The Challenges and Enablers of Maker-Centered Learning Experiences in Formal Education

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ABSTRACT

The Challenges and Enablers of Maker-Centered Learning Experiences in Formal Education

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Maker-centered education, inspired by the Maker Movement, has gained popularity in schools for its creative, hands-on approach, yet its integration into formal K-12 settings remains complex and underexplored. This thesis investigates key challenges and enablers for teachers in adopting maker-centered education by investigating the challenges reported in the current K-12 literature, the factors experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered education into K-12 formal education settings, and the potential learning outcomes of an interdisciplinary maker-centered learning experience in the context of higher education.

This thesis presents three manuscripts. Manuscript 1 reports the results of a scoping review that identified 105 studies reporting challenges in maker-centered education integration in 10 primary areas. Findings revealed that although one third of studies mentioned challenges, most lacked detailed explanations. Notably, challenges varied based on educators' level of experience with maker-centered education; however, only a minority of studies that identified challenges involved experienced teachers in maker-centered education. These findings highlight the need for further research with experienced educators of maker-centered education to better understand these challenges.

Manuscript 2, a qualitative study involving 21 educators with maker-centered education experience, provided insights into both known and newly identified challenges, together with factors that facilitate integration. The findings highlighted the need for further research in each of the challenge areas, particularly regarding learning outcomes of maker-centered education as some remain unconvinced of its learning potential.

In manuscript 3, I document a maker-centered learning experience in which I participated during my doctoral program that resulted in publishable scientific findings, contributing valuable evidence toward the educational benefits of maker-centered education.

This thesis reveals numerous educator-perceived challenges when implementing maker-centered education, underscoring the need for a structured approach for successful integration of maker-centered education programs in formal education settings. With a greater understanding of these factors, the Guiding Questions Framework for Developing a Maker-Centered Education Program and a set of recommendations were developed to help education leaders and educators develop and implement maker-centered education programs in formal education settings so that students can benefit from its many affordances.

Keywords: maker-centered education, maker-centered learning experiences, Maker Movement, formal education, challenges and enablers

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CONTRIBUTION OF AUTHORS

Manuscripts 1: I was the primary author of manuscript 1. A research assistant (Don Undeen) was hired for the role of second reviewer for the screening phases of the scoping review process, however, I was solely responsible for all other phases of the scoping review (i.e. development of the scoping review protocol, retrieval of articles, data extraction, data analysis, and writing of the manuscript). Dr. Davidson provided feedback when necessary for each phase of the process.

Manuscript 2: I was the primary author of manuscript 2, with Dr. Ann-Louise Davidson as co-author. I was responsible for all phases of the study (i.e. interview protocol development, data collection, data analysis, and writing of the manuscript) with the assistance of Dr. Davidson for some of the data collection and analysis. Dr. Davidson also provided feedback when necessary for each phase of the process.

Manuscript 3: I was the primary author of manuscript 3, with Dr. Clothilde Brochot, Dr. Ann-Louise Davidson, Barbara Layne, and Ali Bahloul as co-authors. While the aim of the project was collectively determined, I was solely responsible for the development of the prototypes, the interpretation of results, and the writing of the manuscript. Dr. Brochot assisted in the collection of data. All co-authors provided feedback on the manuscript.

All three manuscripts will be submitted for publication upon approval of this thesis. Manuscript 3 has already been presented at the 2022 International Society for Respiratory Protection annual conference (https://www.isrp.com/virtual-2022-papers/1347-abstracts-virtual/file, p. 21).

Use of AI: A large language model (LLM, ChatGPT-4o) was used in a limited way for the production of this thesis. The LLM was used to reformulate a small number of paragraphs into more concise text and to assist in the generation of questions for the questions framework based on the findings of the thesis. In all cases, I modified and added to the text that the LLM generated to reflect my intended meaning.

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General Introduction

Introduction

In 2009, I was assigned to work with Ryan (pseudonym), a 9-year-old child who had already lived what many of us are fortunate enough never to experience in our lifetime. After the murder of his sister, Ryan was removed from his family and placed in foster care in a city he was not familiar with. He found himself in a home for boys who were older than he was, most having had very troubling childhoods. He was alone, scared and traumatized.

At that time, I was working as a resource teacher in a suburban elementary school. I worked with students individually or in small groups to improve their basic academic skills, typically in reading, writing and math. I used the popular methods of teaching that I had been exposed to, mostly involving pen-and-paper exercises of some kind. Most students responded well to my sessions, enjoying our time together and improving rapidly in their academic performance, but I realize now that it was most likely due to the individual attention and tutoring I was giving them more than the actual methods I was using that led to my success.

The first day I met Ryan, I knew my usual approach was not going to work. He spent the entirety of our first session crying uncontrollably in the darkest corner of the classroom. No matter what I did, I could not console him. I quickly realized that before I could work on his academic skills, we needed to get him past his emotional distress. I spoke with the school's behavioural therapist and we decided to develop a series of activities that would allow him to express himself through his hands by building things, painting, drawing, and using a variety of physical materials that would help him not only externalize his thoughts, but also reconnect with the outside world. We used hammers and nails to create nail boards for string art, electric drills to make spin art, Paper-Mache to make models of planets and superheroes, and we even managed to plaster both of his hands to make life-size replicas of superhero gauntlets (an activity that required a lot of trust on his part). After two weeks we saw his first smile, after a month, we heard his first laugh. We started to see a whole new Ryan.

At this point we were better able to assess Ryan's academic abilities. He was three years behind his peers in reading, writing and math. He needed to catch up on a lot, and quickly. The problem? He hated school. He revealed to me that his experience of school thus far had been one marked with confusion and frustration with the work, and ridicule from what he felt were unsympathetic teachers. As much as he liked working with me, he refused to engage with anything he perceived was related to 'school work', namely reading, writing, and math. I needed to find another way to engage him.

I began by bringing things in to class that I had found fascinating as a child: magnets, kaleidoscopes, microscopes, Lego building sets, and much more. He seemed interested, but nothing captured his attention enough for me to use it as a 'Trojan horse' to get him engaged with reading, writing or math. Then I discovered he liked magic tricks. Not being a magician and no way capable of doing anything related to slight-of-hand myself, I decided to learn how to do some simple card tricks. Each day, I came in and showed him a new card trick. He was fascinated and we'd spend the whole session perfecting each new trick. Eventually, our repertoire of tricks grew and we were learning them so quickly that he started to confuse the procedures of the various tricks. I suggested that maybe we should write them down and create a catalogue of instructions for the tricks that we could refer to when we couldn't remember them (yes, very sneaky, I know). He was in! So, we wrote all the tricks down (mostly me at first, but shifting to him progressively as he became more confident with his writing and less satisfied with my writing style) and we created a booklet he carried with him everywhere. Finally, I was getting somewhere! But not with math…

Remembering a school activity planting and growing beans that I had enjoyed as a child, I decided to attempt the activity with Ryan. I suggested to him that we plant a bean seed and watch how it grows and learn about what it needs to grow and thrive. He was very interested. Each day, we would check on the bean and see how much it had grown. One Monday, when we returned from the weekend, he was amazed at how fast it had grown during the two days that we had been away and was convinced it had grown faster than in previous days. I mused about how there was no way of knowing because we had not measured and kept track of its growth. He suggested we plant another bean so that we could measure and see if its growth stays the same (is constant) or if it changes as the plant matures. While we were at it, we also decided to plant a few other bean seeds to see how different conditions would impact the plants' growth (I used the term 'we' when working with Ryan because he was very fearful of failure. If it was 'our' project, then he was not solely responsible if something failed. At the end, however, I let him take all the credit for the work.).

To make sure we collected all the necessary data we wanted to gather, we wrote a plan for the experiment (we designed the plan together, but he wrote it). Each day, he wrote down our observations and recorded the various plants' growth in a table and on a graph. And what did we find? Ryan was right! The beans that had the necessary conditions did in fact grow faster at some points in their development than at other times. We decided this was noteworthy and that we should take what we had already written down and prepare a report that he could share with others. Once we finished the report, we put it in a presentation folder and he presented it not only to his class, but at a special meeting with the school's principal. For the first time since being in school, Ryan had created something he was proud of, and it involved reading, writing, AND math!

With some simple, well-chosen 'hands-on' activities (some of which were more closely related to 'making,' such as miniature wooden furniture building), Ryan went from a child who literally hid in the corner of the classroom crying the first day I met him, to beaming with pride with the report he had written, presenting his work to the principal. The impact of these experiences on Ryan was evident to me, both academically and emotionally. This child who had lived through so much by the age of 9, and who had hated school and refused to engage in what he perceived was 'school work', was now not only happy to be at school, but quickly improving academically. Eventually he even relented and engaged in more apparent "school work" as he felt more confident that he would succeed at it.

My experience with Ryan was an unusually ideal situation because I worked with students individually or in groups with no more than six students at once, in a context where I had the liberty to attempt innovative approaches with students (including what I now recognize as maker-centered approaches), which is rarely possible given the lack of resources in schools. However, I saw the potential of using 'hands-on' approaches with students whenever possible. Other than calling them 'hands-on' experiences or experiential learning, however, I did not know much more about these types of pedagogical approach.

It was only in 2016, when I attended a mini maker faire, that I discovered the Maker Movement and realized the potential of 'making' for education. Thinking back to Ryan's case, I immediately saw the learning and psychological potential of maker-centered education, particularly for struggling students. My goal for my doctoral research was to explore and uncover the conditions under which teachers would best be able to engage in these types of approaches with diverse students by identifying the challenges and enablers that teachers encounter when attempting maker-centered education with students. The following dissertation presents what I found.

In the following section, I will introduce the Maker Movement, explore its impact on education, and discuss the potential benefits of incorporating maker activities into educational settings. I will also examine the challenges of integrating maker-centered education into formal education and highlight the need for further investigation in this area.

The Maker Movement

The Maker Movement refers to a “movement of hobbyists, tinkerers, engineers, hackers, and artists committed to creatively designing and building material objects for both playful and useful ends.” (Martin, 2015, p. 30). In the context of the Maker Movement, ‘making’ refers to:

> [a] class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a ‘‘product’’ of some sort that can be used, interacted with, or demonstrated. Making often involves traditional craft and hobby techniques (e.g., sewing, woodworking, etc.), and it often involves the use of digital technologies, either for manufacture (e.g., laser cutters, CNC machines, 3D printers) or within the design (e.g., microcontrollers, LEDs). (Martin, 2015, p. 31)

Those who engage in ‘making’ or ‘maker activities’, often self-identify as ‘makers’ (Dougherty, Dale, 2013), which is the term I will use in the thesis.

The Maker Movement, like most movements, has an unclear beginning. Scholars and makers generally indicate the Maker Movement beginning at approximately the time Dale Dougherty created Make Magazine in 2005, and the globally popular Maker Faires, also initiated by Dougherty in 2006 (Marsh et al., 2017). Although Dougherty popularized the terms ‘making’ and ‘maker’, the movement likely has origins much earlier than 2005.

Some scholars and makers focus on the history of the Hacker Movement in the mid- to late-twentieth century, and the computational and Internet revolution in the late-twentieth and early-twenty-first century, as the origins of the Maker Movement (Hatch, M, 2014). The Hacker Movement originated with the Tech Model Railroad Club, a student-run club at MIT in the USA, and has evolved into the well-established Hacker Culture (*Tech Model Railroad Club*, n.d.). Although hacking primarily involved computers at first, it has evolved into hacking physical objects as well (Marsh et al., 2017).

Other scholars and makers posit that the Maker Movement has a broader origin stemming from the crafts and the do-it-yourself movements (Fox, 2014; Kuznetsov & Paulos, 2010). For example, Fox (2014) argues that the current Maker Movement stems from a long-existing series of do-it-yourself (DIY) movements that has three waves: subsistence DIY, which refers to people producing for themselves what they consume; industrial DIY, which refers to kit consumption where people buy mass-produced kits with instructions to construct the items themselves (e.g. Ikea furniture and robotics kits); and Third Wave DIY where the two first waves are combined such that the efficiency and cost effective mass production of industrial DIY and the liberty to create personalized objects to suit specific needs or desires of subsistence DIY are merged.

Regardless of its origins, the Maker Movement has been enormously popular. For example, since the first Maker Faire in the San Francisco Bay Area in 2006, nearly 1,500 Maker Faires have occurred globally with over 7.5 million attendees (*Maker Faires at a Glance*, 2024). Maker Faires have taken place in countries as diverse as Nigeria, Moldova, Brazil, Germany, Czech Republic, Japan, Italy, Mexico, Spain, Costa Rica, South Korea, Sweden, France, Australia, and Canada (*Maker Faires at a Glance*, 2024). Although Maker Faires have undoubtedly spurred the rapid growth of the Maker Movement, the movement's overall growth has largely been attributed to the advent of affordable, easy-to-use, digital fabrication tools (e.g. 3D printers, laser cutters), cheap and easily sourced electronics (e.g. microcontrollers, microcomputers), and online networks that afford collaboration and knowledge sharing (Dougherty, Dale, 2013; Hatch, M, 2014; Martin, 2015). These new technologies, once only available to trained professionals, now allow the layperson to create sophisticated and precise working objects that resemble professionally made products (Cohen et al., 2017). As such, the Maker Movement has been touted as a democratizing force as it is claimed to allows individuals to become active agents in the use of tools and technologies and reduces people's reliance on developers and manufacturers, allowing them to become producers themselves (prosumers) and not simply consumers (Anderson, Chris, 2012; Bardzell et al., 2017; Dougherty, Dale, 2016; Hatch, M, 2014; Stoltenberg et al., 2024; Tanenbaum et al., 2013; Unterfrauner et al., 2018).

The Maker Movement is not without criticism, however. Despite claims of its democratizing potential, some have suggested that the Maker Movement has not been as effective at democratization as some have claimed. Hunsinger and Schrock (2016) point out that the Maker Movement tends to promote capitalist structures as makers purchase considerable amounts of digital fabrication technologies, tools and materials to produce their artifacts, artifacts that Lakind et al (2019) argue are often developed for the purpose of sales. Sivek (2011) highlighted that influential promoters of making, such as Make magazine, implicitly encourage the use of costly digital fabrication tools through the types of advertising they include. And in some cases, arguments for the inclusion of making in education have been criticized for their capitalist agendas as making in education is viewed as "a tool to produce an economically productive workforce and society" (Lakind et al., 2019; p. 236). In developing countries, Waldman-Brown and Muthui (2015) noted that promoters of the Maker Movement tend to adopt neo-colonial approaches where elite participants compete with existing local grassroots initiatives, rather than supporting them. In both developing and developed countries, the Maker Movement has also been criticized for its lack of adequate inclusion and representation of women, minority groups, and economically marginalized populations (Clapp et al., 2017; Marsh et al., 2017; Saari et al., 2021). In many cases, makerspaces (physical spaces where communities of makers gather and engage in making using shared tools and equipment) are members-only with monthly fees, further limiting access to marginalized populations.

Despite the criticisms of the Maker Movement, the activity of making itself is still posited to have many affordances for education due to its collaborative, creative, and interdisciplinary approach to problem-solving (Giusti & Bombieri, 2020; Hachey et al., 2022; Hartikainen et al., 2023; Martinez & Stager, 2013; Morado et al., 2021; Vossoughi & Bevan, 2014). As a result, schools are increasingly developing educational programs that attempt to replicate the types of activities makers engage in (Schad & Jones, 2020).

The Maker Movement and Education

While the exponential advances in technology and the development of online networks have facilitated the growth of the Maker Movement, these same changes, with the increasing demands of globalization, and the demographic shifts we have experienced in the last few decades, are resulting in changes in our lived experience that are progressing faster than schools are currently adapting (Care et al., 2018; Education Commission, 2016; Grand-Clement et al., 2017; OECD, 2016; Saavedra, 2020; *Spark & Sustain: How All of the World's School Systems Can Improve Learning at Scale*, 2024; Torkington, 2016). For a few decades now, scholars and experts in industry have expressed concern that youth emerging from formal educational systems are not adequately prepared for current and future professional and civic life (Hatch, M, 2014; Marsh et al., 2017; *Spark & Sustain: How All of the World's School Systems Can Improve Learning at Scale*, 2024; Tucker, 2011). Although education systems of most nations have been slow to adapt to these new changes (OECD, 2016; *Spark & Sustain: How All of the World's School Systems Can Improve Learning at Scale*, 2024), there are indications of shifts away from solely focusing on declarative and procedural knowledge towards approaches that include the development of independent learning, critical thinking, problem-solving, knowledge transfer to new contexts, and collaboration so that graduates of formal education are able to continually adapt to changes in information, technology, employment, and social conditions (Care et al., 2018; Creese et al., 2016; Grand-Clement et al., 2017; OECD, 2016). Countries like Australia, Great Britain, France, Mexico, Brazil and Canada have all introduced education reforms that place a greater emphasis on skills suggested to be necessary to succeed personally and professionally in the 21st century (Care et al., 2018). Quebec, for example, introduced cross-curricular competencies to its education plan (*Québec Education Program*, 2001) and has more recently developed the Digital Action Plan for Education and Higher Education (*Digital Action Plan for Education and Higher Education*, 2018) in an effort to further address the development of digital skills.

The focus of many of these shifts has been toward what have been called '21st century skills' (Care et al., 2018; *Framework for 21st Century Learning Definitions*, 2019). Twenty-first century skills are posited to be a set of skills that are crucial, now more than ever, to be able to function adequately in 21st century civic and professional realities (Care et al., 2018). Although no agreed upon list of '21st century skills' exists, they generally include digital skills such as digital literacy and information technology literacy; transversal skills such as problem-solving, design thinking, and critical thinking; interpersonal skills such as communication and collaboration; intrapersonal skills such as self-regulation, autonomous learning, and adaptability; and global citizenship skills such as empathy for others, cultural literacy, and environmental awareness (*Framework for 21st Century Learning Definitions*, 2019).

In efforts to develop said '21st century skills', schools have been seeking novel teaching approaches that promote their development. When the Maker Movement emerged, many scholars and educators recognized its potential for learning and suggested that making in formal education settings could provide learners with authentic learning experiences and develop many of the said '21st century skills' that school systems had been emphasizing (Blikstein, 2013; Halverson & Sheridan, 2014a; Kurti et al., 2014; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013), claims that have been supported by more recent research (Iwata et al., 2020; Timotheou & Ioannou, 2021).

Since the early 2010s, research on maker activities has suggested that participation in making activities (whether in formal education settings or not) has been associated with multiple learning benefits. Maker-centered education has been associated with the use and development of digital skills like computing and programming (e.g. Blikstein et al., 2017), computational thinking (e.g. Yin et al., 2020), online communication skills (e.g. Rafalow, 2016), and skills around the use of the most recently available technology (e.g. Blikstein et al., 2017; Rafalow, 2016). Maker activities have also been associated with transversal skills such as design thinking (e.g. Liu & Li, 2023; Marsh et al., 2017; Papavlasopoulou et al., 2017), experimentation and iteration (e.g. Blikstein et al., 2017; Petrich et al., 2013; Vossoughi & Bevan, 2014), creativity (e.g. Liu & Li, 2023; Soomro et al., 2023; Weng et al., 2022); problem-solving (e.g. Becker &

Jacobsen, 2023; Bevan et al., 2015; Blikstein et al., 2017; Forbes et al., 2021; Ng et al., 2023); and critical thinking (e.g. Forbes et al., 2021; Trust et al., 2018; Weng et al., 2022). Interpersonal skills associated with maker activities include collaboration (e.g. Blikstein, 2013; Davidson, 2018; Dixon & Martin, 2017; Giusti & Bombieri, 2020; Gutwill et al., 2015; Herro et al., 2021; Martin, 2015; Papavlasopoulou et al., 2017) and collaborative knowledge creation (Davies et al., 2023; S. Riikonen et al., 2020), while intrapersonal skills in the context of maker activities include intellectual risk-taking (Petrich et al., 2013; Vossoughi & Bevan, 2014), resourcefulness (e.g. Avendano-Uribe et al., 2022; Ito, M et al., 2010; Sheridan & Konopasky, 2016), persistence (e.g. Bevan, 2017; Davidson & Sanabria, 2018; Petrich et al., 2013), tolerance for error (e.g. Anderson et al., 2019; Bennett & Monahan, 2013), self-regulation (e.g. Agency by Design, 2015; Vossoughi & Bevan, 2014), and self-directed/autonomous learning (e.g. Halverson & Sheridan, 2014; Kurti et al., 2014; Martinez & Stager, 2013; Sheridan et al., 2014). Some research also suggests that making can improve academic performance as a whole (Papavlasopoulou et al., 2017), particularly for at-risk students (J. M. Hughes, 2017), and especially in the science, technology, engineering, and mathematics (STEM) subjects (Blikstein, 2013; Tillman et al., 2014). In addition to skills development and academic performance improvements, maker activities have been associated with student increased interest in STEM (Togou et al., 2020; Weng, Chiu, & Jong, 2022), writing (Davis et al., 2021), and a general improvement in school attendance (Wilson & Gobeil, 2017). Studies also noted improvements in students' sense of confidence (Becker & Jacobsen, 2023; Togou et al., 2020), self-efficacy (Das, 2020; Schlegel et al., 2019; Susmitha et al., 2018), agency (Becker & Jacobsen, 2023), and growth mindset (Vongkulluksn et al., 2021).

The theoretical justification for the affordances of maker-centered education is most often drawn from constructionism. Constructionists posit that concepts and systems are constructed by learners and that these concepts/systems are developed through lived experiences and authentic inquiry (Papert, 1980, 1993). With each new experience, and subsequent reflection, learners modify or confirm existing concepts/systems they hold. As a consequence, concepts cannot be directly transmitted to students but, instead, must be gained through carefully created environments and experiences that are conducive to learning (Papert, 1980, 1993).

Constructionists place a large importance on using 'objects-to-learn-with' as they propose that learning is mediated by creating personally motivated, shareable objects for two reasons: 1) these objects are used by the learner to externalize mental models, build on them and re-internalize the modified models through the creation and physical manipulation of the objects and, 2) through sharing and discussions about these objects learners further develop their understanding of the concepts around the object as they attempt to verbally articular their ideas and receive feedback and insight from those they interact with (Ackermann, 2001; Niemeyer & Gerber, 2015; Papert, 1980, 1991). Research in embodied cognition supports Papert's idea of the importance of manipulating physical objects to construct abstract ideas (e.g. Alibali & Nathan, 2012; Bazzini, 2001; Castro-Alonso et al., 2024; O'Connor, 2017) and research in mathematics has also demonstrates that objects can act as physical substantiations of abstract ideas that are meaningful to children (e.g. Fyfe et al., 2014). Research has also demonstrated the learning benefits of articulating abstract ideas through sharing and communication (e.g. Martinez & Stager, 2013; Stevens et al., 2013).

Papert (1980) also places a particular importance on affect in the learning process. He points out that, without the motivation to reflect on experiences, the learner is not likely to construct complex concepts and systems around these experiences. Therefore, the motivation and engagement of the learner is crucial for learning to occur (see also Drodge & Reid, 2000). Learners must be interested in what they are doing, which is best accomplished when learning activities are interest-driven (Papert, 1980). Self-determination Theory (Deci, E. L. & Ryan, R. M., 1985) supports these claims as motivation is heavily impacted by a person's sense of autonomy (i.e. feeling free to choose how and when to act or participate in an activity) and relatedness (i.e. how the person relates to the task, people, and environment in which they find themselves; (Deci, E. L. & Ryan, R. M., 1985; Ryan & Deci, 2017).

Given the parallels between the tenets of constructionism and the maker ethos, maker activities appear ideal for learning from a constructionist perspective (Laprade, 2021; Martinez & Stager, 2013; Vossoughi & Bevan, 2014). Makers are driven by personal interests to create objects to solve an open-ended problem that is personally relevant to them, they make within a collaborative environment that fosters a culture of learning, and they are able to maximize their learning experience by freely exploring avenues of interest with the support of those around them.

In addition to its theoretical justification via constructionism, maker-centered education holds promise because it represents a unique convergence of multiple long-standing educational approaches and initiatives such as inquiry-based learning, experiential education, integration of technology, interdisciplinary learning and, more recently, STEAM education. Maker-centered education is rooted in inquiry-based learning (J. Hughes, Thompson, et al., 2022), where students begin with a question or problem and explore solutions through investigation and experimentation. Maker-centered education builds upon the legacy of experiential education advocated by thinkers like John Dewey (Halverson & Sheridan, 2014a), emphasizing 'learning by doing' by engaging learners in hands-on activities such as building prototypes, programming robots, or crafting artistic projects, to help learners develop a deeper understanding of concepts. The movement thrives on the integration of cutting-edge technologies, such as 3D printers, laser cutters, microcontrollers, and digital fabrication tools. This aspect of maker education aligns with the push for technology-rich classrooms (e.g. Quebec's 2018 release of the Digital Action Plan for Education and Higher Education), ensuring students gain familiarity with the latest tools and skills believed to be essential for the 21st-century.

Interdisciplinary learning is another important hallmark of maker-centered education. It encourages students to draw upon knowledge from diverse fields such as science, engineering, mathematics, art, and design (Ioannou & Gravel, 2024). For instance, a project to create an automated greenhouse might combine biology, coding, physics, and environmental science. This approach mirrors broader educational efforts to break down traditional discipline silos and foster holistic learning, preparing students to tackle complex, real-world challenges that require multiple perspectives and skill sets. Furthermore, maker-centered education embodies the principles of STEAM (Science, Technology, Engineering, Arts, and Mathematics) by merging technical problem-solving with creative expression. By integrating the arts and other crafts that have long-been done and advocated for in schools (e.g. woodshop; Bailey, 1906)) into the STEM subjects, maker-centered education mirrors real-world innovation processes where creativity, manual skills and technical expertise are equally important (see LaMore et al., 2013 for an example of research that suggests a correction between arts and crafts experience and graduation in STEM subjects).

Finally, maker-centered education resonates with the long-standing educational aim of empowering students to become active participants in their communities and the wider world.

Through projects that address real-world problems or meet community needs, students see the relevance of their learning which can develop a sense of agency and purpose (Blikstein, 2013; Vossoughi et al., 2016). This empowerment aligns with traditional educational ideals of preparing learners to make meaningful contributions to society (e.g. Bailey, 1906).

