendly*" and from whom they could see a passion for STEM (*"[the educators] all went on to study science and they speak about it with the same joy as I do which is wonderful"*).

As mentioned previously there are three main strands to the TWC, namely physics, mathematics, and technology-engineering. The data shows that mathematics was the most popular strand with 87% of students

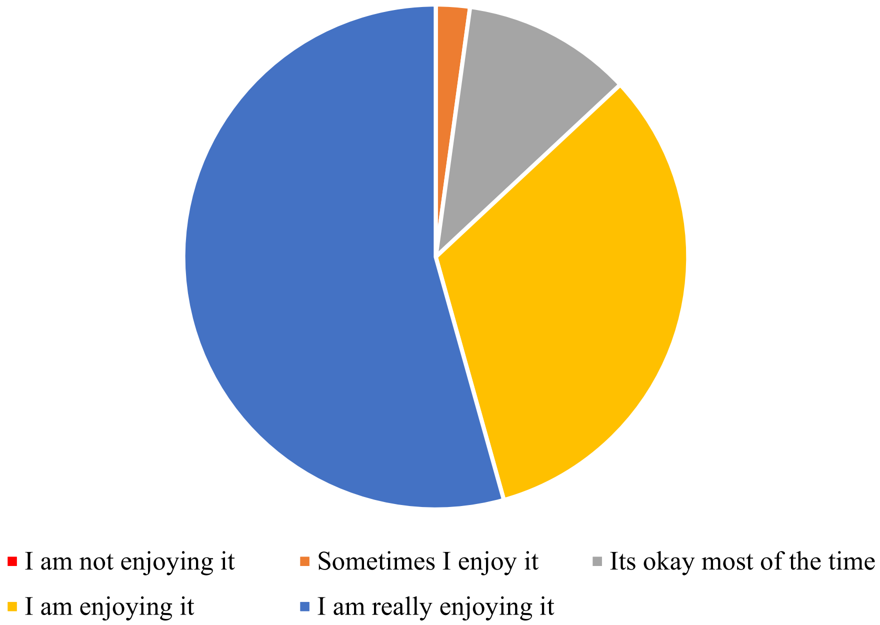

Figure 1. Students Enjoyment of Trinity Walton Club Experience

stating that they enjoyed it, in comparison to 83% for technology-engineering and 70% for physics. Participants found the streams "*interesting*" and "*enjoyed learning about the application of different formulas and theorem's*" along with the *"practical elements and project work"*.

Knowledge and Skill Development

Overall, the majority felt that they have learned a lot of new STEM knowledge through their TWC experience ("*I have learned lots of new STEM knowledge that I can tell my friends and teachers about and amaze them", "I find that I am seeing more STEM in everyday life, and have a better idea of how a lot of things work*"). Some participants mentioned that they could now see the "*interconnections between the STEM subjects and how they should be viewed as a whole*". For example one student mentioned how *"STEM is very interlinked and one thing leads to another"*.

In one of the questions, participants were asked what skills they felt they had enhanced throughout their TWC experience. The main skill that emerged from the alphas' responses was team-work (mentioned in approximately 66% or 29 out of 44 responses) ("*My teamwork skills have been improved". "I've become much better at working in groups*"). Problem solving was mentioned in approximately 57% or 25 out of 44 responses (*"Using my own initiative to solve problems has really been enhanced"*). Other skills such as thinking outside the box and communicating were also popular responses.

Confidence and Interest in STEM

It is clear from the data collected that students' confidence in their ability to do science or mathematics in school had improved as a result of their TWC experience (*"I expanded my STEM knowledge and this made me more confident to do science and maths". "My confidence has improved and I'm less afraid to ask questions and, if I'm not sure of the answer, I don't mind having a try"*).

Although participants were not asked directly about their interest, the theme did feature in many of the responses. Some alphas said they were more interested in STEM since joining TWC ("*I feel that I have gotten more interested in topics relating to STEM because of my experience in the Walton club*"). This interest has led them to take a different approach to STEM subjects in school (*"In school I listen a lot closer to physics and maths and think about them more deeply"*), in the media (*"I have…listened more closely to the news when there have been articles about science or physics", "I now search science news on Google to hear about the latest innovation in the industry"*), and in everyday life ("*I now view discoveries through a critical lens with an aim to understand how they work rather than simply excepting them without research*"). A general theme was that participants now "*take a bigger interest in how STEM is applied to the world we live in*" and they now "*question everything both in school and outside"*.

This interest has inspired participants to choose STEM subjects in school ("*I would now pick a maths subject over an art", "It has inspired me to choose to physics for Leaving Cert*"), in college (*"TWC has influenced me into considering a course in Computer Science in college", "I would now choose a college course in one of the stem subjects as it has so many career paths"*), and in their future career paths (*"TWC has definitely made me more aware of all the options for careers in the stem area", "I was* *already considering a job in medicine or the likes but now I feel I may enjoy something more scientific…something that needs you to think outside the box!"*).

DISCUSSION AND CONCLUDING REMARKS

The analysis of the initial feedback indicates that the TWC has the potential to promote interest in STEM. Many of the recommendations from the literature about promoting interest in STEM were referred to by participants in their responses. These points ranged from the educators demonstrating their own interest in the subject matter (Bergin, 1999), to engaging in fun and practical tasks and activities. Examples of such STEM activities in the TWC include problem based learning, experimentation, bringing numbers to life, programming, developing apps and building and controlling robots. All of these activities have the potential to stimulate and trigger participants' interest in STEM. In order to maintain this interest it is important that the tasks are meaningful and that students are involved (Mitchell, 1993). Once again these themes are evident from the analysis. The activities used in the TWC are more *"interactive"* and "*hands-on"* as opposed to some participants' experience of school where the main activities are "*textbook reading*", "*listening to our teachers talk up at the board for an hour*" or "*just sitting down and taking notes or doing questions"*. Participants liked that "*everything we do at the Walton club we can relate to real life and things that go on around us"*. Furthermore the review of literature suggested that problem solving and social interaction can help promote student interest (Del Favero et al., 2007; Hidi and Harackiewicz, 2000). It is obvious from the responses of participants that these activities are common place in the activities of TWC ("*I've enhanced my team-work and problem solving because we work in teams a lot and it's good mixing with new people"*).

Other findings from the analysis also highlight the potential for the TWC in promoting interest. Perhaps the most encouraging is that many participants are now inspired to choose STEM subjects in school, in college and in their future careers. This is important given the concerns alluded to in the literature regarding the uptake of STEM at each of these levels. Many participants in the survey declared that they would now consider choosing a STEM subject such as physics in school and college as a result of their experiences in TWC ("*it has inspired me to choose to physics for leaving cert and college as I am interested in it*", "*my opinion of physics which was my least favourite section of the three sciences has completely changed and I feel excited when we start a physics topic*").

Another important finding from the data was that participants can now see the connections between STEM subjects and how they are "*interlinked"*. This is essential as discipline-specific content in STEM should not be divided, but addressed and treated as one dynamic, fluid study (Merrill, 2009). Students need to see the connections between "different subjects" to see their relevance and use in everyday life (Breiner et al., 2012). This will further promote interest not just in the individual subject but in STEM disciplines as a whole. This is important given that those who are interested in a particular domain are more likely to develop the skills needed to operate within it (Csikszentmihalyi, 1990).

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Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education

Lieve Thibaut [1]*, Stijn Ceuppens [1], Haydée De Loof [2], Jolien De Meester [1], Leen Goovaerts [1],
Annemie Struyf [2], Jelle Boeve-de Pauw [2], Wim Dehaene [1], Johan Deprez [1], Mieke De Cock [1],
Luc Hellinckx [3], Heidi Knipprath [1], Greet Langie [1], Katrien Struyven [4], Didier Van de Velde [5],
Peter Van Petegem [2], Fien Depaepe [1]

[1] *Katholieke Universiteit Leuven*, BELGIUM
[2] *Universiteit Antwerpen*, BELGIUM
[3] *GO! onderwijs van de Vlaamse Gemeenschap*, BELGIUM
[4] *Vrije Universiteit Brussel*, BELGIUM
[5] *Katholiek Onderwijs Vlaanderen*, BELGIUM

***Corresponding Author:** lieve.thibaut@kuleuven.be

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ABSTRACT

The shortage of graduates in Science, Technology, Engineering and Mathematics (STEM), has led to numerous attempts to increase students' interest in STEM. One emerging approach that has the potential to improve students' motivation for STEM is integrated STEM education. Nonetheless, the implementation of this new instructional strategy is not straightforward due to the lack of consensus about instructional practices in integrated STEM. This paper contributes to this challenge by providing a well-defined framework for instructional practices in integrated STEM in secondary education, based on the results of a systematic review of existing literature. The framework contains five key principles: integration of STEM content, problem-centered learning, inquiry-based learning, design-based learning and cooperative learning. The proposed framework has several benefits, including its applicability in the classroom and the possibility to describe integrated STEM on multiple dimensions. Nonetheless, further research is necessary to investigate the effects of integrated STEM on students' cognitive and affective learning outcomes.

Keywords: secondary education, integrated STEM, systematic review, instructional practices

INTRODUCTION

Need for Integrated STEM

In recent years, the importance of providing students with a strong education in Science, Technology, Engineering and Mathematics (STEM) has been stressed. Qualified STEM professionals are needed to remain economically competitive in the global market and to fill contemporary demands such as ensuring sufficient and sustainable energy, efficient healthcare and well-considered technology development (Bøe et al., 2011). Moreover, all citizens, even non-STEM professionals, should have the skills and competences necessary to deal with the challenges of our information-based and highly technological society (National Society of Professional Engineers, 2013). STEM-literacy, i.e. the awareness of the nature of science, technology, engineering, and mathematics and the familiarity with some of the fundamental concepts from each discipline, should be an educational priority for all students (Bybee, 2010; National Academy of Engineering and National Research Council, 2014).