Recognizing the value of maker experiences for students, schools are increasingly building makerspaces and integrating learning programs that involve making into their curricula in efforts to capitalize on the potential learning affordances of the Maker Movement within the context of formal education (Schad & Jones, 2020). However, despite of the numerous efforts by school systems and educators to replicate the spontaneous social phenomenon of the Maker Movement within schools, it is unlikely that the movement's ethos can be fully recreated in the context of formal education (Cohen et al., 2017). For this reason, scholars such as Clapp et al. (2017) and Caratachea and Monty Jones (2024) refer to school learning activities that attempt to integrate making as ‘maker-centered learning experiences’, or MCLEs for short, to distinguish these activities from the ‘making’ that takes place in maker communities. Likewise, I will use this term throughout this dissertation to refer specifically to learning experiences designed to include elements of making.

Statement of the Problem

Despite the enthusiasm for integrating MCLEs into formal education settings, some have expressed concerns about challenges that may arise when attempting to do so (e.g. Campos et al., 2019; Jocius et al., 2020; Kumpulainen & Kajamaa, 2022). As Kervin and Comber (2021, p. 80) point out, “Classrooms are geographically and institutionally bounded places with physical features, cultural histories, and social roles.” Formal education settings are highly structured environments and will likely present challenges when attempting to integrate student-driven, non-linear, process-based learning activities such as MCLEs (Kervin & Comber, 2021; Novotny, 2019). Jocius et al. (2020) noted:

> Researchers have expressed concerns that institutional constraints of formal learning environments might restrict much of what makes making so powerful in informal learning environments, such as play, imaginative design thinking, and makers' autonomy in choosing which problems to approach and how to solve them. (p. 397)

Researchers have speculated about the challenges that are likely to occur when integrating MCLEs into formal education (Blikstein et al., 2017; Blikstein & Valente, 2019; Flores, 2016; Honey & Kanter, 2013; Martin, 2015; Martinez & Stager, 2013), and many studies have identified challenges in passing, but overall, the research explicitly studying these challenges is limited (Hansen et al., 2019; Hira & Hynes, 2018; Jocius et al., 2020; Petrovich et al., 2022; Walan & Gericke, 2022). In conducting a preliminary literature search for the purposes of this dissertation, while I found many papers that mentioned that there would be challenges integrating MCLEs into formal education, most that identified challenges only discussed them briefly. I was only able to find 10 papers where the primary topic of the paper was to identify tensions and challenges of integrating MCLEs into formal education, and even they were limited in scope and approach.

For example, only 3 of the 10 articles reported on challenges identified by educators with experience in MCLEs: the first only involved two teachers (J. Hughes, Robb, et al., 2022), the second reported solely on the challenges associated with setting up a school-based makerspace (Cross, 2017), and the third reported solely on the challenges encountered during one MCLE experience in a school setting (Hansen et al., 2019). Of the other seven studies, two involved teachers with no prior experience with MCLEs (Bower et al., 2020; Jocius et al., 2020), one did not indicate teachers' level of experience with MCLEs (Thompson, 2021), and one primarily involved pre-service teachers (11 of the 13 participants; Rodriguez et al., 2021). The three remaining studies reported challenges identified by researchers, one limited to challenges with teacher identity (Campos et al., 2019), one based on setting up a lab school (Bull et al., 2016), and one based on reflections from observations from experiences with teachers and schools while conducting research (Stornaiuolo & Nichols, 2021).

Other researchers have noted similar observations in their own review of the literature (J.-Y. Kim et al., 2020; Marshall & Harron, 2018). For example, Kim et al. (2020) noted that the research on the challenges of integrating MCLEs into formal education from teachers' perspective is limited and Marshall and Harron (2018) pointed out that many of the studies that are conducted in formal education settings are one-off experiences that do not speak to the long-term challenges that schools and educators may encounter. Penuel and Fishman (2012) noted that research investigating new educational programs often focus on the development and evaluation of the learning activities themselves, while largely neglecting to consider the complex infrastructural changes that are needed to make the programs fully integrated and sustainable. Unfortunately, at this time, the research into maker-centered educations programs in formal education appears to be following the same pattern.

This is not to say that challenges with MCLEs in schools have not been reported widely. My readings of the literature over the last few years have been peppered with mentions of challenges here and there, but rarely in studies that intended to investigate these issues. This points to the need for a more systematic review of the literature to identify reported challenges, even in studies that do not explicitly investigate challenges with MCLEs in schools as part of their research goals.

A brief overview of the scholarly discussions of the challenges that may be encountered by educators when attempting to integrate MCLEs into their teaching practices appear to fall into a few dominant themes, namely, 1) unrealistic expectations about the learning benefits of digital fabrication technology (e.g. Powell, 2021), 2) tensions related to pedagogical approaches to facilitating learning experiences (e.g. Bevan, 2017; Riikonen et al., 2020), 3) curriculum and standards requirements (e.g. Becker & Jacobsen, 2022; Bennett, D & Monahan, P, 2013; Cohen et al., 2017; Justice, 2015; Kurti et al., 2014; Martinez & Stager, 2013; Tofel-Grehl et al., 2017), 4) assessment (e.g. Blikstein et al., 2017; Flores, 2016; Honey & Kanter, 2013), and 5) training and professional development (e.g. Blikstein & Valente, 2019; Powell, 2021). See Manuscript 1 where I discuss these themes in more depth.

Notwithstanding the challenges, there is evidence of teachers who have apparently succeeded in integrating MCLEs into their teaching practices (e.g. Lockley, 2016; Martinez & Stager, 2013; Wardrip & Brahms, 2016), which suggests that integrating maker-centered education programs into K-12 formal education settings may be possible. In fact, Dougherty (2016) notes that among the strongest proponents of making in education are the educators themselves. Given that teachers typically have some latitude in their teaching practices and how they cover the curriculum (Martinez & Stager, 2013), there may be ways for educators to integrate MCLEs into their teaching practice even if schools and governing bodies are not yet providing the ideal conditions to do so.

At this time, little is known, however, about the circumstances under which these teachers were able to integrate MCLEs into their teaching practices, the challenges they have faced as they integrated MCLEs into their teaching, and what they felt enabled them to succeed. By gaining insight from experienced educators who have integrated MCLEs into their practices it may be possible to better understand factors that help or hinder teachers' ability to integrate these types of learning experiences into their classroom.

Research Questions

This thesis aimed to answer three research questions:

1) What challenges are highlighted in current research literature regarding teachers' efforts to integrate maker-centered learning experiences into formal K-12 educational settings?
2) What factors do experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered learning experiences into K-12 formal teaching?
    a. What are the perceived challenges faced by educators in K-12 formal education who have experience with maker-centered education, as they integrate maker-centered learning experiences into their teaching?
    b. What factors do educators in K-12 formal education, who are familiar with maker-centered education, perceive as facilitating the integration of maker-centered learning experiences into their teaching?
3) What are the potential learning outcomes of an interdisciplinary maker-centered learning experience in the context of higher education?

To answer these research questions, the body of this dissertation is presented in three manuscripts. The first manuscript addresses Research Question 1 and consists of a scoping review of the research literature in maker-centered education in K-12 formal education settings with the purpose of identifying the challenges educators encounter when attempting to integrate MCLEs into formal education contexts that have already been reported. The review outlines the characteristics of the research corpus in the topic area and presents the challenges identified in the literature from 2002 to 2022. This scoping review is the first in the field to focus on the challenges of integrating maker-centered education into K-12 formal education settings.

The second manuscript addresses Research Question 2 and reports on a qualitative-interpretive study I conducted with 21 educators experienced with MCLEs to provide us with a better understanding of the challenges and enablers educators may encounter when integrating MCLEs into their K-12 teaching practice. This study is the first in the field to investigate both the challenges and enablers of maker-centered education in K-12 formal education settings with educators experienced with the integration of maker-centered education in schools.

The third manuscript addresses Research Question 3 and describes the result of a maker experience in which I participated that culminated in scientific findings worthy of publication. I have included this manuscript in response to one of the challenges identified in the literature, namely that of education systems lacking evidence of the learning benefits and outcomes of MCLEs. Given the lack of evidence to support the long-term benefits of maker-centered educational approaches on learning, it is my hope that the manuscript provides evidence to this effect until the field is mature enough to provide better examples. I also took the opportunity to preface the manuscript with a short discussion of my own experiences with maker activities to situate myself as an unconventional teacher and researcher and how it might impact my interpretations of the data. This manuscript contributes to a still small body of literature investigating the long-term benefits of maker-centered learning experiences.

Significance of the Thesis

While schools enthusiastically build makerspaces and attempt to integrate maker-centered programs into their curricula, some warn that if not carefully researched, maker-centered education programs risk being short-lived and considered yet another failed approach to pedagogy (Fulfilling the Maker Promise: Year One, 2017; Weiner et al., 2021). Weiner et al. (2021) stated:

> Elements of maker education closely fit the mold of technology-driven reform, which has a long history of achieving flashy, but short-lived change. (p. 266)

A report from Maker Ed and Digital Promise (2017) echoes this warning:

> [I]f schools over-invest in materials without clear plans and objectives, using implementation models supported by research, initiatives may be scrapped without being given a true opportunity to flourish. (p. 5)

To reduce the risk of poor outcomes, Koole et al. (2020) and Stornaioulo and Nichols (2021) urge that research be conducted in order to better understand the conditions needed for successful integration of maker-centered programs and to support educators and education leaders as they work to these ends. Stornaioulo and Nichols (2021) state:

> [A]ny serious effort to integrate makerspaces into K-12 schools must involve meaningful deliberation and reflection about the underlying frictions that animate educational making. (p. 129)

Understanding the challenges and enablers teachers encounter when attempting to integrate MCLEs into their teaching practices can also help us understand why some fail to integrate these experiences, or why some choose not to use MCLEs in their teaching practice. The responsibility for failed education initiatives has been attributed to teachers in the past (Karimi et al., 2017; Saunders, 2022), but perhaps if the conditions within which they were working were better understood, not only could blame be avoided but better conditions provided to improve the chances of success.

The results of this thesis contribute to our understanding of the lived experiences of educators and the conditions that they perceive have hindered or enabled their attempts to integrate MCLEs into their classroom. The goal is to inform education leaders, policy makers, and interested educators of the factors that are affecting teachers so that the necessary improvements can be made in order to increase the likelihood that maker-centered education programs succeed in K-12 formal education settings. The results of my own experience engaging in an MCLE during my doctoral studies also point to the important learning potential MCLEs offer, and the contributions non-experts can make to a field, when given the necessary conditions. As maker-centered education is still relatively new in its current form, the long-term benefits have not yet been observable, therefore these results provide valuable insight into the potential long-term outcomes of maker-centered education.

Introduction to Manuscript 1

The following manuscript aims to address Research Question 1: What challenges are highlighted in current research literature regarding teachers' efforts to integrate maker-centered learning experiences into formal K-12 educational settings? I chose to conduct a scoping review as my own informal review of the literature over the last seven years suggested to me that the research reporting the challenges of integrating MCLEs into K-12 formal education is fragmented and not yet explicitly studied. My aim by conducting a scoping review was to thoroughly investigate what had already been reported in the literature and to organize and categorize the findings in such a way that would avoid unnecessarily replicating previously conducted research and to assist other researchers interested in pursuing research in this area.

The following manuscript presents the results of the scoping review and the justification that was the basis for the second manuscript of this thesis.

Manuscript 1: The challenges of integrating maker-centered learning experiences into K-12 formal education settings: A scoping review

Abstract

Maker-centered education has become popular in schools due to its posited learning and motivational benefits. Due to the recency of this trend, the challenges of integrating maker-centered education into formal education settings is relatively understudied. We identified 350 articles studying maker-centered education in K-12 formal education settings from 2002 to 2022, 105 of which reported challenges associated with integrating maker-centered learning experiences into school settings. Results revealed 10 primary areas of challenges, however, only 10 studies explicitly aimed to investigate the challenges associated with integrating maker-centered learning experiences into formal education settings as their primary aim of research, resulting in few details about the causes and complexities of the various identified challenges. The findings suggest that further, explicit research into the challenges educators encounter when integrating maker-centered education into their teaching is necessary in order to provide teachers with the optimal conditions to use this approach in their teaching.

Introduction

In response to rapid advances in technology, globalization, and demographic shifts that are continually changing our lived experience, educators and school systems are placing a greater emphasis on learning experiences that provide students with the mindset and skills to thrive in an ever-changing world (Care et al., 2018; OECD, 2016). The Maker Movement has recently been the focus of many of these efforts as maker activities have been suggested to provide participants with authentic learning experiences that develop the skills needed to flourish in these shifting contexts (Bertrand & Namukasa, 2020; Blikstein, 2013; Halverson & Sheridan, 2014a; Kurti et al., 2014; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Timotheou & Ioannou, 2021). Given the Maker Movement is a social phenomenon that normally takes place outside of formal education settings, integrating maker-centered learning experiences (MCLEs) into school settings may present some challenges. A failure to understand and ensure the necessary conditions for teachers to successfully integrate MCLEs into their teaching risks a lost opportunity for a potentially powerful approach to providing authentic learning experiences (Weiner et al., 2021), as well as costly time and resource loss for schools that have built makerspaces only to lose them due to underuse (Wilkerson, 2024) or budget cuts (Locke, 2024). Given the relative recency of this popular movement to integrate maker activities into schools, the research in this area is still in its nascency and somewhat fragmented. The following presents the results of a scoping review that investigated the research published between 2002 and 2022 on the use of maker activities in K-12 formal education settings and any challenges that were reported.

The Maker Movement and its Potential for Learning

The Maker Movement refers to a "movement of hobbyists, tinkerers, engineers, hackers, and artists committed to creatively designing and building material objects for both playful and useful ends" (Martin, 2015, p. 30). Its origins are usually traced back to Dale Dougherty's debut of 'Maker Magazine' in 2005 and his launch of the internationally popular Maker Faires in 2006 (Marsh et al., 2017). Since then, the Maker Movement has grown rapidly, to which Dougherty (2013) attributes a combination of increasingly accessible and affordable digital fabrication tools and electronic components, as well as online networks and digital asset sharing platforms.

Martin (2015) defines 'making' as:

> [a] class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a ''product'' of some sort that can be used, interacted with, or demonstrated. Making often involves traditional craft and hobby techniques (e.g., sewing, woodworking, etc.), and it often involves the use of digital technologies, either for manufacture (e.g., laser cutters, CNC machines, 3D printers) or within the design (e.g., microcontrollers, LEDs). (p. 31)

Because of their nature, maker activities are suggested to have the potential to engage and hone a wide array of skills. For example, making has been associated with the use and development of digital skills like computational thinking (e.g. Yin et al., 2020) and online communication skills (e.g. Rafalow, 2016), transversal skills such as design thinking (e.g. Liu & Li, 2023; Marsh et al., 2017; Papavlasopoulou et al., 2017), creativity (e.g. Liu & Li, 2023; Soomro et al., 2023; Weng et al., 2022) and problem-solving (e.g. Becker & Jacobsen, 2023; Bevan et al., 2015; Blikstein et al., 2017; Forbes et al., 2021; Ng et al., 2023). Making has been associated with interpersonal skills like collaboration (e.g. Blikstein, 2013; Davidson, 2018; Dixon & Martin, 2017; Giusti & Bombieri, 2020; Gutwill et al., 2015; Herro et al., 2021; Martin, 2015; Papavlasopoulou et al., 2017) and collaborative knowledge creation (Davies et al., 2023; S. Riikonen et al., 2020; W. Smith & Smith, 2016), as well as intrapersonal skills such as self-regulation (e.g. Agency by Design, 2015; Vossoughi & Bevan, 2014) and self-directed/autonomous learning (e.g. Halverson & Sheridan, 2014; Kurti et al., 2014; Martinez & Stager, 2013; Sheridan et al., 2014). Some research also suggests that making can improve academic performance in general (Papavlasopoulou et al., 2017), particularly for at-risk students (J. M. Hughes, 2017), and especially in the science, technology, engineering, and mathematics (STEM) subjects (Blikstein, 2013; Tillman et al., 2014). In addition to skills development and academic performance improvements, maker activities have also been associated with improved student motivation, personal growth, and other psychological benefits. For example, research has reported that maker experiences have been associated with increases in student interest in STEM (Togou et al., 2020; Weng, Chiu, & Jong, 2022), writing (Davis et al., 2021), and a general improvement in school attendance (Wilson & Gobeil, 2017). Studies also noted improvements in students' sense of confidence (Becker & Jacobsen, 2023; Togou et al., 2020), self-efficacy (Das, 2020; Schlegel et al., 2019; Susmitha et al., 2018), agency (Becker & Jacobsen, 2023), and growth mindset (Vongkulluksn et al., 2021).

While numerous assertions have been put forth regarding the educational benefits of maker activities, the precise mechanisms of learning through these activities are unclear. Developed by Seymour Papert (1980, 1991), constructionism is among the most commonly referenced learning theories by researchers when discussing learning through maker activities (e.g. Blikstein, 2013; Blikstein et al., 2017; Cohen et al., 2017; Dousay, 2017; Kurti et al., 2014; Martinez & Stager, 2013; Petrich et al., 2013; Resnick & Rosenbaum, 2013). Constructionism proposes that learners actively construct concepts and systems through their lived experiences and authentic inquiry (Papert, 1980, 1993). Through each new experience and the process of reflection, learners affirm or adapt their existing concepts and systems. Consequently, concepts cannot be transmitted directly to students; rather, environments that foster learning need to be established (Papert, 1980, 1993).

Constructionism places significant importance on the utilization of 'objects-to-learn-with' (Papert, 1980, 1993). Learning, according to this theory, is facilitated by the creation of personally motivated and shareable objects for two primary reasons: 1) learners employ these objects to externalize mental models, enhance them, and re-internalize the modified models through the creation and physical manipulation of the objects, and 2) by sharing and engaging in discussions about these objects, learners deepen their comprehension of the concepts associated with the objects as they endeavor to articulate their ideas verbally (Ackermann, 2001; Niemeyer & Gerber, 2015; Papert, 1980, 1991). Merely manipulating and creating objects is insufficient for learning, however. Papert (1980) places particular importance on affect in the learning process. He emphasizes that without genuine interest in the activity, learners lack the motivation to reflect on experiences and are unlikely to construct complex concepts and systems around those experiences. Therefore, the learner's interest is crucial for effective learning to take place (see also Drodge & Reid, 2000).

Without conflating the principles of constructionism and MCLEs, several proponents of constructionism propose that maker activities are ideal for learning (Martinez & Stager, 2013; Vossoughi & Bevan, 2014). Makers, motivated by personal interests, engage in the creation of objects or digital designs to address open-ended problems that are relevant to them. They work collaboratively within an environment that nurtures a culture of learning, enabling them to enhance their learning experience by exploring various avenues of interest with the support of their peers. To replicate similar outcomes in formal education settings, learning environments must provide learners with comparable experiences. Maker learning experiences should be fueled by learners' interests, guided by educators, and situated in environments where knowledge and skills are applied authentically in real-life contexts described by many researchers (Drodge & Reid, 2000; Martinez & Stager, 2013; Vossoughi & Bevan, 2014).

As a result of its popularity and the potential value of maker experiences for developing these essential skills for the future, schools have embraced makerspaces and attempted to integrate maker-centered programs into their curricula in efforts to capitalize on the learning affordances of the Maker Movement within the context of formal education (Schad & Jones, 2020). Given the sometimes-rigid structures of formal education settings, integrating maker activities into school settings may pose some challenges.

Maker-Centered Learning Experiences in Formal Education Settings

Despite the enthusiasm for incorporating MCLEs into formal education settings, concerns have been raised regarding challenges that education leaders and educators face when attempting to integrate these experiences into their schools (Campos et al., 2019; Jocius et al., 2020; Kumpulainen & Kajamaa, 2022). Questions arise about how to successfully integrate MCLEs while preserving the claimed learning affordances they are suggested to possess in their natural contexts (Cohen et al., 2017; Halverson & Sheridan, 2014a; Hira & Hynes, 2018; Humburg et al., 2021; Jocius et al., 2020). As highlighted by Kervin and Comber (2021, p. 80), "Classrooms are geographically and institutionally bounded places with physical features, cultural histories, and social roles." Formal education settings, characteristically highly structured, may encounter challenges when integrating student-driven, non-linear, process-based learning activities like MCLEs (Kervin & Comber, 2021; Novotny, 2019). Jocius et al. (2020) noted:

> Researchers have expressed concerns that institutional constraints of formal learning environments might restrict much of what makes making so powerful in informal learning environments, such as play, imaginative design thinking, and makers' autonomy in choosing which problems to approach and how to solve them. (p. 397)

Speculations about the challenges that arise during the integration of MCLEs into formal education settings have been discussed by some researchers (e.g. Becker & Jacobsen, 2022; Bennett, D & Monahan, P, 2013; Bevan, 2017; Blikstein, 2018; Cohen et al., 2017; Honey & Kanter, DE, 2013; Justice, 2015; Powell, 2021; Riikonen et al., 2020), and numerous studies have acknowledged challenges in passing. However, very few studies have explicitly studied these challenges in K-12 formal education settings (Hansen et al., 2019; Hira & Hynes, 2018; Jocius et al., 2020; Petrovich et al., 2022; Walan & Gericke, 2022). Scholarly discussions about the challenges that educators may face when attempting to integrate MCLEs into their teaching practices appear to fall into five dominant themes: 1) unrealistic expectations about the learning benefits of digital fabrication technology (e.g. Powell, 2021), 2) tensions related to pedagogical approaches to facilitating learning experiences (e.g. Bevan, 2017; Riikonen et al., 2020), 3) curriculum and standards requirements (e.g. Becker & Jacobsen, 2022; Bennett, D & Monahan, P, 2013; Cohen et al., 2017, 2017; Justice, 2015; Kim et al., 2020; Kurti et al., 2014; Lee et al., 2020; Martinez & Stager, 2013; Tofel-Grehl et al., 2017), 4) assessment (e.g. Blikstein et al., 2017; Flores, 2016; Honey & Kanter, 2013), and 5) training and professional development (e.g. Blikstein & Valente, 2019 (e.g. Blikstein & Valente, 2019; Powell, 2021).

Unrealistic expectations about the learning benefits digital fabrication technology: One challenge is that schools may have misconceptions about digital fabrication technology and its role in student learning. Martin (2015) points out:

> There is a seductive, but fatally flawed conceptualization of the Maker Movement that assumes its power lies primarily in its revolutionary tool set. In this view, deploying these tools in school settings will lead to transformations in education. Given the growing enthusiasm for making, there is a distinct danger that its incorporation into school settings will be tool-centric and thus incomplete. (p. 37)

Cohen (2017) adds:

“Simply equipping a school’s media center with a 3D printer or offering robotic clubs after school will do little to systematically leverage the affordances of the emerging maker technologies to improve student learning. (p. 222)

Although maker-centered education as it is currently understood is a relatively new trend, the misconception of the implicit learning benefits of media and technology is not (as demonstrated in the Clark and Kozma debate) and there is little evidence to suggest that the integration of technology in schools in the past has led to substantial improvements in learning or school functioning (Weiner et al., 2021). Scholars warn that if this misconception is not corrected, similar mistakes could be made with the introduction of maker-centered education programs.

Pedagogical approaches to facilitating learning experiences: Constructionists suggests that pedagogical approaches to MCLEs must focus primarily on maintaining the characteristics of making in school settings so as to take advantage of the affordances of making as it occurs naturally in informal settings. As such, the primary focus is on maintaining learner autonomy by shifting the teachers’ role from instructor to guide (Clapp et al., 2017; Marsh et al., 2017; Resnick et al., 2016). Much like the emancipatory pedagogical approach described by Marsh and colleagues (2017), the distinct role of the teacher as knowledge provider to passive students is broken down so that students take on more responsibility for their own learning while teachers act as guides. Martinez and Stager (2013) point out that moving from instructionist to constructionist pedagogical approaches will likely be difficult for many teachers as there persists a cultural perception of the teacher as the imparter of information where the ‘right way' to teach is to lecture.

Curriculum and standards requirements. Among the most voiced concerns about teachers' ability to integrate MCLEs into their classroom practice are constraints related to curriculum and standards requirements (Bennett & Monahan, 2013; Cohen et al., 2017; Justice, 2015; Kurti et al., 2014; Martinez & Stager, 2013). Scholars suggest that challenges related to curriculum are three-fold. First, there is currently no agreed upon curriculum for maker education (Cohen et al., 2017; Strycker, 2015). as the skills developed through making are difficult to define and operationalize as they are predominantly internal mechanisms that are hard to observe directly (e.g. creativity). Without clear learning goals, educators have little to guide them as they choose and design learning experiences and learning programs for their students (Care et al., 2018). Second, maker projects are divergent in nature possibly resulting in students exploring different concepts (Bennett & Monahan, 2013; Kurti et al., 2014; Lindsey & DeCillis, 2017). With divergent solutions to a problem, it can be challenging for a teacher to ensure that all students learn the same target concepts (Bennett & Monahan, 2013), creating challenges for teachers who need to ensure that required curriculum content is addressed (Bennett & Monahan, 2013; Cohen et al., 2017; Justice, 2015; Kurti et al., 2014; Martinez & Stager, 2013). Third, the targeted learning goals of maker education primarily consist of transversal skills that do not fit neatly into a single discipline (Bennett & Monahan, 2013; Honey & Kanter, 2013; Martinez & Stager, 2013; Petrich et al., 2013). As most curricula are divided by discipline (Care et al., 2018), there is an apparent lack of 'fit' for the skills maker-centered education aims to foster. It is possible that where subjects are taught by specialized teachers, they may not feel responsible for ensuring that they also target these transversal skills if it is not part of their required curriculum. Even if teachers do decide to focus on these skills, there may not be any place on report cards to note student performance in these areas.

Assessment. Possibly the most cited challenge associated with the integration of MCLEs into schools (Blikstein et al., 2017; Flores, 2016; Honey & Kanter, 2013; Resnick et al., 2016), assessment poses a major challenge for maker educators for three primary reasons: (a) the skills targeted in maker education have not been operationalized for teaching and assessment purposes with no clear guidelines on what students of various ages and levels of development are capable of (i.e. learning progressions) when it comes to the skills developed through making (Care et al., 2018), (b) the skills developed through maker-centered education are often difficult to observe or test (Blikstein et al., 2017; Care et al., 2018), and (c) assessment measures can disrupt student engagement with a learning activity and reduce motivation to take creative risks during the activity (Honey & Kanter, 2013; Kohn, A., 2010; Resnick et al., 2016). As the need for assessment in formal education may be unavoidable at this point, teachers wishing to integrate MCLEs into their classrooms may encounter challenges when it comes to assessment (Blikstein et al., 2017; Flores, 2016).

Training and professional development: The amount and type of training that teachers receive in maker-centered education and constructionist pedagogies may affect their ability and willingness to integrate MCLEs into their teaching practice. Observations from attempts to integrate computer technologies into the classroom when they first emerged indicated that training and professional development was essential for the uptake of these technologies by teachers (Cohen et al., 2017). Blikstein and Worsley (2016) argue that too often new technology is introduced into educational settings with the belief that their benefits are self-evident only for them to be pushed aside when they appear to fail to deliver. They argue that introducing maker education and digital fabrication technology to schools without appropriate training may also prove to be ineffective, resulting in teachers either creating ineffective MCLEs or not integrating them into their teaching at all.

Review Questions

Given the relative newness of the movement to integrate maker activities into formal education settings and the nascency of research in this field, the challenges teachers may encounter integrating MCLEs into their teaching are relatively unexplored. It is vital that research deepens our understanding of the challenges teachers may encounter so that we can better understand why some fail to integrate these experiences, or why some choose not to use MCLEs in their teaching practice. As some have warned, maker activities have many potential benefits for students but, if not carefully researched, maker-centered education programs risk being short-lived and considered yet another failed approach to pedagogy (Fulfilling the Maker Promise: Year One, 2017; Weiner et al., 2021).

Therefore, this scoping reviews aims to address the following three review questions:

1. How are the published articles on maker education in k-12 formal education settings characterized in terms of bibliographic classification, methodology, and primary topic?
2. What proportion of the published articles on maker education in k-12 formal education identifies implications of integrating maker education into these settings?
3. What implications of integrating maker education into formal k-12 education settings have been identified in the research literature?

The objective of this review is to map the research that has been conducted in k-12 formal education settings and to identify gaps in the current literature to inform further research.

Methods

This section describes the rationale for a scoping review and outlines the details of the search strategy, inclusion criteria, data extraction process and data analysis.

Scoping Reviews

A scoping review was selected for the purposes of this review. Scoping reviews "map rapidly the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as stand-alone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before" (Mays et al., 2001). Given the relative newness of research in maker education and the wide variety of topics and settings that have been considered, a scoping review of the literature provides an overall picture of the research that has been conducted thus far in maker education and the gaps that remain in the literature, specifically in k-12 formal education settings (Arksey & O'Malley, 2005). Like other systematic review methodologies, scoping reviews are rigorous and intended to be reproducible (Booth et al., 2022).

Search Strategy

Four electronic databases that include education publications were used to collect the literature for the review. ERIC and Education Source were used as they are among the leading databases for education publications. Scopus is among the largest comprehensive electronic databases and was used to ensure that literature not published in conventional education publications would not be overlooked. Finally, PsychNet was included given the close overlap between psychology and education research.

Two search strings were used for this review. The first search string was composed of two dimensions (see Table 1). The first dimension consisted of terms related to making and

Table 1

Search String 1

Dimension	Search Field	Search Terms
Making	Author-supplied key words	"digital making" or fablab* or fab-lab* or "fab lab*" or "fabrication laboratory" or makerspace* or "maker-space*" or hackerspace* or "maker movement" or "maker mindset" or "digital fabrication" or “maker education” or “maker-centered”
K-12 Formal Education	All	“formal education” or school* or class or classroom* or “teacher education” or “teacher professional development” or “teacher training” or “K-12” or “elementary school” or “primary school” or “middle school” or “high school” or kindergarten

maker education with the exception of the terms ‘making’ and ‘maker’ which were included in the second search string. This dimension was limited to author-supplied key words as only articles with some element of this dimension as the primary focus of the article were desired. The second dimension attempted to limit the results to k-12 formal education settings. As some articles investigating maker education may involve contexts both within and outside formal education, this dimension was not limited to author-supplied keywords. Boolean OR operators were used within each dimension with an AND operator to link the two dimensions. This combination of Boolean operators ensured that all results contained at least one term from each dimension of the search string.

Due to the ubiquitous use of the terms ‘maker’ and ‘making’ to refer to a multitude of activities unrelated to maker-centered education, a separate search was conducted using these two terms only for the ‘making’ dimension, and with the addition of a third dimension of terms to be excluded (see Table 2). This third dimension was not included in the first search to avoid

Table 2

Search String 2

Dimension	Search Field	Search Terms
Making	Author-supplied key words	making or maker
K-12 Formal Education	All	“formal education” or school* or class or classroom* or “teacher education” or “teacher professional development” or “teacher training” or “K-12” or “elementary school” or “primary school” or “middle school” or “high school” or kindergarten
Excluded terms	Author-supplied key words	"policy maker*" or “policy-maker*” or "curriculum maker*" or "decision maker*" or “decision-maker*” or “decisions-maker*” or "*-making" or "* making"

inadvertently excluding relevant articles because they discussed both making and one of the excluded terms (e.g. an article discussing policy making in maker education). Additionally, the third dimension was limited to author-provided key terms to avoid excluding relevant articles that use these terms in-text but not as a primary focus.

Both search strings were compiled using a scoping search strategy where preliminary database searches were conducted using search terms from known highly relevant articles (Booth et al., 2022). Relevant search terms found among the author-supplied key words were identified from the results.

To minimize the risk of relevant articles being missed by the above search strategy, already existing literature reviews in maker education and reference lists of included articles were scanned for missing articles. Finally, similar to Smolarczyk and Kröner (2021), the literature search was limited to articles published beginning January 1, 2002 to align with the foundation of the first FabLab in 2002. Databases were searched on December 31st, 2022.

Although there is a tight link between maker-centered education and STEAM (science, technology, engineering, arts and mathematics) education, they are not synonymous approaches. Maker-centered education is one approach to STEAM education, therefore, STEAM education was not included among the search terms.

Study/Source of Evidence Selection

The retrieved articles were screened using Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org). Covidence is a web-based software platform that facilitates collaborative systematic reviews by supporting title and abstract screening, full text review of references, and data extraction.

A two-stage screening process was used to select the articles for inclusion in the review. Articles were first screened using their titles and abstracts to exclude articles that were unmistakably irrelevant to the review. For the remaining articles, a second stage of screening was conducted to determine eligibility through full-text review. Two reviewers screened all articles with consensus to resolve any conflicts between decisions to include or exclude publications. Both reviewers are researchers in maker education.

Articles were included based on the following criteria:

1. The primary focus of the publication is on making in K-12 formal education (excluding home schooling);
2. The making involves the creation of tangible objects;
3. The publication reports empirical results derived from qualitative, quantitative or mixed methods data;

4. The publication is an academic publication (peer reviewed journals or books/book chapters). Of the grey literature, conference proceedings and doctoral theses were included.

As scoping reviews aim to map the existing literature, articles are included without consideration of methodological rigour, as recommended by Tricco et al. (2016).

Data Extraction and Analysis

Data extraction and thematic analyses were conducted by the first author, with verification of the findings by the second author, a suggestion from Booth et al. (2022). To minimize reviewer bias, a charting form was developed to record the key information necessary from each source to answer the review questions, as suggested by Booth et al. (2022). A thematic analysis of the noted implications relevant to the integration of maker education in k-12 formal education was conducted using MAXQDA 2022 (VERBI Software, 2021).

Bibliographic Characteristics

Publications were categorized based on document type (research article, conference proceedings, book, book chapter, doctoral thesis, research report), year of publication, research location (country; based on first author's location if research location not indicated in the article), methodological approach (qualitative, quantitative, mixed), study site (school, university, informal setting) and study size (sample size).

Educational Characteristics

Studies were categorized based on educational characteristics of the context of the study such as age range (elementary, middle school, high school, K-12), school type (public, private, other), and manner of integration of maker education (in-class, out-of-class).

Thematic Analysis

Two thematic analyses were conducted. The first identified the primary topic areas of the published research in maker education in K-12 formal education settings and the second identified the primary areas reported in the research regarding implications of integrating maker education into these settings.

To identify the primary topic areas of interest among the studies, we described the primary topic of each study in a single sentence and then used inductive coding to identify main themes.

To identify the main reported implications of integrating maker education into K-12 formal education settings, publications that included implications, either as a stated aim of the study or as an additional observation, were identified and analyzed using MAXQDA 2022. Inductive coding was used to identify themes and subthemes that emerged from the data.

Results

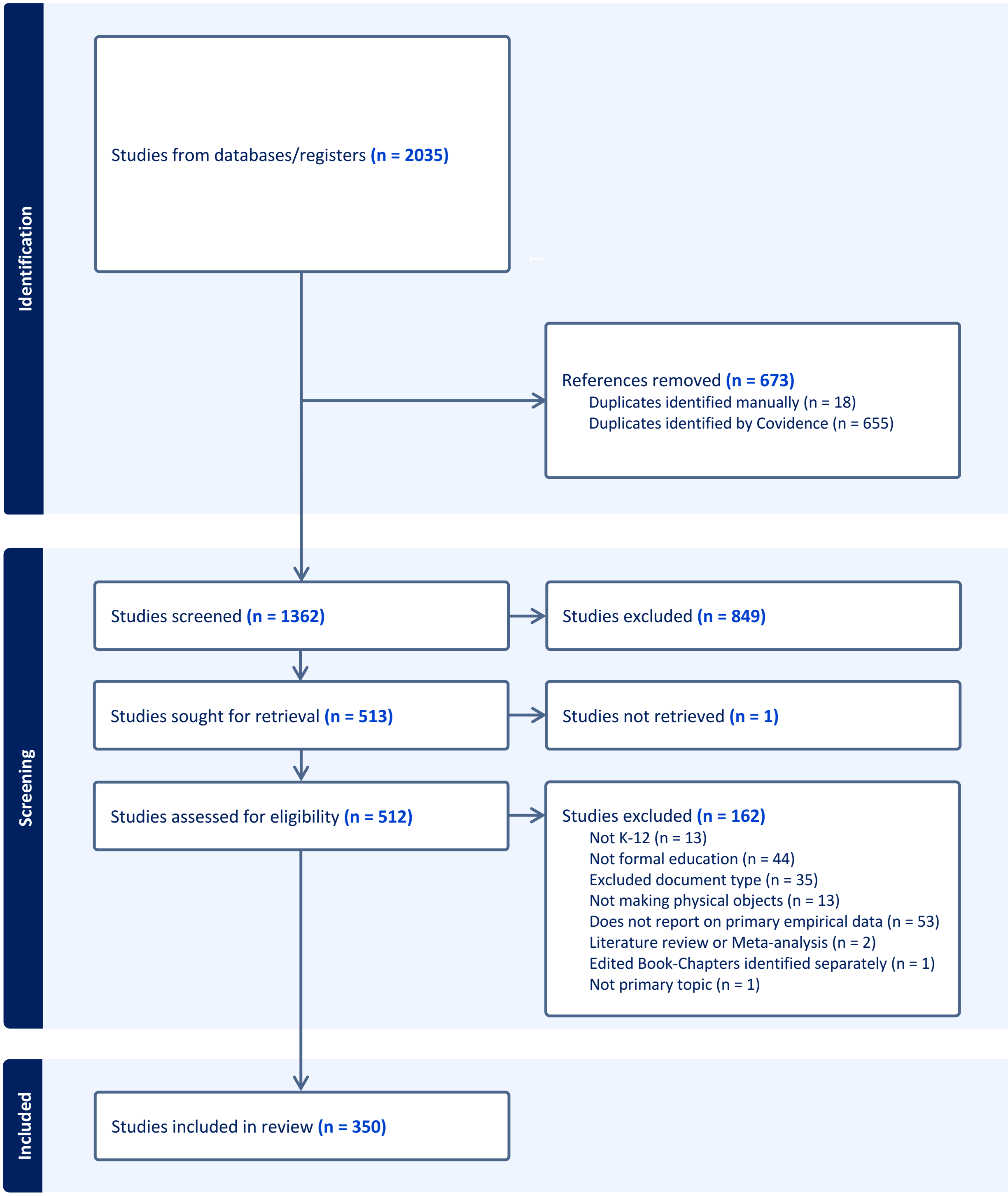
Results of the Screening Process

Of the *n* = 2035 publications retrieved from the four databases, *n* = 673 were identified as duplicates. Title and abstract screening of the remaining *n* = 1362 publications resulted in the exclusion of *n* = 849. The remaining *n* = 513 publications were retrieved for full-text screening. One publication was not retrieved despite efforts to contact the authors.

Of the *n* = 512 publications that underwent full-text screening, *n* = 162 were excluded for not meeting the inclusion criteria (see Figure 1 for a breakdown of the reasons for exclusion). At the end of screening, *n* = 350 publications were retained for analysis.

Figure 1

PRISMA Flowchart



Bibliographic Classification and Methodology of the Included Studies

Year of publication: Although the search parameters were set from January 1, 2002 (the year of the opening of the first FabLab) to December 31, 2022, the earliest publications relevant to this scoping review emerged in 2013 (n = 2). From 2013, published research on MCLEs in K-12 formal education settings steadily increased with a brief plateau from 2017 to 2018 and a slight decline in 2022, presumably due to the impact of COVID-19. From 2017-2022, a minimum of 40 identified articles were published each year with a peak of n = 68 in 2021 (see Figure 2).

Document type: The majority of publications consisted of peer-reviewed research articles (n = 213, 61%), followed by conference proceedings (n = 85, 24%) and doctoral theses (n = 32, 9%). A small portion of the publications (n = 20, 6%) consisted of books, book chapters, and research reports (see Figure 3).

Research location: Nearly half (n = 171, 49%) of studies were conducted in the USA or attributed to the USA based on the first author's affiliation (see Table 3). Approximately a tenth of the research emerged from Finland (n = 33, 9%) followed by Canada, Australia, China and Taiwan with 13 to 19 articles each. Twelve publications (3%) were multinational studies.

Figure 2

Articles Published Per Year Between 2002 and 2022

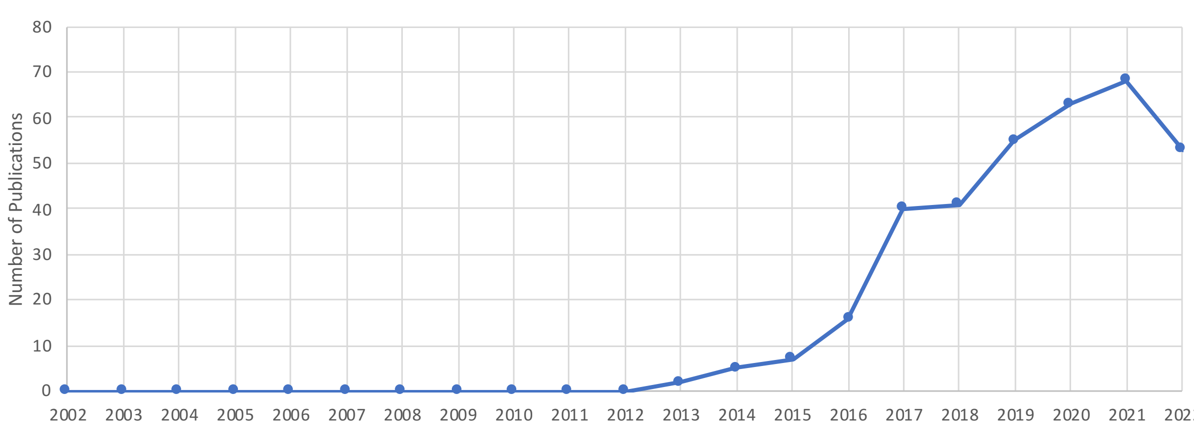


Figure 3

Breakdown by Document Type

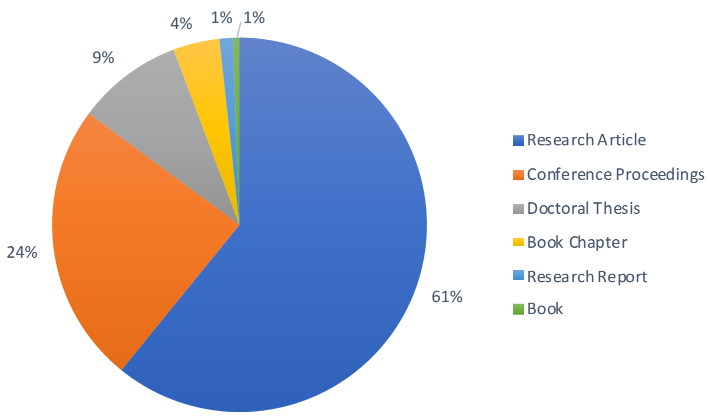


Table 3

Publication by Location

Research Location (Country)	Number of Publications	Percentage of Total Publications
USA	171	48.86
Finland	33	9.43
Canada	19	5.43
Australia	17	4.86
China	15	4.23
Taiwan	13	3.71
Denmark	7	2.00
Singapore	6	1.71
Italy, South Korea, Spain	5	4.23
Brazil, India	4	2.29
Sweden, Switzerland, UK	3	2.57

Israel, Japan, Netherlands, New Zealand, Norway	2	2.87
Austria, Belgium, Cyprus, Egypt, France, Greece, Iceland, Indonesia, Lithuania, Nigeria, Peru, Russia, South Africa, Thailand, Uganda	1	4.29
Multinational	12	3.43
TOTAL	350	100

Methodological approach: The vast majority of studies used qualitative methodologies (*n* = 259, 74%), followed by mixed methods (*n* = 53, 15%), and quantitative approaches (*n* = 38, 11%).

Study site: The majority of studies took place in schools (*n* = 268, 71%), followed by universities (*n* = 58, 15%), and informal settings (usually collaborating with teachers or schools; *n* = 29, 8%). Six studies did not indicate where the research took place, and 15 studies did not occur in a physical location.

Study size: Because evaluations of sample size differ between qualitative and quantitative research approaches, and the majority of the research in this review is comprised of qualitative studies, the sample size of each study was categorized as small if the study involved fewer than 10 participants, medium if the sample consisted of 10 to 20 participants, and large if the sample consisted of more than 20 participants. Given these parameters, 23% (*n* = 79) of studies involved a small sample, 17% (*n* = 60) involved a medium sample, and 60% (*n* = 211) involved a large sample.

Educational Characteristics

Age range: Approximately one-third (*n* = 131, 35%) of studies focused on maker education for elementary school, 18% (*n* = 67) focused on middle school, and 22% (*n* = 84) focused on high school (see Figure 4). Ninety-three studies (25%) targeted K-12 education in general. Twenty-five studies focused on two of the age ranges.

School type: Of the studies that took place in schools, 55% took place in public schools (*n* = 148) and 11% took place in private schools (*n* = 29). Thirty-four percent of the studies (*n* = 91) did not specify whether they took place in public or private schools.

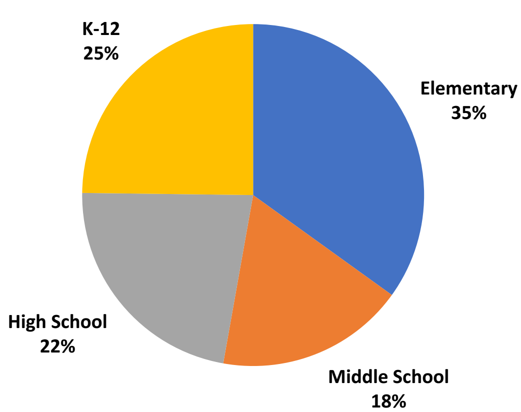
Manner of integration: Of the studies that took place in schools, 72% of the studies reported on making experiences that took place during class time (*n* = 195), while 14% of making experiences took place outside of class time (before school, at lunch time, or after school; *n* = 38). Fourteen percent of studies (*n* = 37) did not specify when the making took place at the school.

Primary Topic

Nine broad areas of research topics were identified: 1) description or assessment of a maker pedagogical approach, initiative, program or space design (*n* = 89, 25%); 2) student learning and development (*n* = 61, 17%); 3) teacher training and professional development (*n* = 58, 17%);

Figure 4

Target Age Range of Publications



4) student perceptions and experiences of MCLEs (*n* = 31, 9%); 5) teacher perceptions and experiences of maker education (*n* = 25, 7%); 6) assessment of learning through making (*n* = 21, 6%); 7) description or assessment of a product, tool, or piece of equipment (*n* = 16, 5%); 8) implications of the integration of maker education into K-12 formal education (*n* = 11, 3%); 9) equity, diversity and inclusion in maker education (*n* = 8, 2%). Thirty articles (9%) were classified as 'other' (see Table 4). Many studies discussed more than one topic, therefore for the purposes of categorization, studies were categorized by their primary topic.

Table 4

Primary Topics

Topic	**Number of Publications**	**Percentage of Total Publications**
Describes or assess a maker pedagogical approach, initiative, program or space design	89	25.43
Student learning and development	61	17.43
Training and professional development	58	16.57
Student perceptions and experiences	31	8.86
Teacher perceptions and experiences	25	7.14
Assessment	21	6.00
Describes or assess a product, tool, or equipment	16	4.57
Implications of the integration of maker education into K-12 formal education	10	3.14
Equity, diversity and inclusion	8	2.29
Other	30	8.57

Description or assessment of a maker pedagogical approach, initiative, program or space design: The most frequently studied topic involved describing and/or assessing maker pedagogical approaches (*n* = 58), maker education initiatives and programs (*n* = 23), and makerspace design for educational purposes (*n* = 7).

Student learning and development: These studies reported on topics such as student development of skills like creativity, problem-solving, collaboration, computational thinking, and entrepreneurship skills (*n* = 20); academic achievement (*n* = 2); psychological development and growth in areas like agency, self-efficacy, identity, and design mindset (*n* = 18); concept development in areas like science, mathematics or art (*n* = 11); motivation (*n* = 5); and learning more broadly (*n* = 5).

Training and professional development: These studies provided descriptions of the design of a training or professional development program (*n* = 30); reported on the teacher competency development from training or professional development (*n* = 5); teacher integration of or willingness to integrate MCLEs after participating in maker-related training or professional development (*n* = 8); teacher perceptions of MCLE training and professional development (*n* = 6); teacher perceptions of MCLEs after training and professional development (*n* = 6); broad changes in teacher lesson plan development after MCLE training and professional development (*n* = 1); reported on the state of training and professional develop in geographic locations (*n* = 1); and the types of training teachers experienced MCLE teachers felt assisted them (*n* = 1).

Student perceptions and experiences: These studies reported on student experiences and perceptions of MLCEs and makerspaces in general (*n* = 9); a specific aspect of an MCLE experience such as collaborative teamwork, emotions experienced, working with a certain type of technology, material, or software ($n = 14$); and attitude shifts toward and perceptions of STEM/STEAM and their related professions ($n = 8$),

Teacher perceptions and experiences: These articles reported on the perceptions and experiences of teachers and pre-service teachers of MCLEs and making in general ($n = 14$); a specific aspect of MCLEs such their ability to elicit student engagement, perceptions of student learning, usefulness of types of equipment, materials, and software ($n = 10$); and perceptions of their own ability to facilitate MCLEs ($n = 1$).

Assessment: Most research on assessment involved studies on the design and evaluation of an approach, tool or framework to assess learning from MCLEs ($n = 15$). Some studies also investigated methods of documenting student learning from these experiences ($n = 3$), as well as teacher-developed methods of assessing student learning from MCLEs ($n = 3$).

Description or assessment of a product, tool, or equipment: Studies in this category described and reported on the efficacy of kits and educational games for MCLEs ($n = 5$), the usefulness of equipment like microcontrollers, virtual reality, online platforms for MCLEs ($n = 5$), and tools for preparing and facilitating MCLEs ($n = 6$).

Implications of the integration of maker education into K-12 formal education: The studies that specifically investigated implications of the integration of MCLEs in schools reported findings from interviews with teachers ($n = 6$) and pre-service teachers ($n = 1$) to identify their experiences and/or perceptions of challenges integrating MCLEs into their teaching, as well as researcher identified challenges ($n = 3$) based on their observations of MCLEs in schools or after setting up their own lab school.

Equity, diversity and inclusion: Studies in this category reported on teacher perceptions and student reactions to MCLEs designed to be more inclusive of students not typically well represented in the maker movement and STEM fields. These included girls (*n* = 3), students of colour (*n* = 2), neurodiverse students (*n* = 1), and students with particular learning needs (*n* = 1), and EDI needs in general (*n* = 1).

Other: Thirty studies reported on a variety of topics related to MCLE integration in formal education settings. These included topics such as observations of MCLEs to identify social interactions that resemble or differ from other classroom activities (e.g. Lacy, 2017), the assessment of selection criteria for maker equipment for making in schools (e.g. Jun, 2018), the investigation of uptake of MCLEs during COVID (e.g. Salas-Valdivia & Gutierrez-Aguilar, 2021), the investigation of whether children making billboards about HIV/AIDS in school can improve community understanding of the disease (e.g. Kendrick et al., 2020), the investigation of the efficacy of a safety training programme for STEM labs and makerspaces (e.g. Love, 2022), the study of the types of knowledge exchange that took place between students, teachers and materials during MCLEs (e.g. Braga & Guttmann, 2019), the investigation of the impact of professional development and an MCLE on teachers' value of career awareness of middle school students (e.g. Schouweiler, 2020), and how MCLEs can reveal giftedness in students (e.g. Saunders, 2022).

Studies Identifying Implications for Formal Education

Nearly one-third (*n* = 105, 30%) of the studies in this review identified challenges associated with integrating maker education into K-12 formal education settings, however, only 10% of the articles (*n* = 36) explicitly aimed to study these implications either as the primary aim of the study (*n* = 10) or as a secondary aim (*n* = 26).

Implications of integrating maker education into K-12 formal education settings

The analysis of the 350 papers revealed 10 areas of challenges related to maker-centered education that were most frequently reported. These include space and equipment, time and scheduling, curriculum and assessment, training and professional development, teacher support, educational leadership, student expectations and capabilities, teacher resistance, education culture, and funds were most frequently reported (see Table 5).