A promising approach in this regard, is the use of an integrated STEM curriculum, which provides opportunities for 'more relevant, less fragmented, and more stimulating experiences for learners' (Furner and Kumar, 2007, p.186). Real-world problems are not fragmented in isolated disciplines as they are taught in schools and to solve these problems people need skills that cut across the disciplines (Beane, 1995; Czerniak et al., 1999). Studies in a broad range of disciplines have shown that students involved in an integrated curriculum perform as well or even better than their peers in traditional instruction with separate disciplines (Czerniak et al., 1999; Hinde, 2005). Moreover, the use of an integrated curriculum has been found to improve students' non-cognitive learning outcomes, such as interest in STEM (Mustafa et al., 2016; Riskowski et al., 2009) and motivation towards STEM learning (Wang et al., 2011), which in turn could lead to increasing numbers of STEM graduates (National Academy of Engineering and National Research Council, 2014).

Current Challenges

Despite the potential benefits and the increased focus on integrated STEM education, implementation of this new instructional strategy faces several challenges. First of all, implementing an integrated STEM approach in an educational system that has a very established segregated and discipline-based structure requires profound restructuring of the curriculum and lessons (Nadelson and Seifert, 2017). Moreover, integrated STEM education often requires numerous materials and resources for students such as construction tools (e.g., saws, measuring devices, and hammers), electronic materials (e.g., computers, design programs, robotics kits, and calculators) and other materials used in design (e.g., wood, styrofoam, glue, cardboard, or construction paper) (Stohlmann et al., 2012). Therefore, creating a school culture and environment that supports an integrated STEM approach to teaching and learning can be costly and time-consuming (Hardy, 2001; Nadelson and Seifert, 2017).

Furthermore, to effectively implement integrated STEM, teachers must have deep knowledge of the science, technology, engineering and mathematics content that they teach (Eckman et al., 2016). Additionally, they must also have specialized knowledge of how to teach STEM content to students—i.e., pedagogical content knowledge (Shulman, 1987). Nonetheless, many teachers report that they feel underprepared to use STEM applications with their students in the classroom (El-Deghaidy and Mansour, 2015). Moreover, a study by El-Deghaidy and Mansour (2015) showed that teachers do not have sufficient understanding of the T in STEM and that they may not have an adequate understanding of the nature of science and technology and the interactions between these two disciplines. Additionally, teachers' beliefs and views about teaching and learning, and their resistance or lack of motivation to change their beliefs and practice, may pose another challenge to the implementation of integrated STEM education (Ashgar et al., 2012).

In addition to the challenges of finding resources and insufficient teacher' knowledge, another major challenge for the implementation of integrated STEM education is the lack of consensus about how integrated STEM learning and teaching should be done. In recent years, many researchers have provided detailed information about the learning units for integrated STEM they designed. However, they often do not explain the instructional principles guiding their design (e.g. Barrett et al., 2014; Gentile et al., 2012). By contrast, other researchers have extensively described their ideas about instructional practices in integrated STEM. However, they often fail to provide a theoretical foundation for these practices chosen (e.g. Moore et al., 2014; Sanders, 2009) and different researchers seem to not always agree about the core instructional practices for teaching integrated STEM. Although several reviews about integrated STEM have been conducted (e.g., Becker and Park, 2011; Gresnigt et al., 2014), they mostly focus on the effects of integration on students' learning outcomes. To our knowledge, no systematic review about instructional practices in integrated STEM education has been done.

Purpose and Research Questions of This Study

The current study aims at addressing the lack of consensus about how integrated STEM learning and teaching should be done. To do so, a systematic review of existing literature about learning theories for and instructional practices in integrated STEM was conducted. Moreover, based on the results of the systematic review, a framework for instructional practices in integrated STEM was constructed. By first conducting a systematic review of existing literature, a theoretical base for the instructional practices in the framework is provided. In the absence of empirical evidence discerning which instructional elements are crucial for the successful implementation of integrated STEM, this is a valuable alternative to provide some form of evidence-based foundation. The specific research questions addressed in the systematic review are:

1. Which learning theories (behaviorism, cognitivism, social constructivism) form the basis of integrated STEM education?
2. Which instructional practices are used in integrated STEM in secondary education?

Methodology

A systematic review was conducted to identify, critically evaluate and summarize the findings of all relevant studies describing learning and teaching in integrated STEM (Gopalakrishnan and Ganeshkumar, 2013)**.** Systematic reviews differ from narrative reviews, which tend to be mainly descriptive and usually focus on a subset of studies that were chosen based on availability or author selection and therefore often include an element of selection bias. By contrast, systematic reviews typically involve a detailed and comprehensive search strategy derived a priori, with the goal of reducing bias by identifying, appraising, and synthesizing all relevant studies on a particular topic (Uman, 2011). For the current study, a systematic review was done using two databases: ERIC and Web of Science. The databases were browsed by using four different combinations of search terms: "Integrated STEM + secondary education" (*n* = 184), "Interdisciplinary STEM + secondary education" (*n* = 86), "Multidisciplinary STEM + secondary education" (*n* = 14), and "STEM integration + secondary education" (*n* = 121), leading to a total of 405 search hits. Overlapping search results were excluded and the dataset was further reduced using four criteria.