Table 5

Identified Challenge Categories

Challenge	Number of Publications	Percentage of Publications Reporting Challenges
Space & Equipment	42	40.0%
Time & Scheduling	34	32.4%
Curriculum & Assessment	27	25.7%
Training & PD	19	18.1%
Teacher support	18	17.1%
Education leadership	12	11.4%
Student expectations & capabilities	12	11.4%
Teacher resistance	8	7.6%
Education culture	7	6.7%
Funds	7	6.7%

Space and equipment

Forty-two studies identified issues related to space and equipment (H. V. Andersen & Pitkänen, 2019; Assaf et al., 2019; Becker & Jacobsen, 2019, 2023; Bower et al., 2020; Cao et al., 2020; C.-S. Chen & Lin, 2019; Cross, 2017; Das, 2020; Daughrity, 2022; Eriksson et al., 2018; Fancsali et al., 2019; Fulfilling the Maker Promise: Year One, 2017; "Fulfilling the Maker Promise: Year Two," 2018; Hansen et al., 2019; Harron et al., 2022; Heilala et al., 2020; Henderson et al., 2017; Humburg et al., 2021; Jaatinen & Lindfors, 2019; Jin et al., 2020; Jocius et al., 2020; Jones et al., 2017; Koole et al., 2017; C. eun Lee et al., 2020; Leinonen et al., 2020; Mehto et al., 2020; Milara et al., 2020; Moorefield-Lang, 2014; Novotny, 2019; Peterson & Scharber, 2018; Rosenfeld et al., 2019; Singh & Kim, 2019; R. C. Smith et al., 2016; L. Song, 2018; M. J. Song, 2021; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017; Tan et al., 2017; Walan & Gericke, 2022; Zhang, 2021). These issues revolved around finding an appropriate space in the school for making, acquiring, and maintaining equipment, and the use of equipment within the scheduling of the school day.

Among the most commonly reported problems was the lack of space in the school for a makerspace (Cao et al., 2020; Henderson et al., 2017; Singh & Kim, 2019; R. C. Smith et al., 2016). Some schools attempted to work around this issue by creating portable maker carts, but making typically involves large amounts of equipment and materials that need to be set up and put away after each session, reducing the amount of time for the actual making (Henderson et al., 2017). When making took place in the regular classroom, issues also arose as classroom spaces are sometimes not large enough for students to move around while making (C.-S. Chen & Lin, 2019) and teachers in one study also felt that permanently having maker equipment and materials in the classroom risked students being distracted when doing non-maker related school work (Singh & Kim, 2019). A lack of storage for materials and in-progress projects was also reported (Cross, 2017; Henderson et al., 2017; Stevenson et al., 2019; Tan et al., 2017), sometimes restricting the types of projects that could be undertaken (Henderson et al., 2017; Tan et al., 2017).

In instances where a dedicated makerspace was created in a school, issues around working with existing architecture arose when using equipment that had safety requirements like ventilation (Harron et al., 2022; Henderson et al., 2017). By virtue of these spaces being shared, challenges around scheduling and availability (Assaf et al., 2019; Henderson et al., 2017) and needing to clear surfaces for each new group (Henderson et al., 2017) were reported.

Regarding equipment, challenges associated with equipment maintenance and malfunctioning, manufacturing time, and cost were reported. One of the most reported challenges associated with equipment was related to maintenance of equipment and equipment malfunction (Assaf et al., 2019; Bower et al., 2020; Daughrity, 2022; Hansen et al., 2019; C. eun Lee et al., 2020; Moorefield-Lang, 2014; L. Song, 2018; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017). One study reported that teachers fear equipment malfunction (Stevenson et al., 2019), which appears to be justified as Bower et al. (2020) reported that 75% of the teachers participants in their study indicated that equipment malfunction constrained what they were able to accomplish with students. Other studies reported that teachers had less time for productive instruction with students given the amount of time they spent on trouble-shooting (L. Song, 2018) and, in some cases, teachers restricted the use of equipment like 3D printers due to the challenges of using them (Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017).

Even when equipment functions well, equipment like 3D printers takes a lot of time for fabrication (Bower et al., 2020; Das, 2020; Hansen et al., 2019; Jones et al., 2017; Moorefield-Lang, 2014), making it challenging for teachers working with multiple students and projects (Moorefield-Lang, 2014) and limited amounts of equipment (Moorefield-Lang, 2014). The length of fabrication was also reported to have an impact on the iteration process and how quickly students can work through improving their design (Das, 2020). Furthermore, use of these technologies for young learners can be problematic (Bower et al., 2020; Leinonen et al., 2020; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017).

A few studies reported challenges related to the high cost of equipment (H. V. Andersen & Pitkänen, 2019; Harron et al., 2022; Humburg et al., 2021; Jones et al., 2017). In some cases, even when funding was available, equipment was still challenging to procure due to regulations on purchasing (Eriksson et al., 2018), as well as determining which equipment to purchase (Eriksson et al., 2018; Milara et al., 2020).

Time and scheduling

Thirty-four studies identified a lack of time and rigid scheduling as constraints for teachers engaging in maker education (Assaf et al., 2019; Becker & Jacobsen, 2023; Bolick & Williams, 2021; Bosch, 2022; Bower et al., 2020; Collins, 2018; Cross, 2017; Fancsali et al., 2019; Harron et al., 2022; Heilala et al., 2020; Henderson et al., 2017; J. Hughes, Morrison, et al., 2022; Humburg et al., 2021; Jones et al., 2017; Justice, 2015; Y. B. Kafai & Vasudevan, 2015; Kjartansdóttir et al., 2020; Kumpulainen & Kajamaa, 2021; Lahana, 2016; C. eun Lee et al., 2020; Leinonen et al., 2020; McKay et al., 2016; Mehrotra et al., 2021; Milara et al., 2019; Peterson & Scharber, 2018, 2018; Powell, 2021; Rosenfeld et al., 2019; Salo et al., 2021; Shively et al., 2021; R. C. Smith et al., 2016; M. J. Song, 2021; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017; Thompson, 2021).

The research reported that time restrictions had implications for teacher professional development and learning (Harron et al., 2022; Justice, 2015; McKay et al., 2016; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019), the planning of maker projects (Fancsali et al., 2019; Harron et al., 2022; Salo et al., 2021; Shively et al., 2021; R. C. Smith et al., 2016; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017; Thompson, 2021), and the type and complexity of maker projects teachers could engage in with their students (Y. B. Kafai & Vasudevan, 2015).

Additionally, teachers both feared and experienced insufficient instructional time with students due to short class sessions or limited assigned sessions per scheduling cycle (Assaf et al., 2019; Bower et al., 2020; Collins, 2018; Cross, 2017; Harron et al., 2022; Henderson et al., 2017; Jones et al., 2017; Justice, 2015; C. eun Lee et al., 2020; Leinonen et al., 2020; Stevenson et al., 2019). In one study, short class sessions were reported to have resulted in teachers' inability to meaningfully engage with students in reflection about their learning during making activities (R. C. Smith et al., 2016). Student opportunities to learn can also be restricted as one study reported that, in order to save class time, teachers provided students with already made parts of the project (Y. B. Kafai & Vasudevan, 2015).

In regards to scheduling, studies reported that teachers experienced difficulty planning extended maker projects due to rigid schedules (Bosch, 2022), and a lack of scheduled maker class time, resulting in them having to request to use time officially dedicated to other subjects for maker projects (Cross, 2017; Henderson et al., 2017). Teachers also lacked opportunities to collaborate with each other for the purposes of multidisciplinary maker projects (Milara et al., 2020; Shively et al., 2021; Thompson, 2021). Interestingly, one study reported that the perception of teachers and school administrators differed as teachers felt they were not provided enough time for collaboration and planning, whereas school administrators felt that they did (Thompson, 2021).

Curriculum and assessment

Twenty-seven studies reported challenges related to curriculum and standards requirements when integrating making into K-12 formal education (H. V. Andersen & Pitkänen, 2019; Becker & Jacobsen, 2019, 2022, 2023; Bevan et al., 2020; Bosch, 2022; Eriksson et al., 2018; Fulfilling the Maker Promise: Year One, 2017; “Fulfilling the Maker Promise: Year Two,” 2018; Harron et al., 2022; Henderson et al., 2017; Heredia & Tan, 2021; J. Hughes, Morrison, et al., 2022; Jocius et al., 2020; Jones et al., 2017; Justice, 2015; Y. Kafai et al., 2014; Kervin & Comber, 2021; Kjartansdóttir et al., 2020; Leonard et al., 2022; Powell, 2021; Rosenfeld et al., 2019; M. J. Song, 2021; Spieler et al., 2022; Stevenson et al., 2019; Thompson, 2021; Torralba, 2019; Turner, 2022). The Fulfilling the Maker Promise Year Two (2018) report found that only 7% of the 85 participants indicated that their schools had successfully integrated making into the curriculum. Even in schools where making had historically been well-integrated, growing emphasis on high-stakes testing has resulted in making being increasingly relegated to elective courses and extracurricular activities (Bevan et al., 2020).

Studies reported that teachers are hesitant to adopt making because of perceived contradictions between the types of learning that occur through making and the standards students are required to master (Jocius et al., 2020; Rosenfeld et al., 2019). Teachers perceive that engaging in maker education would take away time to cover the required curriculum content (Rosenfeld et al., 2019). In the instances where teachers are willing to deviate from the required curriculum to capitalize on the affordances of learning through making, they need to justify these deviations to administration (Davis et al., 2021; Powell, 2021; Torralba, 2019). In some contexts, this is particularly challenging as regional curriculum conformity requires that teachers even teach using the same approaches (Harron et al., 2022).

Some studies reported that teachers have difficult making connections between making and the curriculum (J. Hughes, Morrison, et al., 2022; Rosenfeld et al., 2019) with some research calling for guidelines on how to connect the two (M. J. Song, 2021). Some even suggest that a scaffolded curriculum that includes maker concepts should be developed (Henderson et al., 2017).

Some studies noted that teachers and school leadership find that prescriptive curricula constrain what teachers are able to do with their students (H. V. Andersen & Pitkänen, 2019; Bosch, 2022; Y. Kafai et al., 2014; Stevenson et al., 2019). Leonard et al. (2022) reported that the observed maker activities were heavily designed to address curricular goals which steered them away from open-ended, problem-solving experiences. Furthermore, the artificial division of the disciplines was identified as problematic for interdisciplinary approaches like maker education (Eriksson et al., 2018; Spieler et al., 2022).

Related to the challenges associated with curriculum demands, assessment was identified by 17 studies as a problematic aspect of integrating making into K-12 formal education (Alimisi et al., 2020; Becker & Jacobsen, 2023; Bertrand & Namukasa, 2022; Chen & Bergner, 2021; Fulfilling the Maker Promise: Year One, 2017; “Fulfilling the Maker Promise: Year Two,” 2018;

Humburg et al., 2021; Kim et al., 2021; Kim et al., 2020; Leonard et al., 2022; Murai et al., 2019; Ramey & Stevens, 2019; Sheffield & Koul, 2021; Siung et al., 2021; Timotheou & Ioannou, 2021; Veldhuis et al., 2022; Walan & Gericke, 2022; Zhang, 2021). Similar to curriculum integration, the Fulfilling the Maker Promise Year Two (2018) report found that less than 3% of the 85 participants indicated that their schools had successfully integrated assessment for maker education.

The identified challenges with assessment of learning through making stemmed from teachers' lack of knowledge or ability to assess student learning given current conditions, as well as the apparent incompatibility of current assessment measures and the types of learning that occur through making.

Five studies found that teachers have difficulty assessing learning through making (Alimisi et al., 2020; O. Chen & Bergner, 2021; Ramey & Stevens, 2019; Siung et al., 2021; Walan & Gericke, 2022) and have difficulty providing a letter grade for process-oriented learning (J.-Y. Kim et al., 2021). One study reported that teachers had difficulties connecting assessment with the learning objectives of maker-centered learning experiences (Veldhuis et al., 2022). Teachers may struggle with conducting embedded assessment while negotiating the varied needs of students in the classroom while making (Kim et al., 2021; Kim et al., 2020; Murai et al., 2019), particularly when the class size is large (Sheffield & Koul, 2021). Additionally, teachers expressed difficulties with capturing tangible evidence of student learning through making (Murai et al., 2019).

One study reported that available assessment tools were not adequate to capture the learning that takes place through making (Timotheou & Ioannou, 2021). Some research suggests that there is a need to reconceptualize how learning is assessed in these contexts (Ramey &

Stevens, 2019) as the skills developed (e.g. collaboration, perseverance, problem-solving) are difficult to define and assess (Bertrand & Namukasa, 2022; Walan & Gericke, 2022).

Some studies reported that the need for formative and summative assessment constrained the types of maker experiences teachers engaged in with their students (Becker & Jacobsen, 2023; Leonard et al., 2022). In a similar vein, one study reported that assessment interferes with student motivation (Zhang, 2021).

Training and professional development

Nineteen studies identified training and professional development as a challenge in integrating making into K-12 formal education. Several studies reported that teachers felt they needed more training in maker education (Eriksson et al., 2018; Fan, 2022; Fulfilling the Maker Promise: Year One, 2017; Harron et al., 2022; R. C. Smith et al., 2016). Participants in Eriksson's study (2018) also felt that leaders need training in maker education. Despite its apparent importance, several studies reported that teachers lack time for professional development and learning (Harron et al., 2022; Justice, 2015; Peterson & Scharber, 2018; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019). One study also reported that teachers felt there was a lack of training opportunities on maker activities (C. eun Lee et al., 2020).

Several areas were identified by both researchers and teachers in regard to training for teachers. These include training in the use of digital fabrication technologies (Harron et al., 2022; Leinonen et al., 2020; Norouzi et al., 2021; Shively et al., 2021), safety in makerspaces (Love, 2022), the benefits of making for learning (Siung et al., 2021), planning maker curricula (Fan, 2022; C.-Y. Lee et al., 2021), making connections between making and existing curricula (Rosenfeld et al., 2019; Shively et al., 2021), and skills in facilitating maker projects (Fan, 2022; Ramey & Stevens, 2019).

Teacher support

Eighteen studies identified instances where teachers would benefit from support, both in and out of the classroom (H. V. Andersen & Pitkänen, 2019; Harron et al., 2022; Heilala et al., 2020; Henderson et al., 2017; Heredia & Tan, 2021; Jocius et al., 2020; Karimi et al., 2017; Y. J. Kim et al., 2020; Kjartansdóttir et al., 2020; Koh et al., 2022; Lahana, 2016; C. eun Lee et al., 2020; Nemorin & Selwyn, 2017; Rosenfeld et al., 2019; Sheffield & Koul, 2021; R. C. Smith et al., 2016; Stevenson et al., 2019; Wong Shui Huen, 2020).

Studies reported that teachers spearheading maker initiatives in school may work alone in their efforts (H. V. Andersen & Pitkänen, 2019; Kjartansdóttir et al., 2020) or with a limited number of colleagues, requiring them to put considerable time and effort into the initiative (Wong Shui Huen, 2020). One study reported that teachers expressed the need for support from other teachers to co-create maker projects (Stevenson et al., 2019)

Class size was a concern identified in several studies (Harron et al., 2022; Heilala et al., 2020; Heredia & Tan, 2021; Jocius et al., 2020; Karimi et al., 2017; Y. J. Kim et al., 2020; Koh et al., 2022; Lahana, 2016; C. eun Lee et al., 2020; Nemorin & Selwyn, 2017; Rosenfeld et al., 2019; Sheffield & Koul, 2021; R. C. Smith et al., 2016). Teachers expressed concerns and challenges related to addressing each student's needs when facilitating maker learning experiences with large groups (Harron et al., 2022; Lahana, 2016), maintaining student engagement (Heredia & Tan, 2021; C. eun Lee et al., 2020), assessing each student's learning (Y. J. Kim et al., 2020; Sheffield & Koul, 2021), and maintaining student safety when having to monitor a whole class of students using potentially harmful maker tools (Henderson et al., 2017). As a result of the high student to teacher ratio in some contexts, one study reported that students had to wait for their teacher's assistance (Nemorin & Selwyn, 2017).

Educational leadership

Twelve studies identified educational leadership as important in the integration of making into schools (H. V. Andersen & Pitkänen, 2019; Cao et al., 2020; Cross, 2017; Fancsali et al., 2019; Fulfilling the Maker Promise: Year One, 2017; Otero & Blikstein, 2016; Rosenfeld et al., 2019; Salo et al., 2021; Stevenson et al., 2019; Thompson, 2021; Turner, 2022; Zhang, 2021).

Educational leaders were identified as important for the acquisition of and decisions related to funding (Turner, 2022), installing and re-enforcing schoolwide frameworks around maker education (Thompson, 2021), and supporting teachers in their efforts to integrate making into their teaching practices (H. V. Andersen & Pitkänen, 2019; Cross, 2017; Rosenfeld et al., 2019; Stevenson et al., 2019). Reported problems that arose around educational leaders included leadership neglecting to support maker education initiatives (Cao et al., 2020), lacking unity around goals and outcomes (Fulfilling the Maker Promise: Year One, 2017; Salo et al., 2021; Zhang, 2021) and neglecting to provide adequately developed curricula for maker education (Zhang, 2021).

Student expectations and capabilities

Twelve studies identified student resistance as a factor that influenced teachers' ability to engage in making with students (Becker & Jacobsen, 2023; Bower et al., 2020; Das, 2020; Daughrity, 2022; Heilala et al., 2020; Henderson et al., 2017; J. Hughes & Morrison, 2018; Kjartansdóttir et al., 2020; Kumpulainen & Kajamaa, 2022; C. eun Lee et al., 2020; Somanath et al., 2017; Tan et al., 2017).

Studies found that students were not always interested and motivated to participate in making (Kumpulainen & Kajamaa, 2022), and that some students were unable to engage in making independently (Heilala et al., 2020). Some studies reported that students lacked perseverance (Henderson et al., 2017), especially for struggling learners and those with learning disabilities as they exhibited learning helplessness (C. eun Lee et al., 2020). Students were also found to be resistant to risk taking with projects (Henderson et al., 2017; Tan et al., 2017), and feared failure (Kjartansdóttir et al., 2020; Somanath et al., 2017). In many cases, students expected to be told what to do (Becker & Jacobsen, 2023; Bower et al., 2020; Henderson et al., 2017; C.-Y. Lee et al., 2021). Some students also resisted the iteration process and receiving feedback (Das, 2020), and others were found to be reluctant to participate when shifts in roles took place in the classroom (Jocius et al., 2020). Issues like fine motor skills were also found to be a hindrance as some students struggled with tasks that required precise movements (J. Hughes & Morrison, 2018).

Teacher resistance

Eight studies identified teacher resistance as a challenge for the integration of making in schools (Alimisi et al., 2020; Assaf et al., 2019; Bower et al., 2020; Cross, 2017; Heilala et al., 2020; J. Hughes, Morrison, et al., 2022; Koole et al., 2020; Walan & Gericke, 2022). Some studies reported that teachers were uncomfortable engaging in making without maker expertise (Cross, 2017) and feeling incompetent in maker related areas (Assaf et al., 2019; Heilala et al., 2020; J. Hughes, Morrison, et al., 2022; Walan & Gericke, 2022). Some teachers lacked confidence with the technology (Bower et al., 2020) and others felt intimidated by it (Koole et al., 2020). Studies also reported that teachers feared failure (Koole et al., 2020) and looking incompetent in front of their students (Alimisi et al., 2020).

Education culture

Eight studies identified broader issues related to education culture which have implications for the integration of maker education into schools (Davis et al., 2021; Heredia &

Tan, 2021; Justice, 2015; Shively et al., 2021; Singh & Kim, 2019; Somanath et al., 2017; Thompson, 2021; Lacy, 2017). Studies report that it is difficult to integrate maker education when teacher-directed instruction is perceived to be superior for learning outcomes (Davis et al., 2021; Thompson, 2021) and when learning is perceived to be most effective when students 'look serious' (Heredia & Tan, 2021; Singh & Kim, 2019). One study reported that current emphases on STEM heavily influenced how MCLEs were undertaken in one school as they were designed to be appear more like science activities than crafting activities (Lacy, 2017). Another study reported that in some contexts, rigid educational cultures heavily discourage non-conformist approaches to teaching, making the integration of maker education extremely challenging (Somanath et al., 2017). Even where educational culture is not so rigid, expectations from leadership and other teachers influence teachers' ability to change their practice (Shively et al., 2021). Furthermore, teachers are expected to make ground level changes that are not always reflected by changes at higher levels of the education system (Justice, 2015).

Funds

Seven studies identify aspects related to funding as a challenge for integrating maker education into K-12 formal education (H. V. Andersen & Pitkänen, 2019; Assaf et al., 2019; Cao et al., 2020; Cross, 2017; Singh & Kim, 2019; M. J. Song, 2021; Turner, 2022). Three studies identified funding issues as among the top challenges in integrating making into formal settings (H. V. Andersen & Pitkänen, 2019; Assaf et al., 2019; Cross, 2017). In one study, two-thirds of school librarians indicated that the lack of a makerspace at their schools was due to a lack of funding (Cao et al., 2020), and in a second study, limited funding resulted in the administration's reluctance to allow students to use maker equipment in the fear that students would break it (Singh & Kim, 2019).

Discussion

The aim of this scoping review was to map the research that has been conducted on learning through making in k-12 formal education settings to identify current challenges these settings are encountering and gaps in the current literature with the goal of informing future research.

To accomplish this, the following three review questions were addressed:

1. How are the published articles on maker education in k-12 formal education settings characterized in terms of bibliographic classification, methodology and topic?
2. What proportion of the published articles on maker education in k-12 formal education identify implications of integrating maker education into these settings?
3. What implications of integrating maker education into formal k-12 education settings have been identified in the research literature?

Review Question 1: How are the published articles on maker education in k-12 formal education settings characterized in terms of bibliographic classification, methodology and topic?

Three-hundred-fifty research publications were identified for this scoping review. Although the time limits of the searched literature spanned from January 1st, 2002 to December 31st, 2022, the earliest identified publications that studied maker education in K-12 formal education emerged in 2013. From that point onwards, research in this area has steadily increased to more than 40 new publications per year for the last five years of the review interval. The majority of publications consisted of peer-reviewed research articles using qualitative methodologies and large sample sizes. Most studies took place in schools.

Nearly half of the research either took place in or was affiliated with the USA by the first author's location. A fair number of studies have also been conducted in Finland, Canada, Australia, China and Taiwan. Although 15 countries only had one study associated with them, over 35 countries were represented in the research.

The reviewed research indicates a fairly even distribution of studies across the K-12 range with many having been conducted in public schools. Unfortunately, a large portion of the studies did not indicate the type of school in which they were conducted, which reduces the ability to discern any differences in challenges that public versus private schools encounter integrating maker education into their classrooms.

The most commonly studied topics among the publications were descriptions or assessments of maker pedagogical approaches, initiatives, programs or space design; student learning and development; and teacher training and professional development. Other topics included student perceptions and experiences of maker education; teacher perceptions and experiences of maker education, assessment of learning through making; description or assessment of a product, tool, or piece of equipment; implications of the integration of maker education into K-12 formal education; equity, and diversity and inclusion in maker education.

Review Question 2: What proportion of the published articles on maker education in k-12 formal education identify implications of integrating maker education into these settings?

One-hundred-five (nearly one third) studies in this review identified challenges associated with integrating maker education into K-12 formal education settings. Despite its apparent importance, only 10 articles explicitly aimed to address these implications as the primary objective and 26 articles addressed these implications as a secondary objective. The disproportionality between the number of studies that identify challenges and the number of studies that examine these challenges suggests that further research with the primary goal of understanding these challenges needs to be conducted.

Review Question 3: What implications of integrating maker education into formal k-12 education settings have been identified in the research literature?

In the reviewed studies, challenges related to space and equipment, time and scheduling, curriculum and assessment, training and professional development, teacher support, educational leadership, student expectations and capabilities, teacher resistance, education culture, and funds were most frequent.

Challenges with finding a physical space in schools for maker education arose whether making was to take place in a dedicated makerspace (Assaf et al., 2019; Harron et al., 2022; Henderson et al., 2017) or a regular classroom (C.-S. Chen & Lin, 2019; Singh & Kim, 2019). While dedicated makerspaces may seem ideal, issues of scheduling (Assaf et al., 2019; Henderson et al., 2017) and time loss due to clean-up were reported (Henderson et al., 2017). Making in classrooms also had challenges as students may not have enough space to move around while making and can potentially be distracted by the maker materials when not making. In regard to equipment, challenges associated with equipment malfunctioning (Assaf et al., 2019; Bower et al., 2020; Daughrity, 2022; Hansen et al., 2019; C. eun Lee et al., 2020; Moorefield-Lang, 2014; L. Song, 2018; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017) and manufacturing time (Bower et al., 2020; Das, 2020; Hansen et al., 2019; Jones et al., 2017; Moorefield-Lang, 2014), and cost (H. V. Andersen & Pitkänen, 2019; Harron et al., 2022; Humburg et al., 2021; Jones et al., 2017) were reported.

Limited time was also found to be a major challenge for teachers. Teachers reported a lack of time to engage in professional development (Harron et al., 2022; Justice, 2015; McKay et al., 2016; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019), and to plan maker projects (Fancsali et al., 2019; Harron et al., 2022; Salo et al., 2021; Shively et al., 2021; R. C. Smith et al., 2016; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017; Thompson, 2021). Teachers also reported limited contact time with students (Assaf et al., 2019; Bower et al., 2020; Collins, 2018; Cross, 2017; Harron et al., 2022; Henderson et al., 2017; Jones et al., 2017; Justice, 2015; C. eun Lee et al., 2020; Leinonen et al., 2020; Stevenson et al., 2019), which some studies reported impacted the types of projects teachers felt they could engage in with their students (Y. B. Kafai & Vasudevan, 2015; R. C. Smith et al., 2016). Scheduling was also challenging as maker education was sometimes not included officially in student schedules (Cross, 2017; Henderson et al., 2017) and teachers had difficulty finding mutual availabilities to collaborate (Milara et al., 2020; Shively et al., 2021; Thompson, 2021).

Many studies also pointed to challenges related to curriculum, standards, and assessment. Teachers were hesitant to attempt approaches to teaching that deviated from curriculum that addressed state standards (Jocius et al., 2020; Rosenfeld et al., 2019). Maker education was perceived to interfere with curriculum content instruction instead of complementing it (Rosenfeld et al., 2019). In cases where teachers did appreciate that making could complement required curricula, they had difficulty making the connections between the two (J. Hughes, Morrison, et al., 2022; Rosenfeld et al., 2019). Prescribed curricula also sometimes impacted how teachers engaged in making with their students (H. V. Andersen & Pitkänen, 2019; Bosch, 2022; Y. Kafai et al., 2014; Leonard et al., 2022; Stevenson et al., 2019). In terms of assessment, teachers apparently lacked the knowledge or ability to assess student learning from MCLEs (Alimisi et al., 2020; O. Chen & Bergner, 2021; Ramey & Stevens, 2019; Siung et al., 2021; Walan & Gericke, 2022), and encountered tensions with the apparent incompatibility of current assessment measures and the types of learning that occur through making (Bertrand & Namukasa, 2022; Ramey & Stevens, 2019; Timotheou & Ioannou, 2021; Walan & Gericke, 2022).