Firstly, all selected articles had to be peer-reviewed journal articles or book chapters written in English, resulting in the exclusion of, for example, conference papers and dissertations. Secondly, the articles had to focus on the integration of at least three of the STEM disciplines. Articles studying the combination of only two disciplines, for example, interdisciplinary mathematics and science or technology integration in mathematics, were excluded. Thirdly, the articles had to provide a clear description of teaching practices for integrated STEM. Finally, all articles had to describe instructional practices for integrated STEM in secondary education. One rater checked whether the articles met the criteria and in case of doubt, papers were discussed with two other raters until consensus was reached. After applying the criteria only 15 articles remained in the sample. Given the small number of articles, the "snowball approach" was used to retrieve additional publications (Doust et al., 2005). Reference lists of all selected articles were inspected and eight additional relevant articles that met the inclusion criteria were added to the dataset, resulting in a total of 23 articles.

To analyse the articles in the dataset, first a within-case analysis was conducted (Miles and Huberman, 1994). Each article was analysed separately and summarized in a table, consisting of two categories: (1) theoretical grounding and (2) instructional practices. Secondly, a cross-case analysis was done (Miles and Huberman, 1994). The instructional practices extracted from all articles were rearranged and similar elements were grouped, leading to nine different categories. Next, the theoretical framework was composed by focusing on the learning theory and instructional categories named most frequently in the articles of the systematic review.

RESULTS

Theoretical Grounding

Learning theories are typically divided in three categories: behaviorism, cognitivism and social constructivism (Ertmer and Newby, 2013; Greeno et al., 1996). Behaviorism is centered around the idea that one behavior leads to another and does not take into consideration the functions of the mind (Dilshad, 2017; Stavredes, 2011). According to behaviorism, knowledge is an organized accumulation of associations and skills that exists outside a person and can be gained through behavior modification (Greeno et al., 1996; Stavredes, 2011). Therefore, learning is seen as a change in behavior that can be conditioned using positive and negative reinforcements such as reward and punishment (Stavredes, 2011).

By contrast, cognitivism focuses on students' internal mental structures and addresses the issues of how information is received, organized, stored, and retrieved by the mind (Ertmer and Newby, 2013). In accordance with behaviorism, knowledge is considered to exist outside of the person. However, unlike behaviorism, cognitivism focuses on understanding how human memory works to acquire knowledge and promote learning, instead of focusing on behavior (Stavredes, 2011). Therefore, learning is seen as the discrete changes between states of knowledge, rather than changes in behavior. Moreover, learning is described as a mental activity that entails internal coding and structuring by the student and the student is viewed as an active participant in the learning process (Ertmer and Newby, 2013).

Both behaviorism and cognitivism start from the underlying assumption that learning is an individual process (Ertmer and Newby, 2013). By contrast, social constructivism states that learning is socially situated and knowledge is constructed through interaction with others (McKinley, 2015). According to social constructivism, students learn by building personal interpretations of the world based on their experiences and interactions with the environment (Ertmer and Newby, 2013; Stavredes, 2011). Therefore, in accordance with cognitivism, the student is seen as an active participant in the learning process (Ertmer and Newby, 2013).

Table 1. Overview of the instructional practices from all papers, arranged in nine categories

Category	Instructional practices (extracted from papers)[a]
Integration of STEM content	- Multidisciplinary approach - Interdisciplinary approach - Content integration - Context integration - Integrated curriculum with equal attention to two or more disciplines - Curriculum integration with focus on content knowledge - Explicit assimilation/ integration of concepts from more than one discipline. - Integration of technology - Translation of representations from different STEM disciplines - Connections among learning goals, principles, concepts and skills across discipline specific domains - Infusing/merging of two or more STEM content areas
Focus on problems	- Problem-based learning - Problem-centered learning - Project-based learning - Defining, formulating, evaluating and solving problems - Meaningful/motivating/engaging context - Focusing on big ideas, concepts, themes - Open-ended, real-world, authentic problems
Inquiry	- Posing questions - Planning and carrying out investigations - Collecting, analysing and interpreting data/information - Discovery learning - Inquiry-based instruction - Scientific inquiry - Authentic scientific practices/processes
Design	- Learning through design - Design-based learning - Developing and using models - Designing solutions - Engineering design - Design justification - Opportunities to learn from failure and to redesign based on that learning
Teamwork	- Collaborative learning - Cooperative learning - Communicating information - Teamwork - Working in small groups - Working with others - Interdependence in group work
Student-centered	- Student-centered pedagogies
Hands-on	- Hands-on learning - Hands-on activities - Effective use of manipulatives
Assessment	- Understanding student misconceptions & capabilities - Use assessment as a part of instruction - Performance and formative assessment - Writing for reflection - Building on previous knowledge
21st century skills	- Development of 21st century skills

To answer the question: "Which learning theories form the basis of integrated STEM education?", the articles in the dataset were examined for references to learning theories. Of the 23 papers, only seven mentioned an underlying learning theory for instructional practices in integrated STEM: Clark and Ernst (2007); El-Deghaidy et al. (2016); Guzey et al. (2016); Riskowski et al. (2009); Satchwell and Loepp (2002); Shahali et al. (2017); and Wang et al. (2011). Moreover, all seven articles referred to learning theories from the social constructivist category. As mentioned above, this category of learning theories states that knowledge cannot be transmitted, but rather is actively constructed by students based on their existing ideas and their experiences (Driver et al., 1994; Eastwell, 2002). Moreover, the social aspect of social constructivism dictates that learning is a shared, rather than an individual experience (Prawat and Floden, 1994).