Training was also a reported challenge. Several studies reported that teachers did not feel that they had sufficient training to engage in making with their students (Eriksson et al., 2018; Fan, 2022; Fulfilling the Maker Promise: Year One, 2017; Harron et al., 2022; R. C. Smith et al., 2016), but teachers often lacked the time for training (Harron et al., 2022; Justice, 2015; McKay et al., 2016; Peterson & Scharber, 2018; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019) or could not find any available to them (C. eun Lee et al., 2020).

Studies also reported that teachers lacked support in their efforts to integrate making into their teaching. Teachers spearheading maker initiatives often did so alone (H. V. Andersen & Pitkänen, 2019; Kjartansdóttir et al., 2020), with only occasional support from peers (Stevenson et al., 2019). The greatest need for support, however, was in the classroom. Given the typically large student-to-teacher ratio, unsupported teachers in large classes reported challenges related to addressing each student’s needs (Harron et al., 2022; Lahana, 2016), maintaining student engagement (Heredia & Tan, 2021; C. eun Lee et al., 2020), assessing student learning (Y. J. Kim et al., 2020; Sheffield & Koul, 2021), and ensuring student safety when using maker tools (Henderson et al., 2017).

The significance of support from educational leadership has been underscored, considering that leaders often bear responsibility for financial decisions (Turner, 2022), implementing and reinforcing schoolwide frameworks for maker education (Thompson, 2021), and assisting teachers in the integration of maker practices into their teaching methods (Andersen & Pitkänen, 2019; Cross, 2017; Rosenfeld et al., 2019; Stevenson et al., 2019). Challenges arise when leaders lack a unified vision (Fulfilling the Maker Promise: Year One, 2017; Salo et al., 2021; Zhang, 2021) and fail to provide well-developed curricula for maker education (Zhang, 2021), posing difficulties for teachers as they strive to incorporate making into their classrooms.

The support of educational leadership was also highlighted as important as leaders are often responsible for spending decisions (Turner, 2022), implementing and reinforcing schoolwide frameworks for maker education (Thompson, 2021), and assisting teachers in the integration of MCLEs into their teaching (H. V. Andersen & Pitkänen, 2019; Cross, 2017; Rosenfeld et al., 2019; Stevenson et al., 2019). Challenges arise when leaders lack a unified vision (Fulfilling the Maker Promise: Year One, 2017; Salo et al., 2021; Zhang, 2021) and fail to provide well-developed curricula for maker education (Zhang, 2021), posing difficulties for teachers as they strive to incorporate making into their classrooms.

The dynamics of MCLEs in the classroom were influenced by factors associated with student expectations and abilities. There were instances where students lacked interest and motivation to engage in MCLEs (Kumpulainen & Kajamaa, 2022) and faced challenges in working independently (Heilala et al., 2020) or persisting through difficulties (Henderson et al., 2017). Resistance to risk-taking in the creative process was observed among students (Henderson et al., 2017; Tan et al., 2017), who sometimes sought explicit instructions for project completion (Becker & Jacobsen, 2023; Bower et al., 2020; Henderson et al., 2017; C.-Y. Lee et al., 2021). Additionally, some students were resistant to the iterative process and receiving feedback (Das, 2020).

The teachers themselves experienced challenges with their own lack of expertise (Cross, 2017) and feelings of incompetence (Assaf et al., 2019; Heilala et al., 2020; J. Hughes, Morrison, et al., 2022; Walan & Gericke, 2022). Some teachers lacked confidence with the technology (Bower et al., 2020) and others felt intimidated by it (Koole et al., 2020). Some teachers also feared failure and looking incompetent in front of their students (Alimisi et al., 2020).

Broader issues related to education culture were also identified. In most cases, educators are encouraged to embrace innovative teaching methods. However, entrenched beliefs about traditional teaching and learning practices often limit the extent to which teachers feel comfortable exploring alternative approaches (Davis et al., 2021; Heredia & Tan, 2021; Shively et al., 2021; Singh & Kim, 2019; Somanath et al., 2017; Thompson, 2021).

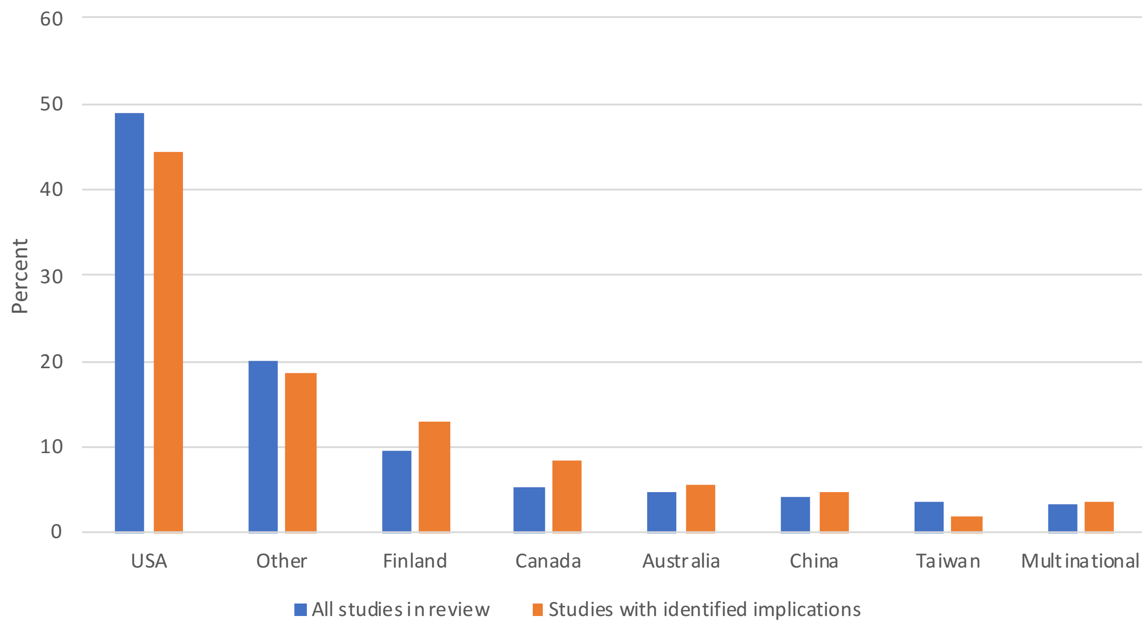
Finally, a small set of studies suggested that a lack of funding can be a hindrance to integrating making in schools due to the cost of equipment and training needs (H. V. Andersen & Pitkänen, 2019; Assaf et al., 2019; Cao et al., 2020; Cross, 2017; Singh & Kim, 2019; M. J. Song, 2021; Turner, 2022).

Implications for Future Research

The results of this review indicate that research in maker education in formal settings is on the rise. However, there are many areas yet to be explored, particularly in education systems outside of the USA. With such a large representation of studies from the USA, it is difficult to determine if other education systems around the world are encountering the same problems. That said, when comparing the proportion of research in each country for all studies to the studies that identify implications for maker education in schools, the overall proportion of these studies is similar (see Figure 5), suggesting that, regardless of where making is being integrated into schools, challenges are arising. Research in educational contexts different from those in the USA

Figure 5

Proportion of Publications Per Country Overall Compared to Proportion of Publications Per Country for Studies That Identified Implications



could provide more insight into the types of challenges and affordances that other approaches to education may have for maker education.

One-third of articles in this review identify challenges associated with integrating making into K-12 formal education, but only a small proportion of studies explicitly examine these challenges. As a result, although many challenges were identified, other than assessment and teacher professional development, which has received some attention, little research has been conducted specifically in the other challenge areas.

Finally, research specifically gaining insight from experienced teachers in maker education in formal education settings is also needed. Of the studies that identified challenges included in this review, only a third (n = 35, 33%) included participants who had some experience with maker-centered education. Teachers with prior experience in maker-centered education may provide us with a clearer understanding of the challenges of integrating maker education into K-12 formal education settings. For example, a rapid comparison of the challenges reported in studies involving teachers who were novices to MCLEs versus studies involving teachers who were experienced with MCLEs revealed that novice teachers to MCLEs reported more challenges related to meeting curriculum requirements than their experience counterparts. Novice teachers to MCLEs reported feeling pressure to be compliant to state standards (Davis et al., 2021), that state curricula constrain their ability to engage in maker activities (Stevenson et al., 2019) and that MCLEs compete with the time necessary to cover the required state curriculum (Bosch, 2022; Fernandez et al., 2020). Only one study that included experienced teachers in MCLEs identified challenges involving curriculum, however, namely that teachers found it frustrating and time consuming to justify every deviation from the standard curriculum they made when integrating activities such as MCLEs (Powell, 2021). On the other hand, studies with teachers experienced in MCLEs more frequently reported challenges related to assessment and reporting than their novice colleagues. While a few studies involving novice teachers to MCLEs reported that these teachers identified assessment as problematic, the explanations for these challenges were vague, stating only that they did not know how to assess learning that resulted from engaging in MCLEs (Humburg et al., 2021; Walan & Gericke, 2022) and that they wanted ready-made assessment tools (Alimisi et al., 2020). The research with experienced teachers in MCLEs report that they too encounter challenges with assessment (O. Chen & Bergner, 2021), but provides more details as to the reason. For instance, experienced teachers in MCLEs reported that conventional assessment methods are not adequate to capture learning through MCLEs (Timotheou & Ioannou, 2021) and that, even if they were, reporting methods are not compatible with process assessment methods (J.-Y. Kim et al., 2021). Experienced teachers in MCLEs also expressed concerns about finding effective ways to capture tangible evidence of student learning during the process of MCLEs to avoid solely assessing the final product (Murai et al., 2019, 2022). The difference in the reported challenges associated with curriculum and assessment suggests that teachers with and without experience with MCLEs perceive the challenges differently and warrants further investigation.

Limitations

Making is difficult to define because it encompasses a wide range of activities, tools, materials, and creative processes, often blurring the lines between art, craft, engineering, and innovation. Some definitions restrict making to forms that include digital technologies (e.g. Anderson, Chris, 2012; Blikstein, 2013; Cohen et al., 2017; Sheridan et al., 2014), while others consider making more broadly as a “process of imagining, creating, refining, and sharing a custom artefact” (“The Maker Movement in Education,” 2014, p. 492). As the review process drew from a constructionist understanding of learning, included studies were those that explicitly identified the activity they were undertaking as making of physical objects. This means that many studies that involved creative activities that some may consider making were not included in this review.

This review also only included studies that are pertinent to formal education as it is presently. Therefore, those that investigated making that touches on aspects of learning and student development that some argue should be, or may one day be, integrated into formal education were not included.

Finally, scoping reviews do not evaluate the quality of research (Booth et al., 2022). As such, the results of poor-quality studies may be represented among the reported findings. Given that the purpose of this review was to identify potential challenges for further research, the inclusion of all studies, regardless of quality, is still valuable in identifying all possible directions of further research.

Conclusion

Although research investigating maker-centered education in K-12 formal education is still in its infancy, the number of studies in this area is increasing rapidly. Given the numerous challenges that teachers are encountering that have already been identified in the research, it is essential that further investigations be conducted in order to better understand the sources of these challenges so that they can be addressed while MCLEs are also still relatively new in schools. Research has pointed to many potential benefits of MCLEs for learning, but if the necessary conditions for teachers to effectively integrate MCLEs into their classroom are not identified and met, maker-centered education may at best be implemented in an impoverished form, reducing its potential for student learning, or at worst be abandoned as yet another failed education initiative (Fulfilling the Maker Promise: Year One, 2017; Koole et al., 2020; Stornaiuolo & Nichols, 2021; Weiner et al., 2021).

Introduction to Manuscript 2

Manuscript 2 aims to address Research Questions 2: What factors do experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered education into K-12 formal teaching? The scoping review presented in the previous chapter of this thesis identified 10 primary areas of challenges that were reported in the literature from 2002-2022 nd that were related to integrating MCLEs into K-12 formal education settings. However, only 12 of the 350 identified articles explicitly studied the challenges associated with maker-centered education in schools as their primary focus, with only 3 involving teachers experience with MCLEs. As a result, although a wide range of challenges were identified, the causes and complexities of these challenges were not detailed. The qualitative-interpretive study presented in the following manuscript aimed to provide more insight into the causes and complexities of the challenges that teachers encounter when attempting to integrate MCLEs into their teaching, as well as the enablers that aided them during this process. By better understanding the challenges and enablers teachers encounter with MCLEs in schools, policy makers and education leaders can better provide the optimal conditions necessary for teachers to successfully integrate MCLEs into their teaching.

Manuscript 2: Educator perceptions of the challenges and enablers for the integration of maker-centered learning experiences in K-12 formal education settings.

Abstract

For over a decade, the Maker Movement has attracted educators and leaders with its potential to build essential 21st-century skills and positive dispositions. Consequently, many schools and education systems have adopted maker inspired activities to enhance student learning. However, the nature of these activities often conflicts with traditional educational practices, posing challenges for integration into formal education settings. The aim of this qualitative-interpretive study was to document and analyze the perceived challenges and enablers teachers encounter when integrating maker-centered learning activities into their teaching practice. Twenty-one educators with experience integrating maker-centered education into K-12 formal education settings were interviewed from both English and French speaking Canada, and the United States of America. The findings confirmed challenges already reported in the literature, provided a greater understanding about the causes and consequence of these previously reported challenges, as well as identified some challenges not already reported in the literature. Additionally, participants identified enablers and provided recommendations to circumvent some of the identified challenges.

Introduction

For over a decade, the Maker Movement has captured the attention of education leaders and educators due to the assertion that the activities involved can foster positive dispositions and a range of skills essential for personal and professional success in the 21st century (Blikstein, 2013; Halverson & Sheridan, 2014a; Kurti et al., 2014; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013). As a result, numerous schools, and in some instances, entire education systems, have sought to incorporate activities resembling those found in maker contexts to leverage their learning benefits for students (Care et al., 2018; Lacy, 2017). However, the inherent nature of maker activities present a challenge for formal education applications, as it often contradicts traditional practices in formal educational settings (Blikstein, 2013; Lacy, 2017; Leonard et al., 2022; Nemorin & Selwyn, 2017). Understanding the challenges and enablers that educators encounter when attempting to integrate maker-centered learning experiences (MCLEs) into their classroom is critical to provide the necessary conditions for teachers to succeed with these efforts. The following article presents what is currently known about the challenges associated with integrating maker activities into K-12 formal education settings, the aim of this study, the results from interviews of 21 educators with experience integrating maker activities into school settings, and recommendations for providing the optimal conditions for teachers integrating maker-centered education into their practice.

The Maker Movement and Maker-Centered Education

The Maker Movement, as defined by Martin (2015, p. 30), refers to a "movement of hobbyists, tinkerers, engineers, hackers, and artists committed to creatively designing and building material objects for both playful and useful ends." Its inception is often credited to Dale Dougherty, who introduced 'Maker Magazine' in 2005 and initiated the globally renowned Maker Faires in 2006 (Marsh et al., 2017). The movement has since experienced rapid growth, which Dougherty (2013) attributes to the increased accessibility and affordability of digital fabrication tools, electronic components, online networks, and digital asset-sharing platforms.

The nature of maker activities is suggested to hold the potential to cultivate a diverse range of skills. Martin (2015) defines making as

> [a] class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a ‘‘product’’ of some sort that can be used, interacted with, or demonstrated. Making often involves traditional craft and hobby techniques (e.g., sewing, woodworking, etc.), and it often involves the use of digital technologies, either for manufacture (e.g., laser cutters, CNC machines, 3D printers) or within the design (e.g., microcontrollers, LEDs). (p. 31)

Given the diverse range of activities makers engage in, making has been associated with the development of a variety of skills such as digital skills like computational thinking (e.g. Yin et al., 2020) and online communication skills (e.g. Rafalow, 2016), transversal skills such as critical thinking (e.g. Forbes et al., 2021; Trust et al., 2018; Weng et al., 2022), design thinking (e.g. Liu & Li, 2023; Marsh et al., 2017; Papavlasopoulou et al., 2017), creativity (e.g. Liu & Li, 2023; Soomro et al., 2023; Weng et al., 2022) and problem-solving (e.g. Becker & Jacobsen, 2023; Bevan et al., 2015; Blikstein et al., 2017; Forbes et al., 2021; Ng et al., 2023). Making has been associated with interpersonal skills like collaboration (e.g. Davidson, 2018; Dixon & Martin, 2017; Giusti & Bombieri, 2020; Herro et al., 2021; Papavlasopoulou et al., 2017) and collaborative knowledge creation (Davies et al., 2023; S. Riikonen et al., 2020; W. Smith & Smith, 2016), as well as intrapersonal skills such as self-regulation (e.g. Agency by Design, 2015; Vossoughi & Bevan, 2014) and self-directed/autonomous learning (e.g. Halverson & Sheridan, 2014; Kurti et al., 2014; Martinez & Stager, 2013; Sheridan et al., 2014). Moreover, research suggests that making can improve general academic performance (Otero & Blikstein, 2016; Papavlasopoulou et al., 2017), particularly for at-risk students (J. M. Hughes, 2017), and especially in the science, technology, engineering, and mathematics (STEM) subjects (Blikstein, 2013; Tillman et al., 2014). In addition to skills development and academic performance improvements, maker activities have been associated with student increased interest in STEM (Togou et al., 2020; Weng, Chiu, & Jong, 2022), writing (Davis et al., 2021), and a general improvement in school attendance (Wilson & Gobeil, 2017). Studies also noted improvements in students' sense of confidence (Becker & Jacobsen, 2023; Togou et al., 2020), self-efficacy (Das, 2020; Schlegel et al., 2019; Susmitha et al., 2018), agency (Becker & Jacobsen, 2023), and growth mindset (Vongkulluksn et al., 2021).

In addition to the emerging reports of the learning benefits of maker activities, there is also theoretical justification for these benefits. Among the most commonly cited learning theories to justify the affordances of maker activities for learning is constructionism (e.g. Blikstein, 2013; Blikstein et al., 2017; Cohen et al., 2017; Kurti et al., 2014; Martinez & Stager, 2013; Petrich et al., 2013; Resnick & Rosenbaum, 2013). Initially developed by Seymour Papert (1980, 1991), constructionists posit that concepts and systems are constructed by learners and that these concepts and systems are developed through lived experiences and authentic inquiry (Papert, 1980, 1993). Consequently, concepts cannot be 'transmitted' to learners. Instead, environments conducive to learning must be created (Papert, 1980, 1993).

Based on constructionism principles, the many affordances of maker activities for learning stem from a few key characteristics of maker activities and the Maker Movement. First, constructionists posit that learning is mediated by creating personally motivated, shareable objects referred to as 'objects-to-think-with'. These objects are used by the learner to externalize mental models, build on them and re-internalize the modified models through the creation and physical manipulation of the objects (Ackermann, 2001; Niemeyer & Gerber, 2015; Papert, 1980, 1991). Making involves creating either a physical or digital object of some kind with which learners can interact. Second, through sharing and discussions about these objects learners further develop their understanding of the concepts around the object as they attempt to verbally articulate their ideas and receive feedback and insight from those they interact with (Ackermann, 2001; Niemeyer & Gerber, 2015; Papert, 1980, 1991). The Maker Movement places a strong emphasis on the sharing of objects. For example, makers have presented their creations at events like Maker Faires and online through a multitude of platforms. The sharing of ideas, solutions, and even software and technology through open-source sharing are also encouraged by and among makers (Cohen et al., 2017; Halverson & Sheridan, 2014). Third, Papert (1980) places a particular importance on affect in the learning process. He argues that, without the motivation to reflect on experiences, the learner is not likely to construct complex concepts and systems around these experiences. Therefore, the motivation and engagement of the learner is crucial for learning to occur (see also Drodge & Reid, 2000). Learners must be interested in what they are doing, which is best accomplished when learning activities are interest-driven (Papert, 1980). As makers voluntarily engage in maker activities and are typically very passionate about making, the activities are necessarily interest-driven. Given these parallels, maker activities appear ideal for learning from a constructionist perspective (Martinez & Stager, 2013; Vossoughi & Bevan, 2014).

Due to the widespread appeal of the Maker Movement, the theoretical justification for the learning benefits of maker experiences, emerging research findings, and the conviction of these learning benefits by some educators and education leaders, educational institutions are progressively establishing makerspaces and incorporating maker-centered learning experiences (MCLEs) into their curricula. This strategic move aims to leverage the educational opportunities presented by the Maker Movement within formal education settings (Schad & Jones, 2020).

Maker-Centered Education and Formal Education

Despite many potential benefits, some have expressed concerns that education leaders and educators may face challenges integrating these experiences within their schools (Campos et al., 2019; Jocius et al., 2020; Kumpulainen & Kajamaa, 2022). Questions emerge about how to effectively incorporate MCLEs while preserving the claimed learning advantages they are suggested to offer in their natural settings (Cohen et al., 2017; Halverson & Sheridan, 2014a; Hira & Hynes, 2018; Humburg et al., 2021; Jocius et al., 2020). As emphasized by Kervin and Comber (2021, p. 80), "Classrooms are geographically and institutionally bounded places with physical features, cultural histories, and social roles." The inherently structured nature of formal education settings may pose challenges when integrating student-driven, non-linear, and process-based learning activities such as MCLEs (Jocius et al., 2020; Kervin & Comber, 2021; Novotny, 2019). Jocius et al. (2020) noted:

> Researchers have expressed concerns that institutional constraints of formal learning environments might restrict much of what makes making so powerful in informal learning environments, such as play, imaginative design thinking, and makers' autonomy in choosing which problems to approach and how to solve them. (p. 397)

In a recent scoping review (Duponsel & Davidson, in preparationb), we investigated the reported challenges associated with integrating MCLEs into K-12 formal education, and revealed that the literature has reported multiple challenges encountered by educators as they attempt to integrate MCLEs into their teaching. The review identified 10 categories of challenges: 1) space and equipment, 2) time and scheduling, 3) curriculum and assessment, 4) training and professional development, 5) teacher support, 6) educational leadership, 7) student expectations and capabilities, 8) teacher resistance, 9) education culture, and 10) funds (see Duponsel &

Davidson, in preparation, for a more in-depth discussion of the challenges associated with each category).

Although the breadth of the identified challenges was quite expansive, we found that, in most cases, the challenges were reported in studies that did not aim to study the associated challenges of integrating MCLEs into formal education and therefore did not provide detailed information about the challenges. While 105 of the 350 studies included in the review reported challenges associated with integrating MCLEs into schools, only 10 of the studies focused primarily on identifying and describing these challenges, with a further 26 studies investigating challenges as a secondary objective.

We also noted that there was evidence of differences in the identified challenges between studies that involved teachers with and without experience with MCLEs. Teachers without experience with MCLEs reported greater challenges with curriculum and standards, whereas experienced teachers with MCLEs did not share these same concerns. Conversely, while only a small number of studies involving teachers without experience with MCLEs reported difficulties with assessment of learning through MCLEs, a greater number of studies involving teachers experienced with MCLEs reported challenges with assessment. Therefore, we suggested that, although numerous challenges have been reported regarding the integration of MCLEs into K-12 formal education settings, the lack of depth in understanding these challenges and the paucity of research with experienced teachers with MCLEs warrants further investigation into these challenges.

In addition to understanding the challenges teachers may encounter when integrating MCLEs into their classroom, understanding more about the enablers that helped teachers with this integration could be fruitful. By knowing more about what enables teachers to successfully integrate MCLEs into their teaching practice, it may be possible to inform education leaders, policy makers and teachers about what to avoid when initiating maker-centered education programs, as well as to investigate what could be helpful for teachers. Therefore, this study aims to gain insight into the challenges and enablers that teachers encounter when integrating MCLEs into K-12 formal education settings by interviewing educators (teachers, principals, education consultants, and school-based maker specialists) experienced with MCLE integration in schools. The study aims to answer the following research questions:

1) What factors do experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered learning experiences into K-12 formal teaching?
    a. What are the perceived challenges faced by educators in K-12 formal education who have experience with maker-centered education, as they integrate maker-centered learning experiences into their teaching?
    b. What factors do educators in K-12 formal education, who are familiar with maker-centered education, perceive as facilitating the integration of maker-centered learning experiences into their teaching?

Methodology

This study uses a qualitative interpretive approach to reveal educators' perceptions of the challenges and enablers associated with integrating MCLEs into K-12 formal education settings. The following section describes the study design, data collection methods, and analysis methods used to address the research questions.

Research Design

A qualitative-interpretive research design was adopted for this study. Qualitative research attempts to "make sense of or interpret phenomena in terms of the meanings people bring to them" (Denzin & Lincoln, 2018, p. 10). In the case of this study, the goal was to interpret the meanings educators give to their experiences attempting to integrate, or helping teachers to integrate, MCLEs into their teaching practice, to develop an understanding of what they perceive influences teachers' ability to integrate these types of learning experiences into their classroom practices. To do this, semi-structured interviews were conducted with educators (teachers, principals, education consultants, and school-based maker specialists) who have experience with MCLE integration in schools.

Role of the Researcher

> Gaze is filtered through the lenses of language, gender, social class, race, and ethnicity. There are no objective observations, only observations socially situated in the worlds of—and between—the observer and the observed. (Denzin & Lincoln, 2018, p. 17)

As an educator who firmly believes in the potential learning benefits of MCLEs, I am not neutral in my interest in maker-centered education as I have a vested interest in the success of maker-centered programs in schools, particularly as part of the required curriculum. I do believe, however, that not just any interpretation of maker-centered education will result in the full range of learning affordances these experiences have to offer students and that maker-centered education programs need to be solidly grounded in research and aligned with learning theories such as constructionism. While I have extensive experience teaching at the elementary school level (Kindergarten to Grade 6) and working with youth (11-18 years) in out-of-school settings, I have considerably less experience with integrating MCLEs into school settings as I stopped teaching at the start of my doctoral studies. As such, while I am an educator with my own beliefs and opinions about maker-centered education and my own ideas of its integration in my teaching practice within elementary school contexts, I have little understanding of how other educators integrate MCLEs into their teaching practices and the various challenges that they may encounter outside of what is outlined in the literature. For this reason, I position myself as closer to the investigator end of the participant/investigator spectrum (Glesne, 2011). This does not mean, however, that I can remain completely objective given that, despite my best efforts, I have no other choice than to interpret the data through the lens of my own experiences.

Participants

Twenty-one participants were recruited through purposeful sampling as participants with prior experience with the integration of MCLEs were specifically recruited. Based on their current professional titles, participants included 5 teachers, 1 school principal, 6 public consultants (school board/district consultants paid by public funds), 4 private consultants, 3 community makerspace specialists, and 2 school makerspace specialists. Participants occupied their current positions from 2 to more than 20 years with a mean of 7.4 years. Eleven participants were teachers before taking their current position. In total, 16 participants were or are currently teachers, with 14 of the 16 having more than 10 years of teaching experience (see Table 6). To protect the identities of the participants, pseudonyms have been used throughout this article.

To be included in the study, participants were required to speak English or French, work in Canada or the United States of America, and have at least 2 years of experience either integrating MCLEs into their own teaching practice or assisting teachers with the integration of MCLEs into their teaching practice. Participants were also required to align with constructionist conceptions of maker-centered learning. For the purposes of this study, participants were considered as aligning with constructionist views of maker-centered learning if their conception of effective MCLEs consists of experiences that involve a process where students design and

Table 6

Teacher Demographics

Identifier	Country	Current position	Years in current position	Years of teaching experience	Level
Alexandre	Canada	School principal	3 years	9 years	High school
Arjun	Canada	Education consultant (public sector)	2 years	10+ years	K-12
Brigitte	USA	Community makerspace specialist	7 years	10+ years	Middle, High school
Bruce	USA	Education consultant (private sector)	2 years	10+ years	Middle, High school
Camilla	USA	Teacher	10+ years	10+ years	Elementary, Middle school
Caroline	Canada	Education consultant (public sector)	8 years	--	K-12
Charles	Canada	Education consultant (public sector)	10+ years	10+ years	High School
Derek	Canada	Teacher	3 years	3 years	High School
Emma	USA	School makerspace specialist	3 years	10+ years	High School

Jennifer	Canada	Community makerspace specialist	3 years	--	K-12
Jocelyn	Canada	Teacher	10+ years	10+ years	CEGEP
Kevin	USA	Teacher	10+ years	10+ years	Middle, High school
Lilliane	Canada	Education consultant (public sector)	4 years	10+ years	High school
Matthew	Canada	School makerspace specialist	5 years	10+ years	High School
Michel	Canada	Education consultant (private sector)	4 years	--	K-12
Samantha	Canada	Education consultant (private sector)	3 years	--	K-12
Sandy	USA	Community makerspace specialist	7 years	10+ years	High School
Sarah	USA	Education consultant (private sector)	10+ years	--	K-12
Sophie	Canada	Education consultant (public sector)	3 years	10+ years	Elementary
Sylvain	Canada	Teacher	5 years	10+ years	Elementary

Valentine	Canada	Education consultant (public sector)	2 years	10+ years	Elementary

construct a physical artifact with or without the assistance of digital fabrication technologies (e.g. 3D printers, laser cutters) to solve an open-ended problem or achieve a student-determined goal. Teachers deemed to not align sufficiently with constructionist views of maker-centered learning would have been excluded from the study, however, that situation did not arise. It must be noted that this exclusion criterion refers to their conception of effective MCLEs and not the actual implemented experiences as factors in their environment may inhibit their ability to materialize their ideal MCLE in practice.

Data Collection

The data were collected through semi-structured interviews. Interviews help researchers gain information about participants' perceptions and information that is not observable (Yamagata-Lynch, 2010). As the primary goal of this study was to better understand educator perceptions of the challenges and enablers of the integration of MCLEs into formal education, interviews were essential in accessing these perceptions.

To accomplish this, semi-structured interviews were used. Brinkmann (2018) describes the advantages of semi-structured interviews:

> [S]emistructured interviews can make better use of the knowledge-producing potentials of dialogues by allowing much more leeway for following up on whatever angles are deemed important by the interviewee, and […] compared to more unstructured interviews, the interviewer has a greater say in focusing the conversation on issues that he or she deems important in relation to the research project. (p. 579).

Therefore, the foci of the interview were prepared beforehand by creating an interview schedule but the researcher and the participants were permitted to expand on topics they felt were relevant to the goals of the study as the interviews proceeded. Table 7 lists the questions that were included in the interview schedule. As shown below, some questions were modified slightly depending on the role of the educator being interviewed.

Procedures

Ethics approval from the Concordia University Research Ethics Unit was gained prior to the start of the study. TCPS Core Certification for research with human participants was completed.

During first contact, the researcher provided the participants with information about the purpose and procedure of the study to determine if they were interested. Interested participants were sent a consent form by email that they were asked to read through. They were encouraged to contact the researcher for any questions they had. If they agreed to participate in the study they were asked to print, sign, scan (or photograph) the form and return it by email. Only once the signed consent forms were received were participants contacted to arrange a date and time for the interview.

Participants were informed of their right to withdraw their participation and data from the study without consequence both in the consent form as well as prior to the start of the interview.

Once the signed consent form was received, the researcher contacted the participant to arrange a day and time for the interview. Prior to the start of the interview, participants were reminded of their rights as participants and asked if they had any questions. Once any participant questions had been answered and they agreed to continue, the interview began. At the end of the interview, the researcher thanked the participant for their time. Interview recordings were

Table 7

Interview Questions

#	Question
1	Can you tell me about your current role in education and how you got involved with maker education?
2	What types of maker activities have you undertaken with students / What types of maker activities have you helped teachers undertake with students?
3	What are your learning goals for maker education?
4	Can you describe to me one of your most recent maker activities you've undertaken with students? / Can you describe to me one of your most recent maker activities you've helped a teacher undertake with their students?
5	What was helpful in preparing for that activity?
6	What was challenging preparing for that activity?
7	Were there any aspects of the activity that you wanted to do but weren't able to do? if so, why weren't you able to do those things? / Were there any aspects of the activity that the teacher wanted to do but wasn't able to do? if so, why wasn't the teacher able to do those things?
8	What would need to change for an activity like this to work better if it were to be done again?
9	At the school level, what could be done to better help teachers integrate maker activities into their teaching?
10	At the district/board level, what could be done to better help teachers integrate maker activities into their teaching?
11	At the ministry/government level, what could be done to better help teachers integrate maker activities into their teaching?
12	At the societal level, what could be done to better help teachers integrate maker activities into their teaching?
13	Of everything that we discussed, what would you say is the largest barrier to integrating maker education in schools?

transcribed and both audio recordings and transcriptions were saved on a password protected drive. Pseudonyms were assigned to all participants to ensure anonymity.

Data Analysis

The constant comparative method developed by Glaser and Strauss (1967) was used to analyse and interpret the data. Yamagata-Lynch (2010) describes the constant comparative method as a “systematic process of examining and re-examining the data while comparing one source with another to find similarities and differences” (p. 73). Yamagata-Lynch further explains that while the constant comparative method is typically used in grounded theory, it does have applications in other qualitative research approaches.

The constant comparative method uses three stages of coding: open coding, axial coding, and selective coding. In the first stage of coding, open coding is used as an “intense microscopic examination of data that helps investigators identify the complexities involved in participant activities” (Yamagata-Lynch, 2010, p. 73). At this stage of coding, Yamagata-Lynch (2010) recommends that researchers do not restrict themselves in any way in how they code (e.g. categorizing their codes by predetermined themes or theoretical frameworks) but rather to code the data as it presents itself using the smallest units of code possible. Yamagata-Lynch argues that while some researchers begin immediately by coding data-based theoretical elements, she prefers beginning with open coding to “avoid focusing on participant experiences that only map well with theoretically driven codes” (p. 74). She argues that this approach helps researchers remain as open and objective as possible at this stage of analysis. Repeated rounds of open coding continue until the researcher is no longer able to identify new codes in the data, which indicates that the data are saturated and that the next stage of coding may begin. At this stage of coding, Yamagata-Lynch also begins to note "how families of code interact with one another" (ibid, p. 74), which will act as a transition to axial coding.

The second stage of coding is axial coding. At this stage, researchers "identify overarching themes and categories that exist among the codes" (Yamagata-Lynch, 2010, p. 74). Even at this stage Yamagata-Lynch (2010) resists creating themes that 'fit' well into theoretical frameworks choosing to still rely on the data to generate the themes. Only at the third and final stage of coding, selective coding, does Yamagata-Lynch begin to organize the themes by various overarching elements.

The data were coded and analyzed using MAXQDA 2022 (VERBI Software, 2021).

Trustworthiness and Scientificity

Three strategies were used to establish trustworthiness and scientificity of this study: triangulation, audit trails, and member checking.

Triangulation

Triangulation was used to "produce knowledge on different levels [that] go beyond the knowledge made possible by one approach and thus contribute to promoting quality in research (Flick, U, 2018, p. 452). Data triangulation was accomplished in three ways: by interviewing participants from two locations (Canada and the USA), by interviewing participants who occupy differing roles in formal education, and by interviewing participants where the language of instruction is not English (in this case, French).

The first means of data triangulation was done by interviewing participants from different locations but within education systems that are still very similar. The data drawn from participants are more likely to represent the breadth of the potential experiences that educators could have in education systems that resemble those of North America. Although there are differences between the education systems of the two countries (and even within each country as education is a provincial/state responsibility in both cases), education in these two countries shares more similarities than differences, especially compared to other education systems globally.

The second means of data triangulation was accomplished by interviewing educators occupying different roles in their education system. As Flick (2018) interviewed participants occupying different roles to gain further insight into the phenomenon, the participants interviewed in this study also occupied different roles (teacher, school principal, education consultant, school makerspace specialist or community makerspace specialist) to gain a broader and deeper understanding of the challenges and enablers associated with the integration of MCLEs into formal education settings.

The third means of data triangulation was accomplished by interviewing participants whose language of instruction is not English. Prior research has reported additional challenges when integrating MCLEs into schools where the language of instruction is not English as most programming languages and other available resources are predominantly in English (Somanath et al., 2017). By including Canadian participants who work in the French school system, additional challenges that may exist due to the language of instruction should emerge.

Audit Trail

An audit trail was kept for confirmability of the study findings. Halpern (1983) identified six audit trail classifications supported by subsequent researchers (e.g. Bowen, 2009; Lincoln & Guba, 1985): intentions and disposition, instrument development, process notes, raw data, data reduction and analysis, and data reconstruction and synthesis. Intentions and disposition and instrumental development were recorded through the original proposal of this study as the goals and research questions, methodologies and relevant literature were discussed and outlined. Process notes were kept regarding any changes to the interview schedules, as well as the reasoning behind the changes, as data collection progressed. Raw data consisted of interview audio-recordings, which were transcribed and stored on a password protected drive. Data reduction and analysis were documented using researcher notes that described the progression of coding, while a coding frame (O'Connor & Joffe, 2020) that listed the codes organized by higher order code categories with precise definitions of codes and examples from the data were created with the help of MAXQDA 2022 (VERBI Software, 2021), a qualitative data analysis software. Finally, data reconstruction and synthesis were documented using researcher notes and a final report of findings (the dissertation in which this article is included), which included thick descriptions with quotes from participants to justify researcher interpretations, as well as a visual data analysis trail to map coding schemes. Miro (RealTimeBoard, Inc., 2022) was used to develop the visual data analysis trail.

Member Checking

Member checking was used as it ensures that researcher interpretations and understanding of participants' experiences are as accurate as possible (Creswell, 2012). While Morse (2018) suggests that member checking study results is not appropriate as "[p]articipants do not appreciate the theoretical development of the study" (p. 812), member checking the researcher's interpretations of participants' descriptions was done throughout data collection using interviewing techniques such as paraphrasing, asking follow-up questions and questioning for clarification and further information when needed (Seidman, 2019).

Findings and Discussion

Four overarching categories of challenges and enablers were revealed by the data. They were related to: 1) material, virtual and human resources, 2) educational operations and management, 3) training and professional development, and 4) perceptions about learning, teaching, and maker-centered education. The following sections discuss each category drawing on responses from participants and making connections with previously reported findings in the literature. As there is a considerable amount of data to report, participant statements have been primarily paraphrased with a few direct quotes to emphasize participant perspectives.

Material, Virtual and Human Resources

Eighteen of the 21 participants (86%) identified challenges and enablers related to material, virtual and human resources when discussing their own experiences or observations of others' experiences integrating MCLEs in schools. These included aspects related to physical space, equipment, software and online tools, other online resources, and the involvement of specialists and other educational stakeholders.

Material and Virtual Resources

Seventeen participants (81%) identified challenges and enablers related to material and virtual resources such as space, equipment, software and online tools, and other online resources.

Space: Eight participants (38%) identified challenges and enablers associated with finding an appropriate space in the school for the purposes of MCLEs. Similar to reports from the literature, the reported challenges revolved around lacking space in schools (Cao et al., 2020; Henderson et al., 2017; Singh & Kim, 2019; R. C. Smith et al., 2016), working around existing architecture to install equipment with special requirements like ventilation (Harron et al., 2022; Henderson et al., 2017), finding adequate storage for materials and projects in progress (Cross, 2017;

Henderson et al., 2017; Stevenson et al., 2019; Tan et al., 2017), and challenges related to safety requirements (Harron et al., 2022; Henderson et al., 2017). In addition to the challenges reported in the literature, challenges related to the extensive time needed to optimize the space for different projects and purposes emerged. For example, Sylvain explained:

> The management of the spaces has undergone a lot of evolution from the beginning until today. We have changed the organization of the space about four times. It is sure that it is always in movement. […] At the beginning, we were thinking a lot about having small dedicated environments. And with hindsight, we see that, yes, it works with the community, but when I'm with students, sometimes I need the material to be more distributed. […] I would say that after five years […] we are really starting to have a more optimal functioning.

Sylvain's statement above reveals that schools with official Fab Lab experience additional challenges designing their space as they must cater to both their students' needs and the needs of the public given the Fab Lab Charter requirement to make the space available to the local community (MIT Fab Lab, 2012).

Caroline also identified frustration among teachers as efforts to create spaces are often thwarted even once spaces have been dedicated to MCLEs, resulting in a loss of time and money:

> Physical space is often an issue. We've seen in some schools, there was a space and a room assigned to be the makerspace and they spent money and they arranged it and organized it and then they had to take back the room because the student population changed and they had to add it back into a classroom. It's happened a lot.

Regardless of the challenges associated with designing and managing a dedicated makerspace in a school, educators reported that there were several advantages to having these spaces that enable teachers to engage in MCLEs with their students. Emma and Caroline pointed out that makerspaces are excellent places to do MCLEs that are too messy for the regular classroom, while Camilla pointed out the dedicated space in her school allows her to prepare the materials for MCLEs. Finally, in the case of new schools, Lilliane reported that they are being built with learning commons in mind, which is making integrating MCLEs far easier for teachers interested in engaging in them with their students.

Equipment: Fourteen participants (67%) identified challenges and enablers related to equipment. Similar to reports from the literature, these challenges included not knowing which equipment to purchase (Eriksson et al., 2018; Milara et al., 2020), maintaining and troubleshooting malfunctioning equipment (Assaf et al., 2019; Bower et al., 2020; Daughrity, 2022; Hansen et al., 2019; C. E. Lee et al., 2020; Moorefield-Lang, 2014; L. Song, 2018; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017), and the fabrication time of some equipment like 3D printers (Bower et al., 2020; Das, 2020; Hansen et al., 2019; Jones et al., 2017; Moorefield-Lang, 2014).

Lilliane, Sandy, Brigitte and Sylvain (19%) reported challenges revolving around schools not knowing which equipment to purchase. Lilliane mentioned that there is a lack of guidelines and support to help schools decide which equipment to procure as, although there are guidelines in terms of which equipment is industry approved and meets safety standards, these are not sufficient to help schools make purchasing choices that best meets their needs. Sandy reported that she often has school principals ask her for guidance on equipment purchases and that unnecessarily expensive equipment has been purchased due to a lack of appropriate guidance.

She recounted one incident with a school principal, “This principal, she spent $40,000 on a direct to garment printer. […] What? $40,000 for this ridiculous machine! […] I can get you a vinyl cutter and a heat press for less than 500 bucks combined!” Similarly, Brigitte recounted, “They were ridiculous. They [had] a $150,000 lab that maybe 10 kids in the whole district were using. That is not a good return on investment.”

Regarding the practical use of equipment once it has been purchased, some equipment was reported to be more problematic for everyday use in the school than others. When discussing the challenges his school encountered with their makerspace, Sylvain reported that some equipment, like CNCs, is too noisy and cannot be run during the school day, while equipment like 3D printers cannot be interrupted, which is problematic given the length of some prints and the relatively short school day. Sylvain noted:

> After this interview, I will launch a project on the CNC. I would have liked to do it during the week, but it wouldn't have been a good idea because […] 1) it's noisy and 2) we don't want to stop it because, we can restart it, but we’ve had problems with that.

In terms of the equipment in the physical space, Sylvain stated that some equipment is quite large and requires a lot of physical space for safety reasons, which poses problems in school classrooms that were not designed for these purposes. He explained:

> If I think about all this space that's dedicated to the CNC […] it takes up a lot of space in the Fablab. And there is a safety corridor that must be respected, even when it is not in use […]. There are all these rules that are linked to them that make it a large space that is under exploited.

Training and ease of use were also reported to influence which equipment was used more frequently. Valentine reported that teachers often do not use the technology because they lack sufficient training and Lilliane mentioned that teachers often shy away from certain equipment, like 3D printers, in favour of others, like vinyl cutters, because of the latter's greater ease of use. Matthew explained that, for this reason, he views vinyl cutters as more useful in his school than equipment like a laser cutter:

> I have six, eight, Silhouette Cameos, three in two different spaces and I've given one to kindergarten, and I can see a Cameo in every class. These are affordable tools that any school can use. If you can buy a SmartBoard for a public school, you can buy a Cameo cutter. So, a lot of our focus is around these things, not the $40,000 laser cutter that we have.

While participants did not comment on concerns about high costs of equipment as was reported in the literature (H. V. Andersen & Pitkänen, 2019; Harron et al., 2022; Humburg et al., 2021; Jones et al., 2017), Sophie, Camilla, Jennifer, and Alexandre did note that obtaining funding for the consumeable materials needed to use the equipment (e.g. filament for 3D printers) and to replace technology that becomes obsolete is very challenging. Funding appears to be easier to obtain for the initial purchase of equipment, but not for its continued use and maintenance.

Four participants (19%) identified enablers associated with equipment related to increased access to equipment through libraries and community makerspaces, increased ease of use, and purchasing strategies that fascilitate training, trouble-shooting, and maintenance. Lilliane mentioned that for schools that do not have their own fabrication technologies, the increased presence of equipped libraries and community makerspaces is making the technologies more accessible to schools. She suggests that creating local hubs for schools to borrow equipment would considerably cut down on costs as schools are not typically using all of their equipment all of the time and the maintenance of the equipment can be shared. She explained:

> The idea is that the robots, if you get them for a school, they won't be used 24/7. […] It makes sense to share. Same thing with […] technology equipment. Having hubs where people can go […] where it's a makerspace, […] and the different school boards send their students to be making with bigger equipment, […] CNC machines and whatnot. But having hubs [where] you can fund the specialists who will maintain the equipment there.

Lilliane and Brandy pointed out that fabrication technologies are also becoming more accessible to novice teachers to MCLEs because they are becoming increasingly user friendly. Brandy explained that even equipment like laser cutters have become very user friendly, particularly for novices.

Using the same equipment was also mentioned as an enabler when it came to training, maintenance and troubleshooting. Alexandre and Lilliane mentioned that by purchasing the same equipment, training could be simplified and educators could help each other troubleshoot problems. Sarah also encourages schools to purchase the same equipment that she has at her mobile makerspace so that she can lend them the same model machine, which they are familiar with, while she does the repairs. Corey also points out that getting help with fabrication equipment is also easier now as affordable equipment has meant more people have access to it, which has resulted in the creation of collaborative online communities where solutions can be found.

Software and online tools: Six participants (29%) identified software and online tools as an area providing both challenges and enablers. As in the literature, software and online tools were reported more frequently by participants to be enablers in integrating MLCEs into classrooms than sources of challenges. While one study in the literature (Nemorin & Selwyn, 2017) reported a specific challenge with a particular software, participants' remarks about software challenges in this study revolved more around managing the sheer volume of software and tools teachers and students are required to use, as well as concerns around student online safety and online data security. For example, Jennifer and Brigitte mentioned that because there is no standardized use of software and learning management systems, teachers and students are continually learning how to use new software as teacher and school preferences differ or the software being used by a school or district gets changed by leadership. Brigitte expressed her and her colleagues' frustration with continual changing software:

> [W]e keep changing. […] Our schools had one and then during COVID they didn't like that one and so they moved to a different one. And all the work that had been put into the first learning platform was now gone and they had to start over. And I think the school systems have jumped from one ed tech software to another ed tech software. Teachers are getting burned out. They're really tired of rebuilding the wheel.

Another challenge mentioned by educators is related to online data security. Brigitte and Lilliane both mentioned that student data are not adequately secure. Brigitte stated, "I'm using incredibly insecure technology and I'm teaching my kids to use 50 different edtech software because someone sold it to my boss. And nobody seems to care that we are selling our students' digital identity."

Despite the challenges mentioned by Jennifer, Brigitte and Lilliane around software and online tools, four participants (19%) also mentioned enabling characteristics of software and online platforms. Brigitte and Samantha both pointed out that free online software, like TinkerCAD, makes many MCLEs accessible to schools. Kevin added that they are also often very user friendly, which is particularly useful for students and teachers who are novices to MCLEs, and when class sizes are large as students can work independently without needing frequent help from their teacher. Sylvain pointed out that software like TinkerCAD is also very transparent and easily links to concepts in the curriculum, particularly for the STEM disciplines.

Online Resources: Eight participants (38%) identified challenges and enablers related to online resources. The common theme that emerged from the interviews concerning online resources was that there are many online resources that are available, but that they are not always useful or easy to use. Kevin pointed out that while there are many resources available to provide ideas and lesson plans to teachers, they are very time consuming to sift through to find lessons that check all the required curriculum boxes. Brigitte added that in addition to finding a somewhat appropriate activity to do with the students, the resources are often too elaborate and need to be modified for the teacher's specific use, adding more time to the process. She explained:

> Stanford does an amazing program called Scale [but] you have to get a PhD just to read through one of their units! It's like 300 pages! I'm like, no, ain't nobody got time for that. And then I have to recreate everything down to a seventh-grade level anyways.

Jennifer added that in some cases there is also a lack of consistency and organization, which makes it unnecessarily difficult and time consuming for teachers to search through.

Jennifer, Sophie, Brigitte, and Kevin all identified online resources as instrumental enablers for teachers engaging in MCLEs. Sophie identified X (formerly Twitter) and Instagram as particularly helpful, "So many of the ideas for what we ended up having as our program I got from teachers on Twitter and Instagram. I'd see and go oh, my gosh, that's amazing!"

Although the educators acknowledged that there are many online resources available to teachers, they made some recommendations regarding features that would make them even more useful. Brigitte, Arjun, Matthew and Jennifer all recommended that the most effective online resource would be simple and easy to navigate through. Both Brigitte and Arjun suggested that teachers would benefit from an online resource that provides activity plans that are simple to read through and ready to use. Matthew suggested that they also include checklists that can help teachers quickly identify the curriculum concepts covered in each activity so that they can determine if it addresses what they need. Similarly, Jennifer recommended that databases should be indexed by curriculum requirements so that teachers can easily search for activities based on concepts in the curriculum they wish to cover. She also suggests that having a standardized structure for the lesson activities would save teachers time as they would know where in each activity plan they can find the information they are seeking.

Human Resources

Twenty of the 21 participants (95%) identified challenges and enablers related to human resources and the support teachers need inside and outside of the classroom as they prepare and engage in MCLEs with their students. Reported needs related to human resources revolved around support for the planning of MCLEs, support in the classroom while engaging in MCLEs, and technical support and maintenance. School boards and government funded organizations, community organizations and volunteers, specialised personnel, the students, and communities of practice were all reported to be crucial facilitators in the integration of MCLEs into schools.

Support for the planning of MCLEs: As has been reported in the literature, eight participants (38%) indicated that teachers attempting to integrate MCLEs into their teaching or school often work alone with little support (H. V. Andersen & Pitkänen, 2019; Kjartansdóttir et al., 2020) and would benefit from help co-creating MCLE projects and programs (Stevenson et al., 2019). As a result, these teachers often dedicate considerable time and effort into the integration of

MCLEs (Wong Shui Huen, 2020), which, as Camilla and Valentine pointed out, is often over and above their existing responsibilities. Camilla described her experience:

> You need appropriate support. Teachers need either the time or there needs to be somebody dedicated to do maintenance, because right now I'm drowning. And I was putting in 80 to 90 hours a week. And I was like, I can't do this.

Not only does this overwhelm teachers, but as Bruce, Michel, Camilla and Charles explained they have all witnessed first-hand, when these teachers either burn out or leave the school, the programs typically shut down as no one else is willing or capable of taking their place. Charles noted:

> We've seen makerspaces come and go. Some schools had a couple of teachers that got really involved, created a space, got the stuff in there, started using it. And then those teachers would either retire or go somewhere else and then most of the time those spaces became classrooms again or just fell apart.

Support in the classroom: As touched upon in the literature (Harron et al., 2022; Koh et al., 2022; Rosenfeld et al., 2019), six participants (29%) highlighted the need for support in the classroom as teachers facilitate MCLEs. In addition to feeling overwhelmed by large class sizes (discussed further in the Logistical Functioning section), participants reported that teachers can feel overwhelmed by the pedagogical and technical responsibilities of facilitating MCLEs, especially when they are not at ease with digital fabrication technologies. Matthew noted

> Even if you're doing a canned project, you're going to have five hands go up saying “Sir,” or “Ma'am, it's not working for me.” You got to have the ability to deal with that kind of potential roadblock. […] Oftentimes, teachers are given these spaces but they don't have the confidence yet to help the students.

Derek remarked that he is regularly asked to assist teachers in their classroom when facilitating MCLEs so that they could focus on the pedagogical aspects of the experience while he addressed the technical needs that arose. He commented:

> The more I look at the way the science program is built, and the way there's a technician that manages the chemicals in the back of the classroom, I think technology programs need something similar; someone who is not the teacher, but has the technical backgrounds to be the technician. If the school has any CNC equipment, 3d printers, laser cutters, routers, whatever it might be, and maybe a library of electronic components, it will be amazing to have somebody who managed that, who was able to help with the technical aspects of class, while there was a teacher trained in teaching the subject matter and classroom management and all those things, taking care of the teaching of the class. So, if we're talking about the future of education, I think that would be something to look at very strongly: building out tech programs with a technician who has a computer science background, and has a maybe some kind of engineering background, but is not necessarily the teacher.