Table 2. Overview of the instructional categories present in each paper

Authors	**Integration**	**Focus on problems**	**Inquiry**	**Design**	**Teamwork**	**Student-centered**	**Hands-on**	**Assessment**	**21st century skills**
Asghar et al., 2012	X	X	X		X				
Bryan et al., 2015	X	X	X	X	X				X
Burrows et al., 2014		X	X		X				
Bybee, 2010	X	X	X	X					
Clark and Ernst, 2007		X		X			X		
Debs and Kelley, 2015	X		X	X					
El-Deghaidy et al., 2016	X	X	X		X				
Guzey et al., 2016	X	X	X	X	X	X	X	X	
Guzey et al., 2016		X	X	X	X				
Hernandez et al., 2014		X	X	X	X				
James et al., 2000	X	X	X		X				
Mathis et al., 2017	X	X		X	X	X			
Pearson, 2017	X	X		X					
Riskowski et al., 2009	X			X	X		X		
Roehrig et al., 2012	X	X		X	X				
Satchwell and Loepp, 2002	X	X	X	X	X		X	X	
Shahali et al., 2017	X	X	X	X	X				
Stohlmann et al., 2012	X	X	X		X	X	X	X	
Stohlmann et al., 2011	X	X	X	X	X	X	X		
Stump et al., 2016	X	X	X	X	X				
Valtorta and Berland, 2015	X	X		X					
Wang et al., 2011	X	X	X						
Wells, 2016			X	X					

Instructional Practices

Instructional practices were extracted from all papers and similar elements were grouped, as shown in Table 1. This led to nine categories of instructional practices: integration of STEM content, focus on problems, inquiry, design, teamwork, student-centered, hands-on, assessment and 21st century skills.

A summary of the different instructional categories found in each article is shown in Table 2 and discussed more in detail below.

Integration of STEM content. The first category contains instructional practices that advocate making connections between the different STEM disciplines. Several approaches for achieving these connections exist and the terminology used for these approaches differs among the reviewed articles. For example, Wang et al. (2011) distinguish between multidisciplinary and interdisciplinary approaches. According to them, in a *multidisciplinary approach*, subject-specific concepts and skills are learned separately in each discipline and students are expected to connect the content, taught in different classrooms, on their own. An *interdisciplinary approach*, on the other hand, starts with a real-world problem or issue and focuses on interdisciplinary content and skills (e.g., critical thinking and problem solving), rather than subject-specific content and skills. By contrast, Satchwell and Loepp (2002), provide a different definition for interdisciplinarity. Moreover, they discriminate interdisciplinary approaches from integrated approaches, rather than multidisciplinary approaches. According to them, *interdisciplinary curricula* focus on instruction within one domain, while supporting the content with implicit connections to the other disciplines. *Integrated curricula*, on the other hand, explicitly assimilate concepts from more than one discipline and apply equal attention to two or more disciplines. A similar distinction is made by Roehrig et al. (2012) who differentiate between content and context integration. According to them, *content integration* focuses on the merging of the disciplines into a single curricular activity or unit to highlight "big ideas" from multiple content areas, while *context integration* focuses on the content of one discipline and uses contexts from others to make the content more relevant.

Although there is no consensus about the terminology, most of the reviewed articles do agree that making strong connections between the different STEM-disciplines is necessary for integrated STEM to work. Many papers (e.g., Satchwell and Loepp, 2002; Shahali et al., 2016; Stump et al., 2016) emphasize the importance of applying equal attention to two or more STEM disciplines and/or explicitly assimilating concepts from different

STEM-disciplines. Making integration explicit is critical, because students do not spontaneously integrate concepts across different representations and materials on their own (Pearson, 2017). Therefore, intentional and explicit support to help students build knowledge and skills across disciplines should be provided (Pearson, 2017). Nonetheless, although the importance of explicitly integrating large amounts of STEM content has been stressed, several papers (e.g., Guzey et al., 2016; Pearson, 2017) warn that integration should remain meaningful and purposeful and that more integration is not necessarily better. Moreover, students' knowledge in individual disciplines should be supported. Students require sufficient understanding of the relevant concepts in the individual subjects to connect ideas across disciplines (Pearson, 2017). Therefore, integrated STEM education should also focus on learning goals and standards in the individual STEM subjects, so as not to inadvertently undermine student learning in those subjects (Pearson, 2017).

Focus on problems. The second category entails the use of real-world problems tied to an engaging and motivating context. In the reviewed papers, different terms are used to designate this: problem-centered learning, problem-based learning and project-based learning. Although all of these approaches are student-centered, promote active learning and advocate the use of authentic real-world problems, specific differences between these instructional approaches exist (Ashgar et al., 2012). In project-based learning, students are provided with the desired specifications for the end product and teachers serve as expert coaches that provide guidelines and suggestions for more effective ways to achieve this predetermined final product (Ashgar et al., 2012). By contrast, in problem-based learning, there is no predetermined end product and students are required to identify and define the problem on their own. The goal of problem-based learning is for students to develop problem-solving skills by going through a realistic self-directed problem-solving process. Therefore, the teacher does not provide specific learning guidance, but rather (s)he serves as one possible resource that students can use to achieve their goal (Ashgar et al., 2012). Finally, problem-centered learning holds the middle between project-based and problem-based learning regarding teacher guidance. Although the problem is more open-ended compared to project-based learning, problem-centered learning focuses mainly on applying and transferring knowledge to realistic contexts, while problem-solving skills are seen as an additional outcome (Merrill, 2007; van Merriënboer and Kirschner, 2007). Therefore, in contrast to problem-based learning, a carefully sequenced progression of problems and specific types of guidance are provided (Merrill, 2007; van Merriënboer and Kirschner, 2007).

Nonetheless, despite the different terminology, the same important aspects are emphasized in the different articles. First of all, instruction should start by presenting students with a problematic situation that serves as the organizing center and context for learning (Ashgar et al., 2012; Bybee, 2010). By introducing the problem *at the start* of the learning unit, students can activate existing mental models early in the learning sequence and connect new information and experiences to their prior knowledge in a meaningful way (Ashgar et al., 2012). Moreover, instruction should take place in a motivating and engaging context involving current events and/or contemporary issues. That way, students can link the knowledge and skills to be learned to their personal experiences and meaningful learning is encouraged (Guzey et al., 2016). Finally, the problems presented to the students should be authentic, open-ended, ill-structured, real-world problems (Burrows et al., 2014; Satchwell and Loepp, 2002; Shahali et al., 2017). These are 'messy' problems, often with an abundance of information, that resemble challenges encountered by engineers and scientists in the workplace and allow for multiple solution paths and answers (Ashgar et al., 2012).

Inquiry. A third category entails instructional practices referring to the use of inquiry. In inquiry-based learning, students engage in hands-on activities that allow them to discover new concepts and develop new understandings (Satchwell and Loepp, 2002). Thus, experiental learning is intentionally used to promote knowledge construction (Wells, 2016) and students are encouraged to test their existing ideas by taking things apart, making predictions, observing and recording their explanations (Satchwell and Loepp, 2002). Although inquiry-based learning originated in science education, where it usually entails that students have to engage in authentic science practices (e.g., planning and designing experiments and collecting data), it is not restricted to this domain, but also occurs in mathematical or technological contexts (Satchwell and Loepp, 2002).

In the reviewed papers, several important aspects of inquiry-based learning are mentioned. First of all, questioning is an important part of inquiry-based learning, because it initiates all knowledge building (Wells, 2016). Students are stimulated to question their current knowledge about a given topic and to identify which additional knowledge they require to move forward (Stump et al., 2016; Wells, 2016). Secondly, students should use this prior knowledge to generate new ideas, design and conduct investigations and discover new concepts. Moreover, they not only need to carry out the experiments, students also need to demonstrate their understanding of the concepts explored (Satchwell and Loepp, 2002). Finally, an appropriate amount of guidance should be provided to help students achieve the desired conceptual change (James et al., 2000; Satchwell and Loepp, 2002). Truly authentic inquiry experiences might be challenging for high school students, due to their lack of experience and knowledge, or because they have not reached the level of cognitive development required for abstract thought (Lawson, 1980; Purser and Renner, 1983). Moreover, pure discovery learning without guidance might be ineffective because students may not come into contact with the to-be-learned content (Mayer, 2004). Therefore, teachers need to provide guidance by questioning students to help them discover flaws in their reasoning and/or research design, ultimately helping them to arrive at a solution (Buck et al., 2008).

Design. The fourth category refers to the use of technological or engineering design. By actively engaging students in engineering design challenges, they not only learn about engineering design processes and engineering practices, but also deepen their understanding of disciplinary core ideas (Guzey et al., 2016; Hernandez et al., 2013; Shahali et al., 2016). Engineering design activities can strengthen students' knowledge of science, technology and mathematics, because they fill the gap between factual content knowledge, abstract knowledge and application (Riskowski et al., 2009).

In the reviewed papers, several aspects of qualitative engineering design are mentioned. First of all, effective design challenges should be open-ended, authentic, hands-on, and multidisciplinary (Shahali et al., 2016). These are challenges that represent industry problems, allow students to explore or develop technologies and require them to work with incomplete information and to consider constraints, safety, risks, and alternative solutions (Guzey et al., 2016). Moreover, the engineering design process should entail different iterative phases, such a defining the engineering problem, designing engineering solutions, implementing a solution, testing the solution and evaluating and optimizing the solution (Bryan et al., 2015; Wells, 2016). Furthermore, throughout the design process, students must manage risk and uncertainty, consider prior experience and learn from failure (Bryan et al., 2015; Guzey et al., 2016). In addition, a final requirement for qualitative engineering design is the incorporation of design justification (Bryan et al., 2015; Wells, 2016). Students should be able to demonstrate what they have learned in the design process, justify their design decisions by means of this newly acquired knowledge and make recommendations about the design, based on the results of their tests (Bryan et al., 2015; Wells, 2016). This design justification serves as an effective mechanism for revealing student development and therefore facilitates conceptual change (Wells, 2016).