Technical support: Seven participants (33%) identified challenges and enablers related to technical support. Sophie and Lilliane both remarked that teachers are now being expected to troubleshoot and maintain equipment as a technician would have done in the past. While speaking about the maintenance of equipment and school makerspaces, Sophie remarked:

> We used to have a computer tech who would be assigned to the school a couple of days a week, who ran the lab and would help teachers in the lab. That doesn't really exist in the elementary schools any more so it would have to be a teacher.

Matthew, Sandy, Camilla, Alexandre, and Brigitte noted that teachers spend considerable time on maintenance and troubleshooting equipment failure, often during class, which, as Matthew noted, has consequences on student engagement as students become frustrated when they cannot get the equipment to work:

> We had another one yesterday where a student came in to do some embroidery, and the embroidery machine kept breaking. […] And so students quickly lose their excitement over their project when they get excited and the machine keeps failing.

The need for someone with technical expertise in schools to help with the maintenance of equipment, as well as trouble-shooting when technical issues arise, has been previously reported in the literature (Fattizzo & Vania, 2021). Sylvain noted that at his school, "Without the help of myself and my fellow technicians, projects like these would not happen."

For those participants who reported that there was assistance in their region for teachers engaging in MCLEs with their students, the key facilitators related to human resources that were reported included school boards and government funded organizations, community organizations and volunteers, specialised personnel, and communities of practice.

School boards and government funded organizations: School boards and government funded organizations were mentioned by multiple participants (*n* = 10, 48%) as critical enablers for teachers integrating MCLEs into their classrooms. Jennifer, Brigitte, Valentine, Arjun, Michel, Charles, and Sophie pointed to their critical role in providing in-person, online, and video training programs, as well as opportunities to experiment with equipment and materials before teachers and schools make purchases. Caroline, Sophie, Samantha, Valentine, Lilliane, Michel, Arjun, Jennifer, and Charles also noted that consultants from school boards and these organizations provide considerable individual support to teachers, whether it be in preparation for MCLEs, in-class support, online consultations or even general moral support. For example, Sophie described her role as a consultant at her school board:

> In our department, it's a bit like a customer service role. If a principal calls and wants guidance and support, I'm the person who can give it to them. […] It's generally working with teachers. Like principals are quite overloaded so the principal may say, “I had this teacher who has this idea, and are you willing to work with them.” So for a couple of months, I've been going to a school that's got this room that's ready to go. We have been populating a drive with activities for Grades 1 through 6, and making sure that the physical space is set up. I've been helping her with her ordering when she does get little bits of cash to buy things. I'll be doing some lunch and learns with the staff for robotics and things like that. So that everybody knows a little bit about what's going on in there.

Community organizations and volunteers: Nine participants (43%) also pointed to other organizations such as community makerspaces, mobile makerspaces, Fab Academy and Maker Ed, public libraries and industry partners as enablers for MCLEs in schools. Emma, Kevin, Sandy, and Sarah all mentioned that they, or teachers they know, have benefited from training programs, community makerspaces, organizations like Maker Ed, and programs like Fab Academy offer. Sandy and Sarah mentioned that some of these organizations have even helped teachers access training by acquiring funding to pay teachers to take professional development. Sarah described one of these paid training programs:

> I have an English teacher, math teacher, science teacher, and they're all developing something using maker tools and maker education as a basis for the unit that they've always wanted to develop. They're paid for it. And they work together and collaborate and learn the skills that they need to learn that kind of thing.

Brigitte, Lilliane and Sandy also reported that community and library makerspaces were very helpful for their local schools as they helped principals and teachers select appropriate equipment to meet their needs, often by loaning equipment to schools to try before purchasing. Sandy mentioned that her local makerspace even helps the school with repairs when equipment malfunctions:

> I'm working a lot with principals. […] I have a catalogue of the machineries that I can support. There's a million different kinds of 3d printers out there, you should only buy one of these two […] because those are the two that I know best and that are the most prevalent in the district. And if it breaks you can just bring it to me and I'll give you a brand new one and then I'll fix it when I get time.

Sandy, Bruce and Brigitte also referred to mobile makerspaces as very helpful. They reported that mobile makerspaces play a key role in encouraging schools to engage in MCLEs by visiting schools and facilitating MCLEs with students. They mentioned that mobile makerspaces provide teachers with in-class support and help them develop projects that both interest the students and meet curricular objectives. For example, Bruce described the types of support his mobile FabLab offers local schools:

> Every time I brought a mobile Fab Lab to a high school, we would partner with teachers. We would know what curriculum they were going to teach when I was there, and then the teacher and myself would basically co-teach the class and it was project based and they would make whatever the learning proof was for that class.

Sylvain, Alexandre, Lilliane and Matthew also pointed to community volunteers as very helpful contributors to their school's maker programs. Not only do they help with meeting the needs of large groups of students in a classroom, but many of them have expertise that teachers lack that have proven to be helpful with certain MCLEs. Similarly, Sylvain pointed out that industry partners have been helpful at his school as they have provided expert help on projects that were related to their industry:

> We had a kind of ambassador who came from [X] Robotics, who came to present robotic arms, and left them with us for a few weeks. […] It was rich for the students because it was someone who had seen the field. And it was someone who accompanied them, […] someone from that world who came to help us. It's been very rich.

Specialized teachers/personnel: Seven participants (33%) pointed to the benefits of having specialized teachers or personnel (maker experts) to help with the integration of MCLEs in schools. Matthew and Emma noted that teachers or personnel with both pedagogical and maker expertise can be uniquely helpful in supporting maker-centered programs because they have an appreciation of both academic and maker contexts. Matthew remarked, “There's a subcategory of teacher that's not there to teach the math, the sciences, the core standard, but is there really for design and gluing things together and finding these opportunities within the natural uniqueness of each school.”

Sophie and Bruce both mentioned that in these roles they were able to help initiate maker-centered program in schools and Emma and Sophie were able to apply for and acquire funding due to their familiarity with MCLEs and the needs of the school. Matthew pointed out that because of their unique positions bridging the academic and maker worlds, they can be particularly helpful in reducing teacher anxiety about MCLEs and making connections with the curriculum:

> I'm the only specific teacher in design. The teachers that have been assigned the design classes teach science and social sciences, so design is not really in their wheelhouse to

> begin with. So, it's important for me to get them excited about making, […] and that the concepts are important and relate to the content [they] need to address.

Sylvain, Matthew, Derek, Emma, and Bruce all pointed to the important roles specialized personnel can take on as they can provide one-on-one support to teachers in their preparation and facilitation of MCLEs, help teachers make connections with the required curriculum, and train teachers on specific technology or processes. Emma, Bruce, Matthew, Jocelyn and Derek were also instrumental in creating the maker-centered curriculum at their schools. And in schools that have a makerspace or even just digital fabrication technology, as Emma pointed out, these personnel can also help run the space and maintain the equipment. In the case of their respective schools, Sylvain and Sophie stated that their maker-centered programs would not be possible without the presence of these specialized personnel. Sophie stated:

> I can name some schools where it's happening […] the common denominator in the programs where it's successful is when a commitment is made to having a person attached to the room and the space and the program. A lot of schools develop a space in the hopes that teachers will use it and I have never seen that work, ever. It becomes a dumping ground, the stuff ends up walking away. There needs to be somebody attached to it.

Students: Seven of the educators (33%) also noted that students have been and can be instrumental in the success of MCLEs in the classroom due to their help. Camilla explained that her students are a huge help for her as she runs MCLEs both during and after school. She explained, “My students run it all, I'm the only adult that runs it. And then like I have anywhere between 12 and 20 student helpers and they facilitate it all.”

Bruce also explained how students can be instrumental in helping teachers who are less confident with technology:

> [O]ne of the other really important factors in making sure it happens in a school is engaging the students as experts. Students have more time, and they have more inclination and honestly, just better with technology than the teachers for the most part. So being able to have some type of a club or an elective class or something on these different tools so you're basically now seeding classes with students who actually know what they're doing. They can also serve as experts to help teachers because the students are going to be far more comfortable before the teachers ever are. And having those skilled students around the school in different classes where a teacher's never truly alone when it comes to technology is a great critical mass.

Sandy described a situation with one of the teachers she worked with where this is well demonstrated:

> I have this one teacher, she's a sixth-grade teacher, she's adorable. She really wants to do this stuff. She's got to be at least 60, 65. She's the exact thing you think of when you think of an elementary school teacher; she wears long dresses, she's a little heavy, curly flowy hair. She's so sweet. Her first year, she picked two of her students to be the technical people for her and they were the ones who knew how to 3d print stuff and she just kind of oversaw. And then the next year, she had them come back down from seventh grade and teach a couple of more sixth graders. So they created this club of kids who knew the tech side of it. She's been with me since 2017. She's great. She couldn't 3D print something if her life depended on it [but] her kids make great stuff.

Communities of practice: Eight participants (38%) indicated that having some form of community of practice was essential for teachers, whether it be with their colleagues, through a local group or organization, or even indirectly through online platforms like Twitter. Camilla, Matthew and Emma noted that teachers often work with each other to design and prepare MCLEs. Sarah, Samantha, and Caroline remarked that teachers without a community of practice often feel alone and seek to make connections with other teachers through various means such as at training workshops, conferences and through online platforms. While describing an experience she had with a group of teachers who took training together, Sarah noted:

> [E]verybody had a chance to share. We always highlighted things people had done during the week or the week before that we didn't get a chance to share. It was really powerful. They became friends with each other and they're on Twitter; they're always helping each other when they get stuck with things. […] Having a community of practice and not feeling so alone.

Samantha noted the importance of local conferences and their role in connecting both novice and expert teachers in maker education to create communities of practice:

> There's an annual conference called the Nova Scotia IT camp […] that was a Friday evening and a Saturday at the start of November. A lot of teachers come and share the cool things that they're doing in their classroom. And that can be a great way for new teachers who maybe want to do some of that stuff to see what happens. […] A lot of the interactions I've had with teachers recently have been through those conferences. I am seeing all the teachers who are already into it. Some of them are experts at it, a bunch of them were relatively new teachers, and trying to get into it. But that kind of a community can make a big difference.

Educational Operations and Management

All 21 participants (100%) identified challenges and enablers related to educational operations and management, such as logistical functioning (e.g. time and scheduling), curriculum and assessment requirements; hiring and employment regulations; funding, and leadership.

Logistical Functioning

All participants (100%) identified challenges and enablers related to logistical factors such as time and scheduling, the separation of the disciplines, and class size when integrating MCLEs into the classroom.

Time and scheduling: Similar to reports in the literature, 14 participants (67%) reported lack of time and challenges related to scheduling as particularly problematic for the use of MCLEs in schools. As was reported in the literature, participants identified not having enough time to prepare for MCLEs (Fancsali et al., 2019; Harron et al., 2022; Salo et al., 2021; Shively et al., 2021; R. C. Smith et al., 2016; Stevenson et al., 2019; Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot, 2017; Thompson, 2021), not enough time in student schedules to engage with students in MCLEs (Assaf et al., 2019; Bower et al., 2020; Collins, 2018; Cross, 2017; Harron et al., 2022; Henderson et al., 2017; Jones et al., 2017; Justice, 2015; C. E. Lee et al., 2020; Leinonen et al., 2020; Stevenson et al., 2019), and not enough time for professional development and learning (Harron et al., 2022; Justice, 2015; McKay et al., 2016; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019).

Valentine, Matthew and Jennifer highlighted that teachers do not have enough time to plan MCLEs. Jennifer estimated that it takes approximately 10 to 20 hours to plan a worthwhile MCLE, for which Matthew noted that late start mornings and one-hour spares are not sufficient time to prepare these experiences. As a consequence, Camilla, Kevin, and Valentine noted that many teachers resort to using their personal time to prepare MCLEs. Valentine noted:

> In the schools, there's very little time. You have staff meeting time, you have PLC time, etc. […] Something needs to be done about that, because teachers […} work more than our set time. We work at home. That's not right. Our life is not just at the school. We already do above and beyond.

Another set of challenges related to time revolved around scheduling. Participants identified not having enough time in the student schedules as a challenge that impacts what they can do with students. Brigitte, Sylvain and Matthew identified scheduling as one of their biggest challenges. Matthew noted:

> [I]f you're scheduling design as a one period every week where you know, by the time they get started, they only have 30 minutes to make, you're not going to get very far. So find a way to make it a double-period, at least. But ultimately the scheduling of classes and the way schools are scheduled is the number one friction point between maker education as far as I'm concerned.

Matthew and Brigitte further explain that these short class periods impact what teachers can do with students, and that it limits the learning benefits of the MCLEs. Brigitte explained:

> [T]he reality is, learning is rarely fun in the process of really learning. It is very challenging. It can be very emotional, it can be very frustrating. And then when you get to the other side of learning, there is immense joy. […] And I think because we say once a week for 45 minutes, there's not enough room for the hard learning, so to avoid anxiety you don't do the hard stuff. But then you also don't get the immense joy.

Nine (43%) of the educators stated that teachers do not have sufficient time to train and gain experience with MCLEs and digital fabrication technologies. Sandy pointed out that, because teachers do not have time during the school day for training and experimenting with technology and ideas, it has to take place after school or during the summer. Valentine noted that even on pedagogical days teachers may not have time for training in MCLEs as they have lost considerable control over what they can do on these days: "You have some ped days […] that's something that teachers have lost quite a lot about is […] control of the ped days."

Additionally, Valentine and Lilliane stated that, in some cases, release days are available to teachers for training in MCLEs, but in Valentine's case, only for teachers who teach at STEAM designation schools, and in Lilliane's case not enough replacement teachers are available to give teachers release time.

Recognizing the challenges associated with time, some participants (Jennifer, Brigitte, Sandy) reported that some schools are attempting to reduce the challenges related to time and scheduling by offering special days throughout the school year that are dedicated to special projects, or in Valentine's case by creating a schedule that has longer class periods, enabling teachers to more easily engage in MCLEs with their students. They remarked that these changes significantly improved teachers' ability to engage in more complex and learning rich MCLEs with students. Sandy described the circumstances in a unique school she worked in that heavily facilitated MCLEs by providing a schedule conducive to these types of projects:

> We had these courses that the school called modules, which were project-based learning classes that met every single day, for a total of seven or eight hours over the whole week. On one day, they met for three straight hours, so you could like really get work done.

Separation of Disciplines: Similar to reports in the literature (Eriksson et al., 2018; Spieler et al., 2022), five participants (24%) identified the separation of disciplines as challenging for engaging MCLEs use. Sarah noted that it is difficult to get teachers from different disciplines to collaborate on MCLEs because each is focused on their own discipline, while Matthew, Sylvain, Sarah and Sophie said that even if teachers did want to collaborate across the disciplines it is very difficult to coordinate their schedules and ensure that they have the same students in each of their classes.

> They need some time for teacher collaboration for the purpose of STEAM education so that they can decide on the materials, they can plan what the problem is going to be. They can integrate their curriculum. They need to talk. They need to sit down, and it shouldn't be during their lunch period.

Sylvain and Matthew added that government requirements on time spent on each discipline adds to this challenge as combining disciplines muddies the waters when it comes to teachers justifying their teaching time. Sylvain explained, “Each subject is allocated a certain number of hours, six hours to one, eight hours to another, depending on the level. It’s very frustrating and is the reason we do not take interdisciplinary approaches.”

In the case of Quebec, Canada, Sarah pointed out that the division of disciplines by language further complicates the matter as the subjects she feels are most relevant for MCLEs are taught in the language she does not teach:

> My interest had always been in teaching science and teaching in a very hands-on way and I was frustrated by the fact that the program at the school board at which I teach, gives all of that to the French language teacher.

Class Size: Six participants (29%) echoed reports from the literature stating that large class size (or more accurately, the large student to teacher ratio) is a significant challenge for teachers engaging in MCLEs with their students (Harron et al., 2022; Heilala et al., 2020; Heredia & Tan, 2021; Jocius et al., 2020; Karimi et al., 2017; Y. J. Kim et al., 2020; Koh et al., 2022; Lahana, 2016; C. eun Lee et al., 2020; Nemorin & Selwyn, 2017; Rosenfeld et al., 2019; Sheffield & Koul, 2021; R. C. Smith et al., 2016). As Brigitte and Derek explained, with such large numbers of students for each teacher, it is difficult for teachers to attend to all students' needs as well as provide timely feedback on students' progress (J.-Y. Kim et al., 2021; Y. J. Kim et al., 2020; Murai et al., 2019; Sheffield & Koul, 2021). Derek recounted from his experience:

> There are 20 kids asking me questions. "How do I get the gas sensor to work?" "How do I get the water pump to work?" And I can only be in one place at a time. With 5 or 10 students, that's super doable, but with 20 and only one teacher in the classroom, mentoring 20 separate projects, that's hard.

Consequently, as Lilliane noted, teachers attempting to engage in MCLEs with large groups often revert to more teacher-centered practices as the high student to teacher ratios are not conducive to student-centered approaches: "When people have big groups, they revert back to a more prescriptive [approach], restricting the scope of the projects."

Curriculum and assessment requirements

Twenty of the 21 participants (95%) identified challenges and enablers related to curriculum and standards, and assessment when integrating MCLEs into the classroom.

Curriculum and standards: Sixteen participants (76%) identified curriculum and standards as influencing teachers' ability to integrate MCLEs into their teaching. The majority of challenges related to curriculum and standards identified by participants were similar to those reported in the literature. Namely, participants reported that teachers were often hesitant to integrate MCLEs into their teaching as they felt it was an add-on and competed with their time to cover the required curriculum (Rosenfeld et al., 2019), some had difficulty making connections between MCLEs and the curriculum (J. Hughes, Morrison, et al., 2022; Rosenfeld et al., 2019) and, even when they were prepared to integrate MCLEs into their teaching, they needed to justify any deviations to standard practice to their administration, which takes time (Davis et al., 2021; Powell, 2021; Torralba, 2019). Challenges related to new curriculum requirements that are not accompanied by the necessary explanations, training, and assessment tools were also identified.

Multiple educators reported that increasing required curriculum content, pressure to cover required curriculum, misconceptions about MCLEs role in covering required curriculum and a lack of required MCLE curriculum all contribute to teachers' resistance to integrate MCLEs into their teaching. Valentine, Emma and Kevin all pointed out that teachers are dealing with ever increasing curriculum demands, as well as continual changes to the curriculum, which results in teachers not only feeling they do not have enough class-time to cover the required curriculum, but also adds to their professional development needs. Valentine explained:

> There was a lot of this influx of digital competencies. There was an influx of digital citizenship, specifically. […] We have sexuality education that came in, we have all of social justices. So there's a lot of PD going on. […] It's just there's a lot coming on the plate at the same time in the last few years I feel. […] And so when you come in with, say, now we're coming in with STEAM pedagogy, it's oh my gosh, it's another thing. And so there's resistance.

Educators from both the USA (Emma, Kevin) and Canada (Arjun, Jennifer, Samantha, Valentine) pointed to pressures to cover the required curriculum and meeting standards as heavily impacting what teachers are willing to engage in with their students. Kevin explained that, because of these pressures, teachers are hesitant to risk using new approaches to teaching if there is no guarantee the students will learn the required content:

> As a teacher, at the end of the day, I feel responsible in some way to somebody to make sure that my kids learn all of the content. […] If I talk at them for an hour, I will be certain that they've learned, that they've heard the things that they need to produce on the test. […] But all the maker stuff, you're handing over a lot of control, and it's not guaranteed that a kid will have [learned it]. […] I'm 100% that they learn it better. I've watched it happen many times where they understand it, they can integrate it, they can apply the concepts better if they've used it. I think everybody knows and the research proves it. But it's that a teacher feels like they're not for certain going to meet the objectives they feel like they have to meet […] and they can see exactly how it's going to work for them, it's hard for them to choose it.

Samantha, Caroline, and Sylvain pointed to ambiguous government additions to required curricula that are causing added problems for teachers. Samantha pointed out that recent curriculum changes that potentially include MCLEs are vague and not accompanied by training and professional development, leaving teachers unsure of how to implement it:

> The grade nine curriculum is […] very general stuff. It was kind of like, “adjust parameters to predict what happens in code”, kind of thing, which is kind of like a double-edged sword because it's, well, any project that you're doing in coding could meet these requirements. But it's hard to make the one-to-one connection. […] They did that without offering a lot of training for teachers. […] So that’s an example of when […] we did get teachers, who are just like, “I need to learn this, I don't know what's going on.”

Sylvain added that recent curriculum additions were not reflected by changes in government regulations on teaching time allotments per discipline: “The government highlighted the importance of digital competencies, but no time was allocated to it [in the students’ schedules].”

Valentine further noted that government exams have still not changed to reflect these new requirements, and Caroline noted that there are not even clear indicators included in the curriculum for teachers to know when students have met the requirements. Caroline noted:

> [I]n terms of communication, and collaboration and content production, they’re more clearly made there in terms of teaching the languages because there's a competency to produce texts and to communicate either through talk or through reading and production. […] It's less obvious when you get to the problem-solving part and the innovation and the creativity.

Bruce, Charles, Brigitte, Emma, Caroline, Samantha, and Michel suggested that if MCLEs are not a well-defined part of the required curriculum, they risk not being integrated by all teachers. For example, Charles pointed out that even though some aspects of MCLEs are required in his region’s curriculum, because it is not yet part of the government exams, teachers are not integrating these aspects into their teaching. Brigitte argued similarly by pointing out that in her region, science is not required in the first years of elementary school, so many teachers do not include it in their teaching. She stated, “Science isn't required in grades K to three, so you have a lot of teachers that are not very comfortable with science and they just don't do it, which is horrifying.”

For teachers who are determined to integrate MCLEs into their teaching, Emma pointed out that they may encounter challenges in doing so due to the need to justify its inclusion. She recounted how she had to creatively integrate MCLEs into her career education in order for her district to accept it:

> So the way that we have gotten it approved in our district is to tie it to careers. So we're investigating careers through making. But we're calling it makerspace. We're using the standards for investigating careers, but we're calling it makerspace.

Kevin pointed out that this problem is further exacerbated by the current lack of ability to demonstrate the learning benefits of making due to a lack of adequate assessment measures (further discussed in the next section).

Although there were many mentioned challenges related to curriculum requirements and MCLEs, educators reported that there are some shifts that are enabling teachers to better integrate MCLEs into their teaching. Sylvain, Lilliane, Camilla, Caroline and Matthew all stated that the introduction of some kind of curriculum that could include MCLEs, even if vague, has been very helpful in giving teachers justification to include MCLEs in their teaching. Camilla explained:

> I'm telling you, the engineering design standards changed my life, because […] these projects all apply to next generation science standards. Whereas before, it was really reaching for why I was doing this besides the soft skills are super valuable to kids.

Assessment: 10 participants (48%) identified challenges and enablers related to assessment. Both the literature and participants reported challenges related to the incongruencies between the learning outcomes of MCLEs and the assessment and reporting requirements of the education system. These included having difficulty providing a letter grade for process-oriented learning (J.-Y. Kim et al., 2021) and requirement to provide grades at regular intervals that are often shorter than the length of an MCLE (Becker & Jacobsen, 2023). Both Canadian (Charles) and

American (Bruce) participants in this study also indicated that in some cases, even though the curriculum had become competency-based, government exams are still summative in nature, creating tensions between teaching practices that would align with competency-based learning such as MCLEs and the expectations of preparing students to succeed on summative exams. Charles explained:

> We're a competency-based system that still gives summative exams. […] I think exams can be thought of differently. […] I think that there can be other ways we can think of evaluating kids. […] If we say we're a competency-based system, then do it. […] I think respecting the program, going back and saying, we're going to be competency-based, we're going to take away percentages, and we're going to look at changing how we evaluate.

Though not mentioned often, some participants identified challenges associated with assessing the types of learning resulting from MCLEs. Camilla pointed out that it can be challenging to assess iterative processes, "[A]ssessment is the hardest. How do you assess iteration? If you didn't iterate two times you get a B?", while Kevin noted that assessment can be challenging when students choose their own projects because they may differ in complexity:

> I have one group of students [who] made a device that went to the internet and checked the weather and then would put the temperature up on an LED screen. And I had another group of students that I was equally proud of because of where they started from with their skill set and they made a laser trip wire where if you put your finger in between an LED and a photo sensor, it would make a sound, which is a much simpler thing to do. But it was creative and it represented a lot of growth for them. […] I would feel immoral if I

was grading the kids who made the trip wire worse than the kids who went to the internet and got data because it's not as sophisticated but they still learned a lot.

Kevin, Sophie and Charles all pointed to current reporting systems as problematic as they do not permit teachers to report in a way that reflects learning resulting from MCLEs. Corey explained:

> We're summarizing learning with just a singular number. […] That's not enough detail. And a B- for me could mean very different things than a B- for somebody else. […] We give a ton of lip service to fixed mindset versus growth mindset, but then […] we're not paying any attention to how a kid grows. I think the maker stuff makes it visible, how a kid grows. […] I think that the makerspace is the easiest way to show that but it would be great if the rest of education could learn from that piece of the maker world, as well. To evaluate kids in a growth sort of way, rather than a way that lends itself so easily to a fixed mindset.

Brian added that another challenge that teachers sometimes encounter is the need to provide grades at regular intervals and that a certain percentage of the grade needs to be represented by exams:

> [T]hese archaic requirements, like, you've got to give X amount of grades by midterms. And so you've got to be kind of creative. [In] some school systems […] tests have to be X percentage of your grade and daily work and so on.

Issues with assessment interfering with the MCLE process were also identified. Matthew mentioned that the processes necessary to capture traces of student learning during the MCLE process can interrupt the flow of the making activity:

> You'll have students who are working and they're loving it, and then they just do nothing on their journal. And so they shouldn't fail a class, even though the journal is a very accurate way to establish their level of effort and their level of their thinking. It sort of slows down the flow as well.

Charles and Bruce also mentioned that if assessment focuses on the final product, students may not be willing to take creative risks in fear of the final product not working. Charles explained, “We're so used to evaluating the final product. But when we do that in schools with making, we risk students not taking those risks because they want to make sure that their final product works.”

Participants in the study identified a few factors that are helping alleviate some of the challenges associated with assessing MCLEs. Matthew and Brigitte reported that online platforms are providing teachers with convenient means of documenting student learning without significantly interrupting the flow of MCLEs. Lilliane added that technology like iPads also can be helpful with younger students to help them document their work in progress, providing teachers with traces of student learning.

Hiring and employment regulations

Seven participants (33%) identified challenges related to hiring and employment regulations for the hiring of experts in digital fabrication and making, as well for introducing MCLEs to schools in general.