Cooperative learning. The fifth category entails the promotion of teamwork and collaboration with others. In the reviewed papers, two approaches to small-group learning are distinguished: collaborative and cooperative learning. Although the papers in the review not explicitly define both approaches, other researches have appointed their difference in teacher guidance as main discriminating factor. In collaborative learning, students structure their own group work, without receiving formal training in small-group social skills. The teacher does not actively monitor the groups and refers all questions back to them, because he wants students to resolve group conflicts on their own (Matthews, 1995). In cooperative learning on the other hand, the teacher moves from team to team, observes the interactions and intervenes when he feels it is appropriate. Moreover, training in small-group social skills is provided and the teacher encourages students to assess the functioning of the group in order to improve the levels of participation and performance (Matthews, 1995).

Although almost all papers in the systematic review refer to the use of teamwork in integrated STEM, the description of how this teamwork should be organized or what the crucial aspects are, is much less elaborated compared to the previous categories. According to Guzey et al. (2016), it is important for students to have sufficient time and multiple opportunities to be involved in teamwork, such that they can improve their teamwork skills. Moreover, several authors (e.g., Bryan et al., 2015; Roehrig et al., 2012; Stohlmann et al., 2011) stress the importance of not only stimulating teamwork skills, but fostering communication skills as well. To do so, students need to be encouraged to communicate science concepts, mathematical and engineering thinking through reading, writing, listening and speaking (Stohlmann et al., 2011). Finally, positive interdependence between the group members should also be stimulated (Ashgar et al., 2012). This means that students should work on tasks that they believe are only soluble if all group members contribute to the effort. Positive interdependence can be achieved through: (1) providing rewards for successful interdependence; (2) having activities in which resources are shared; or (3) providing a task that is too difficult for students to do individually (Johnson and Johnson, 1999).

Student-centered. The next category refers to the use of student-centered pedagogies and was only present in four of the reviewed articles. Guzey et al. (2016) indicate that lessons and activities in an integrated STEM unit should be student-centered, because students develop better understanding and skills through active participation in learning activities. Nonetheless, specific guidelines for implementing student-centered learning are not discussed in the reviewed articles.

Hands-on. The instructional practices in the seventh category refer to the use of hands-on learning, hands-on activities and manipulatives. Through hands-on activities, students are less restricted and can actively experience learning. Moreover, relevance is conveyed through hands-on learning, because it allows students to observe the role of innovation in everyday life (Clark and Ernst, 2007). As with student-centered learning, no specific recommendations for implementing hands-on instruction are given in the reviewed papers.

Assessment. The eighth category deals with assessment and was only mentioned in three of the reviewed articles. According to Stohlmann et al. (2012), assessment should be used as a part of instruction. Moreover,

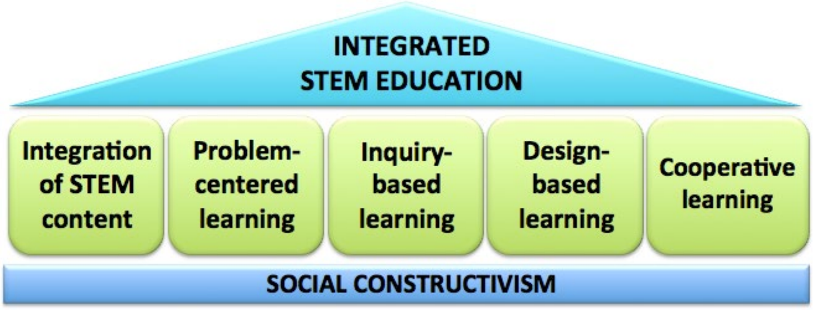

Figure 1. Theoretical framework for instructional practices in integrated STEM

Satchwell and Loepp (2002) dictate that assessments should present students with authentic tasks that require them to connect all key concepts studied in mathematics, science, and technology and should include a scoring rubric.

21st century skills. The final category comprises '21st-century skills', referring to the knowledge, skills, and character traits that are deemed necessary to effectively function as citizens, workers, and leaders in the 21st-century workplace (Bryan et al., 2015). They were only explicitly mentioned in one of the reviewed articles, i.e. Bryan et al. (2015). Although several lists of 21st century skills exist, the ones named by Brian et al. (2015) include creativity and innovation, critical thinking, problem solving, communication and collaboration.

DISCUSSION AND CONCLUSION

A Framework for Teaching Integrated STEM

Based on the results of the systematic review, a theoretical framework for instructional practices in integrated STEM for secondary education was created. To do so, the five categories of instructional elements most commonly present in the papers of the systematic review were selected. These categories were deemed most essential for teaching integrated STEM. Moreover, when different instructional practices were named within the same category (e.g., cooperative learning versus collaborative learning), the strategy with the most emphasis on teachers' guidance was chosen. This approach was used, because the theoretical framework targets secondary students. Since their knowledge and experience is limited, they might need sufficient teacher assistance to achieve conceptual change (De Groof et al., 2012). The final framework consists of five distinctive but related key principles: integration of STEM content, problem-centered learning, inquiry-based learning, design-based learning and cooperative learning. All these principles are rooted in a social constructivist view on learning. An overview of the framework is given in Figure 1.

The first principle, integration of STEM content, refers to the explicit assimilation of learning goals, content and practices from different STEM disciplines. Due to the lack of consensus about terminology, no specific strategy (e.g., multidisciplinary, interdisciplinary or integrated learning) is proposed. Problem-centered learning, the second principle, indicates that learning environments should involve students in authentic, open-ended, ill-structured, real-world problems to increase the meaningfulness of the content to be learned. The third principle, inquiry-based learning, refers to learning environments that engage students in questioning, experiental learning and hands-on activities that allow them to discover new concepts and develop new understandings. Design-based learning, the fourth principle, entails the use of open-ended, hands-on design challenges that provide students with the opportunity to not only learn about engineering design processes and engineering practices, but also deepen their understanding of disciplinary core ideas. Finally, the principle of cooperative learning indicates that students should get the opportunity to communicate and collaborate with each other to deepen their knowledge. All key principles are supported by a social constructivist view on learning, which dictates that knowledge is actively constructed by the students and that learning is a shared, rather than an individual experience.

Although the other instructional categories distinguished in the systematic review were not explicitly included in the framework, this does not mean they are considered to be unimportant. Rather, we believe that many of these categories are overarching aspects that are inextricably linked with one or more of the discerned key principles. For example, both problem-centered learning and inquiry-based learning are student-centered pedagogies and both inquiry-based and design-based learning advocate the use of hands-on learning. Moreover, the 21st century skills named by Bryan et al. (2015) include creativity and innovation, critical thinking, problem solving, communication and collaboration. Hence, although the importance of developing these skills is not denied, they are already largely present in the other key principles, defying the need for a separate category. In addition, assessment is not explicitly incorporated in the framework, because it is an indispensable aspect of any instructional approach (Black and William, 1998) and not specifically linked to integrated STEM education.

Benefits

The framework proposed in this paper is a valuable contribution to the challenge of implementing integrated STEM education and has several benefits. First of all, in contrast to many studies that reduce the instructional strategy for integrated STEM to either inquiry-based learning, problem-based learning or design-based learning (Moore et al., 2014; Mustafa et al., 2016; Sanders, 2009), this framework allows for a more specific and detailed description of instructional practices through the formulation of five key principles. As can be seen by the description of the principles, they are complementary, but also partially overlapping. For example, teacher guidance is an important aspect of both problem-centered and inquiry-based learning and the use of open-ended, authentic problems is advocated in both problem-centered and design-based learning. Nonetheless, all key principles have their own specific characteristics, making it worthwhile to include them all in the framework. Secondly, as opposed to other researchers who have described instructional practices for integrated STEM and failed to explain how the instructional elements were derived (e.g. Bryan et al., 2015), the current framework is the result of a systematic review of existing literature. In the absence of empirical research about which elements are crucial for the successful implementation of integrated STEM, this is a valuable alternative to provide some form of evidence-based foundation. Finally, the framework presented in this paper is widely applicable and can be used both in teaching practice and in educational research. While teachers and educators can use the five principles to develop curriculum materials for integrated STEM in a fine-grained manner, educational researchers can employ them to analyse instructional practices in more detailed and specific ways.

Limitations

Despite the benefits, the current study and resulting framework also have some limitations. Although a systematic review was done to reduce selection bias, it is still possible that other relevant articles exist that were not included in the dataset. For example, we chose to focus solely on integrated STEM in secondary education. Therefore, other interesting articles about related subjects, such as integrated STEM in primary education (e.g., Gresnigt et al., 2014) or design-based learning in higher education (e.g, Gomez Puente et al., 2013) were not taken into account. Moreover, the conclusions of the review are based on a small dataset and many of the articles have one or several authors in common, which could partially explain why the same instructional categories were named in the different papers. Finally, although the framework can be used as a guideline for designing and implementing curriculum materials for integrated STEM, implementation of the five key principles is not straightforward. For example, creating meaningful connections between STEM disciplines is a challenging task. It requires an iterative act of matching and reorganizing learning goals between the different disciplines, searching an appropriate sequence for these goals and incorporating new learning goals. Therefore, teachers need to be willing to invest time and effort in the implementation of integration. Moreover, letting students conduct their own experiments or build a prototype requires extra time. Hence, teachers might struggle to incorporate new instructional practices, such as inquiry-based and design-based learning, since they usually need all their lessons to finish the traditional curriculum in time. Additionally, creating an interdisciplinary learning approach requires cooperation between teachers of the different STEM disciplines, which demands sufficient human, financial, material and infrastructural resources.

Perspectives for Future Research

Although this paper provides an important step towards improving the implementation of integrated STEM education, the need for further research exists. Empirical research is needed to confirm the validity of a framework consisting of five key principles. Next, systematic examination of the effects of integrated STEM, implemented according to this framework, on students' cognitive and affective learning outcomes is required. Moreover, looking at each key principle's individual impact on these learning outcomes could provide information about the necessity of each principle and lead to a refinement of the framework. Finally, the influence of different factors (e.g., teachers' attitudes, school context) on the implementation of integrated STEM could be examined. Insight into these factors could help to improve the implementation of integrated STEM education, therefore ultimately contributing to students' increased motivation for STEM.

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