Hiring regulation and position descriptions: Four participants (19%) identified hiring regulations and position descriptions as problematic. Matthew pointed out that local requirements for teacher certification restricts who can work with students thus limiting maker expertise in schools. Sophie also pointed out that positions are often filled based on seniority, rather the person best fit for the position, which may have poor outcomes. She explained the situation at her former school after leaving to work at her school board:

> I was offered a job working in educational services where I am now. I left for one year, and now I've been gone for four years and, unfortunately, the program has been dismantled, because a lot of it is very personnel driven. And so when you are not at your school, you're replaced by often a teacher from the priority pool, who might be someone who's into that and wants to do it, but might not be.

Kevin also pointed out that in his experience, schools had to be creative with existing position descriptions to get what they were seeking as positions that explicitly include MCLEs as part of the description do not exist in all districts. In some cases where maker experts were hired for their expertise, Derek and Matthew pointed out that they were required to take on roles they were not prepared for as they were placed in teaching positions (because those were the only positions in existence) even though they did not have pedagogical training. Derek explained:

> My background is computer science, soldering, mechanical engineering, that kind of thing. That's my forte. So I'm probably better suited to be the technician and helping those students who come in, and with the technical support for a classroom. […] I would feel more comfortable in that role in a school.

Unions: Five participants (24%) identified the presence of unions as a challenge in the integration of MCLEs in schools. Kevin, Matthew, and Sandy stated that advancement is slow because of resistance from unions in regard to changing teacher practices. Valentine pointed out that, although she can appreciate the need for unions and their resistance given the frequent unreasonable demands on teachers, unions often resist suggested changes, even when there could be potential benefits. She explained:

> [W]hen you bring about change it's almost a knee jerk reaction because you're so used to being taken advantage of in many ways. You think, "Oh, here it goes, you want more out of me? You're trying to squeeze me again?" […] I think that there has been trouble obviously, but understandably, because there's only so much you can squeeze out of people. […] It could be the most healthy supplement ever, but you've poisoned me a few times, I'm not going through that. And so there can be that kind of response from some teachers and from some union reps.

Lilliane also pointed out that, in her region, the unions for elementary and high school are different, making it difficult for educators with expertise in MCLEs to move across the age groups.

Funding

Nineteen participants (90%) identified challenges and enablers related to funding and funding regulations in regard to MCLE integration in schools. While a lack of funding was reported in the literature as challenging for MCLE integration in schools in some cases (H. V. Andersen & Pitkänen, 2019; Assaf et al., 2019; Cao et al., 2020; Cross, 2017), participants in this study did not report a lack of funding as a problem per se, but rather challenges related to regulations around how funds are spent, leadership decisions about how funds are attributed, and a lack of transparency regarding what funds are available to teachers.

Funding regulations: Sandy, Arjun, Emma, Brigitte, Samantha, Alexandre, and Michel (33%) all remarked that, in their experience, funds are available, but that the challenges that arise with funding are often due to the regulations that control how the funds are spent. Sandy described how in one school she worked with, the budget categories meant that the school had significant funds they could spend on equipment, but not on the personnel they felt they needed more urgently. She stated, “I'm working with a school principal right now. She has $150,000 to spend on whatever [equipment] she wants but she has to fire two of her best teachers next year because her teacher budget is going down.”

Arjun and Alexandre also remarked that in their region, schools have funds to purchase equipment, but they are limited to a government-provided list of items and vendors, limiting what schools can purchase and reducing their ability to make purchases at lower cost (e.g. purchasing used equipment). Alexandre noted, “You can't just buy any machine, even in public schools, you have to deal with suppliers.”

In some regions, funding is also linked to student performance and learning outcomes, limiting which schools and programs receive funding. For example, Emma indicated that funding in her region is linked to student test results. She also explained that funding is provided only if students can obtain an approved certificate through their participation in MCLEs:

> In Texas, we have the school accountability system, where it's tied standardized tests. So they have to take their standardized tests and get scores. Then if you have students that are getting certified in things like Autodesk Fusion 360, or Illustrator or OSHA, then those are also points to get you your funds, because that's how the public school system works.

Similarly, Brigitte indicated that funding is available to programs that contribute to skills that will help students join the navy.

Leadership decisions around distribution of funds: Six participants (29%) also indicated that leader decisions around spending have also been problematic. Emma, Kevin and Lilliane all stated that, in their experience, leaders often devote funding to starting a makerspace or maker program without provisions for long-term sustainability. Kevin and Matthew noted that this is evident in how planning for training is often neglected. Kevin explained:

> I think this is kind of common - an administrator finds it fashionable to have a Makerspace or a Fab Lab in a school and so they buy a bunch of equipment, they put it down, and there's zero plan for how to train anybody.

Jennifer added that in her experience funds are again provided for equipment acquisition, with no little to none reserved for the maintenance of the equipment or to purchase the consumables, like printing filament. She noted, "they manage to get the equipment in the first place, but then all the consumables afterwards are not budgeted for." Sophie also noted that funds to update or replace aging and obsolete equipment is difficult to obtain.

Transparency: Another problem related to funding identified by the participants is the lack of transparency around funding. Valentine, Arjun, and Kevin (14%) indicated that this lack of transparency means that teachers interested in introducing MCLEs into their classroom may not know how to obtain funding. Kevin explained:

> [I]n the school systems I've been a part of it is not transparent how much money there is floating around to do different things. For many of the teachers in the district, […] if you're trying to put together a Makerspace in the back corner of your classroom, and just trying to make it fly with the budget that you have, it may not be obvious how much money is there or how much you're getting support from the administrators in your district to make all that happen.

Arjun noted that about half of the funds that are available to teachers in his region are not used each year, suggesting that teachers are not aware of or unable to access these funds.

The enabling factors related to funding that participants mentioned were different depending on location. Participants in Canada indicated that there is considerable government funding for special projects, while participants from the USA pointed to funding from private companies. Funding possibilities for MCLEs in schools were reported by educators from both Canada and the USA, but in different ways, thus they will be reported separately by country.

Canada: Some of the Canadian participants indicated that there are funds available for MCLEs in schools. Jocelyn, Arjun, and Samantha all said that there are pockets of government funds available for these programs. Charles and Arjun indicated that government funding for programs related to MCLEs has been provided for at least the next five year by programs like the Digital Action Plan. Jocelyn, Arjun, and Samantha added that there are pockets of funds teachers can apply for to support projects like MCLEs, and Lilliane pointed out that there are special government funds available for underprivileged schools. Arjun pointed out, however, that although the pockets of funds are available, in some cases, a proposal is needed, which takes time and effort to prepare. He noted, "These things take energy, writing a project. It's a week of your blood and soul, that you are on a toast diet and coffee. I was working alone and I get the things done, but it takes energy.

USA: Brigitte from the USA indicated that the US government also provides funding to support programs and initiatives that support teachers wanting to engage in MCLEs, but that one of the greatest sources of funds comes from the private sector. She described how her organization obtains funding to support MCLEs with local schools:

> There's so much money in workforce development, you would be shocked. It's something like $460 billion a year in America for workforce and development. The average company spends something crazy like $13,000, just getting the person in the front door.

> We're not even talking about the training, just to get them in the front door cost about $13,000. Well, we were able to give career and businesses and educational research organizations and government entities a way to […] work directly with teachers to create a four-day Makerspace project-based learning lessons. […] students are doing research and development, they're learning companies' names, they're seeing who they can be. So that's what we did. And so far, we are able to be completely self-sustaining, and we're able to give all of our resources away.

She pointed out, however, that to access these funds, one has to know where to look and how to approach it. Bruce also mentioned that donations were a major source of funding, particularly from private companies: "[I]n Tennessee and Chattanooga, thanks to funding from Volkswagen, [they] started a STEM high school that had a Fab Lab. It was using project-based learning, integrating the curriculum, it was very successful."

Leadership

While some studies in the literature pointed to leadership as a potential challenge for the integration of MCLEs into schools (H. V. Andersen & Pitkänen, 2019; Cao et al., 2020; Cross, 2017; Fulfilling the Maker Promise: Year One, 2017; Salo et al., 2021; Thompson, 2021; Turner, 2022; Zhang, 2021), all but three participants in this study (*n* = 18; 86%) identified leadership as pivotal for the success or failure of MCLEs in schools, both at the school level and further up in the education system. The reported challenges with leadership in the literature tended to be vague identifying leadership's lack of support for MCLEs in general as problematic (Cao et al., 2020), as well as their lack of consistency and unity around goals and outcomes (Fulfilling the Maker Promise: Year One, 2017; Salo et al., 2021; Zhang, 2021). While participants in this study also acknowledged a lack of consistency among leaders as problematic as it sends mixed and confusing messages to the school community, they also pointed to leaders' misconceptions about the nature of MCLEs and their underappreciation of the efforts teachers invest in creating them.

At the school level, Camilla and Sophie highlighted the direct influence leadership can have on the integration of MCLEs in schools as they have the power to support or terminate maker-centered programs. Sophie explained:

> At one point I had a principal who really thought outside the box. […] She sent me for training […], which was extremely hands on, extremely experiential learning for the kids, to the point where I had a committee of parents who did all the shopping every week for all the stuff I would need for the program. But unfortunately, that principal moved on and with it went the program and the funding, and the outside the box [thinking].

More indirectly, however, Kevin, Charles, Caroline, Matthew and Sandy all highlighted the influence leadership has on culture in schools, and that, in some cases, the culture leadership cultivates may not be conducive to MCLEs. Caroline explained:

> [It] depends on what you're walking into. You can have the best intentions, but then walk into a place where that's the norm and they're used to giving kids control and the kids are set up for it. You're walking into a situation where that feels natural, and you can make it happen. But if you're walking into a place where that's not the case, then it's harder to take risks. It's harder to come in and […] if it's something that's counter to the culture that's already there, then it can be seen as something risky, and you may want to just pull back. […] So it's contextual.

More broadly, participants identified leadership misconceptions about MCLEs as problematic. Brigitte and Emma both pointed to leadership perceiving MCLEs as solely a fun activity, which has resulted in MCLEs only being integrated once the ‘serious learning’ is done. Emma commented:

> I talked to the administration, and they're like, “Well, the teachers can come in after the students take their tests. It's almost like, they see it as a fun extra thing. So, I'm dealing with that mindset in the school.

This misconception also means that making is often promoted as a fun activity, which leads to misguided expectations on the part of teachers and students. Matthew explained:

> It's relegated to being something that a source of fun, not necessarily a source of learning. So if there is learning while they're having fun, hey, that's great, but then it's not seen as actual learning. So that's something really tricky to address.

Sylvain, Matthew and Camilla pointed out that because of these misconceptions about MCLEs, leaders also often under-estimate the practical implications of MCLEs and the time and planning that it takes. Camilla illustrated this point by describing an interaction she had with her school principal:

> [I]f the leadership could recognize what's underneath the iceberg in order to make the program work, […] the storage, the training, the maintenance, none of that's visible. […] He said to me, “I don't know what a STEAM coordinator does”, […] so I said, “Tell me what you need. We've gone to the White House, I've worked with national labs, we've presented all around the West Coast.” I said, “What are you looking for? And what frequency? I can make it happen.” And he [said] to me, “Well, one of those a month sounds good.” Are you kidding me? And I was still teaching nine classes! […] There's just this very unreasonable expectation of what a STEAM coordinator does.

Six of the participants (29%) identified inconsistencies and a lack of alignment among leadership as very problematic for the integration of MCLEs in schools. Jennifer and Valentine noted that leaders appear to have differing opinions on how MCLEs should be conducted leading to conflicting messages. Valentine and Matthew pointed out that this problem stems all the way from the top of the education system as the government itself is inconsistent with its expectations versus provisions they give. Valentine explained:

> [Y]ou want them to do all of the things that [were] proposed in the years back, but not all of our tools in the realm of education are supporting that. […] We need to all be at the same table and […] working towards the same goal. And right now, we don't. And the people who feel it the most, are the teachers who are actually the ones who make it or break it in education. […] If the teacher doesn't perceive that […] the curriculum is on my side, the administrator's on my side, the board is working for me as well […] you're going to hit a snag. We have to make sure those voices are aligning all the way.

Valentine stated that because of these inconsistencies and ever-increasing demands on teachers, the government in her region is not considered an ally by many of the educators when it comes to initiatives like MCLEs in schools:

> I see it in terms of teacher responses, "Oh, here we go again. Here's another thing". It needs to be framed differently. Government needs to be seen more as an ally. There's a lot of history. There's definitely work to be done on that.

While poor leadership was identified as problematic for integrating MCLEs in schools, the opposite was equally true, with educators emphasizing how good leadership can enable MCLE integration in schools despite the numerous challenges. The most commonly noted approach to leadership that promoted the integration of MCLEs in schools was flexible and open-minded leadership. Sandy, Lilliane, Arjun, Kevin, and Camilla all noted that they were most successful in schools where the leadership was flexible, giving them the freedom to try novel approaches without fear of failure. Sarah described a school that was particularly successful with its maker-centered program:

> If I had to answer your question of what's the number one thing that's required for teachers to be able to do this in their classrooms, the answer is an understanding and lenient principal or school leadership team. I was never scared about doing something that might not work out. I was never scared that my principal would think I was doing something weird. […] It was safe for teachers to do weird stuff. […] The whole school was like that. It was a really, really special place.

Participants also pointed to the importance of the manner in which school leadership encouraged MCLEs in their schools. Alexandre, Sophie and Kevin emphasized the importance of continual support from leadership as teachers integrate MCLEs into their practice. Alexandre, a school principal with a successful maker education program described his approach to leadership:

> There is the whole question of leadership which is very important. […] I try to be as present as possible. {…} So being able to give time and lend them a hand when they need it. Instead of saying, "I'm going to stay at my desk and then it's your problem that you ask me for a 3D printer, deal with it," we have to help them because there are things that don't work and that's when teachers give up. What I want is for them not to give up, so I have to be there, I have to support them.

Matthew reported that at his school, where MCLEs have been successfully integrated, the leadership took very small steps to reach their goal, "The head of the school was very clear that we're going to [take] baby steps, but that he wants everyone, junior up to grade 12, to have been exposed to this space." At the same time, he noted that the leadership was quite firm in that all teachers were expected to be involved in some way, a factor that Bruce and Valentine also suggested was important. Bruce mentioned that starting with teachers and staff who would be supportive of MCLEs is essential. He recounted the approach the head of one school took to introduce MCLEs into his school:

> It was a Title 1 school and he was brought in there to kind of reimagine it. So it was an existing school that he, over the course of five or six years, […] he figured out which of [the] staff was best able to do project based learning and willing to do project based learning and slowly moved some staff out, brought other staff in and changed the model of the school and the Innovation Hub.

Sandy suggested that, ultimately, if leadership is able to create a well-supported and open-minded cultured in the school, teachers will step up and meet expectations. She recounted her experience in the school that launched her interest in MCLEs:

> It's a regular public school. […] That was the culture of the school, for teachers to say, "I'm going to try this new class." It might be a disaster; it might be great. […] It was so special. I think it made me the teacher that I am because, not only did it make me want to teach other things besides just math, but also I was never scared about doing something that might not work out. I was never scared that my principal would think I was doing something weird. […] It was safe for teachers to do weird stuff, safe for kids. The idea of teachers doing what they're passionate about, and teaching transdisciplinary and things that they like, I think is really important.

Training and Professional Development

Twenty of the 21 participants (95%) identified challenges with training and professional development (PD) or recommended improvements to further enable teachers to engage in MCLEs with their students. Both the literature and participants in this study identified insufficient training and professional development as among the most critical challenges for the integration of MCLEs into classrooms (Eriksson et al., 2018; Fan, 2022; Fulfilling the Maker Promise: Year One, 2017; Harron et al., 2022; R. C. Smith et al., 2016) and a lack of time for training (Harron et al., 2022; Justice, 2015; Peterson & Scharber, 2018; Powell, 2021; M. J. Song, 2021; Stevenson et al., 2019). Challenges reported by participants related to training and PD revolved around inadequate training in formal teacher training programs, availability of training and PD outside of formal education settings, and challenges associated with having the time and resources to receive training and PD.

One of the primary barriers to training that participants identified was the lack of MCLE training in formal teacher training programs. Jennifer, Valentine, Brigitte, Emma, Michel and Sylvain all pointed out that it is still rare to find teacher training programs that incorporate MCLE training. Jennifer noted:

> They don't have the training. If you look at all the university degrees within teaching, there's not many classes based on robotics, 3d printing, there's not much at all, actually. Some of the classes are still stuck 10, 15 years ago, they haven't really been updated. So, when the teacher finishes with their [degree], they don't have the technology basis to implement this.

Similarly, Michel remarked, “I think what you see more often in an education program is ed tech. Here's how to use SmartBoards. And here's how to use Flipgrid and Google Classroom.”

Referring to his local university, Charles said that his organization does collaborate with a local university to offer a workshop on MCLEs, but that it is once in the four-year program and that, in his opinion, it is insufficient to prepare pre-service teachers to integrate MCLEs in the classroom: “The university does not have a required course, they have one tech course per four years that they offer to the kids. So it's just not enough.” Sophie noted that even during student internships some teacher training programs are resistant to MCLEs:

> I had a student teacher one year when I was half time in my classroom and half time in my studio and I had to sell it. […] I had to sell it to the office of student teacher or whatever it's called, they couldn't understand why this would be a good experience for this kid.

The availability of MCLE training and PD outside of formal training programs may also be problematic in some places as Bruce and Michel both pointed out that training programs are unevenly distributed across their respective countries (USA and Canada). Lilliane also pointed out that while there are many introductory training and PD programs for MCLEs, it is more difficult to find more advanced ones. Among the reasons for this may be due to funding and appointed mandates. Samantha mentioned that the government funding their organization receives has stipulations that limit how much training and PD each teacher is permitted to access for the purposes of allowing a larger number of teachers to access training. As a result, this limits the level of expertise teachers can develop through the program:

> A lot of that program is funded by the government […] and how we set it up is related to how [they] wanted it to go. […] We could only do one thing with any teacher. So that's partly how we set it up, we're going to do one or two hours with [each] class and this is like an introduction. So in theory that can get all the generalist teachers.

In one district where PD programs and consultants are freely available to teachers, Charles noted that these services are underutilized. Participants suggested there may be several reasons for this. As previously mentioned, Matthew and Sandy stated that teachers often do not have time during their schedule for PD and need to do PD outside of regular school hours. Sarah pointed out that this is problematic as many teachers are female and have childcare responsibilities. She suggested that teachers either need to be paid for these hours so that they could cover the cost of childcare, or childcare needs to be provided:

> The program that I've been trying to get money for, and the pandemic interrupted what I was trying to do, was [for] teachers after school, [to] provide them with childcare. […] We would feed them so they didn't have to go out and eat and pay them for their time. Teachers are underpaid. A lot of them have to have second jobs in the United States at least. And we need to invest in them and make it possible for this all to happen.

Sarah also commented that women tend to be more intimidated by the technology that is often used in MCLE training than their male counterparts, "I did a similar thing with Arduino because a lot of women were intimidated by Arduinos." Michel and Lilliane added that in some cases a lack of substitute teachers to replace the teachers who want to receive PD is a barrier.

Of the recommendations made by participants in this study, recommendations related to training were the most prevalent. Regarding the content of training and PD, some participant recommendations were similar to those found in the literature, namely providing training for tools and equipment (Harron et al., 2022; Leinonen et al., 2020; Norouzi et al., 2021; Shively et al., 2021), creating meaningful MCLEs (Fan, 2022; C.-Y. Lee et al., 2021), and aligning MCLEs with the curriculum (Rosenfeld et al., 2019; Shively et al., 2021). Participants in this study also identified the need for training in assessing learning through MCLEs and implementing classroom management techniques conducive to MCLEs.

While the overall emphasis on the content of training was not on tool and equipment use, some participants noted that it is still important for teachers to develop these skills to facilitate MCLEs. Matthew argued that while teachers can consult with technicians for help with technology, it is not sustainable for them to rely on technicians at all times and that some knowledge of how to use the technology is necessary:

> [W]e'll be there to help and there's a lab technician. […] The teachers [that] come right now are just familiarizing themselves with the process. It's very important, though, that the teacher becomes familiar with the tools that they asked to students to use, because otherwise, it's not sustainable.

Kevin also pointed out that while teachers may have the basic knowledge of how to use a piece of equipment, they often do not know how to troubleshoot tech failures:

> The one thing that I can say helps […] is the amount of experience the teacher has with the actual process. So, for lessons I've had, where I'm teaching kids how to do something regarding the vinyl cutter, […] if you do something wrong you can start blinking red and [it] looks terrible. And if you've never run into that, or solved that problem before, you're stuck as the teacher in the room. But I know how to turn it off, move it around while the power is off, and then turn it back on. But if you don't have that experience, it's much harder to make that happen smoothly. I think the biggest thing that I would say is time for teachers to play with the tools and sort of get their own skill.

Valentine, Matthew, and Charles highlighted the importance of training programs including training on how to create MCLEs that are most likely to result in rich learning experiences. To accomplish this, Valentine suggested that training programs should include content that emphasizes why MCLEs are beneficial for learning, how to design MCLEs to encourage problem solving, and how to create interdisciplinary projects.

> Before the professional development on tools, before the explanation of what STEAM pedagogy is for us, it's really the Why. Why is this important? […] We want you to understand that STEAM pedagogy is not an add on, it's a different way of approaching your curriculum. […] I feel that that has been the biggest importance in approaching the making environment. Why is it important for kids to make? […] And then the How. So how do you go about it? How do you not make it an add on? How do you look at your curriculum, and say, where are the opportunities where I can take several teaching objectives, and create a learning situation that involves making? That involves designing, and that involves really at the heart of our pedagogy and STEAM is problem solving. And there's a lot of importance in one knowing what your curriculum is, really understanding what you are as a math and English teacher or if you're a science specialist, really what is in your curriculum and looking at ways to teaching objectives from different disciplines. So not in isolation, and it doesn't have to be from three or four disciplines, at minimum two. […] And so we're breaking the walls of school and the outside world and we're engaging in real world learning problem solving and designing.

Charles also suggested that programs should focus on the maker mindset and the importance of play. Describing one of the training sessions he offers, Chris explained, "I also do a whole maker mindset one where we just play. I bring the materials, I give them open ended tasks, and then they play and then we reflect on it."

In regard to curriculum, Sylvain and Caroline suggested that training should include content on how to make connections between MCLEs and the curriculum. When asked what teachers seek from the MCLE workshops Caroline's organization offers teachers, Caroline noted connections to the curriculum first in her list: "Connections to the curriculum, how to evaluate, knowing where to start, knowing how to organize things." Samantha added that this is particularly true when new curriculum requirements are introduced. Valentine also suggested that teachers often simply need help reframing how they view the curriculum requirements so that they can appreciate how MCLEs can help them cover the required curriculum rather than adding yet another requirement to their teaching load. She described a conversation she often has with teachers:

> We want you to understand that STEAM pedagogy is not an add on, it's a different way of approaching your curriculum. It's like having a destination and you're from the West Island and you're going downtown, you got to go to the Bell Center. And instead of going Route A, which has a similar ETA as route B, you're going to route B. […] It's not supposed to add on more, it just manages your time differently. […] Well, if it's the same A or B, why can't I just continue with A? Well, then now, what does B offer you? B offers you a scenic drive through beautiful villages and countryside, or you can go through the industrial park through A.

Caroline, Matthew and Charles all stated that training needed to include content on assessing learning through making. Matthew explained, "It is hard, though, for teachers to evaluate this because they're not familiar with that way of thinking. […] So that's something that is becoming obvious that there has to be training for the teacher on how to evaluate."

Finally, Sandy suggested that, if needed, teachers should receive training in basic classroom management during MCLEs before engaging in MCLEs in the classroom. She explained:

> [If] you're struggling with basic classroom management […] you maybe shouldn't be talking about how to incorporate a laser cutter in your classroom. Let's talk about classroom management first.

Perceptions about learning, teaching, and maker-centered education

The final category of challenges and enablers identified by all 21 participants (100%) revolved around themes of perceptions about the nature of learning and what learning 'looks' like, and perceptions about maker-centered education and the role of the teacher. Although the vast majority of what has been discusses in this paper thus far could arguably all point to perceptions about what learning is and how it takes place as the root cause of the various challenges, some participants explicitly mentioned these factors, which will be discussed separately here.

Perceptions about learning

Similar to reports from the literature (Davis et al., 2021; Heredia & Tan, 2021; Singh & Kim, 2019; Thompson, 2021), 10 participants (48%) identified challenges and enablers related to current perceptions about learning as they impact teachers, both positively and negatively, as they attempt to integrate MCLEs into their teaching. Matthew, Sophie, Kevin, Charles, Brigitte, and Jocelyn all noted that perceptions about what learning is or what it should look like is impacting teachers as they engage in MCLEs with their students. Matthew and Kevin stated that there are tensions between those who want to take progressive approaches to education and the still dominant traditional approach of lecturing and rote learning, which Valentine and Kevin suggest may stem from doubts about the learning outcomes of MCLEs. Kevin explained that teachers are hesitant to attempt approaches like MCLEs as they feel more confident students will learn the required content from a lecture:

> [I]f I talk at them for an hour, I will be certain that they've learned, that they've heard the things that they need to produce on the test, like whatever that end up test becomes. I can be certain that that has happened to the kid and that it's sort of on them if they didn't learn it, not that that's really how I think about teaching but I know people that do. But all the maker stuff, you're handing over a lot of control, and it's not guaranteed that a kid will have [learned it].

Charles added that these persistent perceptions and collegial pressure continue to influence teachers, "[C]haotic classrooms are seen as unorganized, kids aren't doing anything. There's a lot of luggage and preconceived notions and peer pressure, collegial pressure." For these perceptions about teaching and learning to change, Sophie stated that teachers need to re-evaluate what constitutes teaching and learning:

> I think that's a question teachers need to ask themselves. What does learning really look like and sound like? […] It's got to be a shift in what's valued. […] Is it more important for them to be doing a dictée? Or is it more important for them to be getting down and dirty with something from which they'll actually learn?

Jocelyn further added that these perceptions need not be a barrier as there are many disciplines where learning is not solely viewed as a passive process of absorption of content knowledge and that, though perhaps by a different name, MCLEs have historically been included as part of the learning process:

> There's a very deep history within different kinds of disciplines of making. We have workshops for our mechanical engineering technologies, civil engineering technologies, electrical engineering technologies, the career programs, and […] obviously in fine arts and visual arts and industrial design, and multiple other programs, there are many sites of making that have been around for a long time.

Perhaps the most revealing evidence of the impact of current perceptions about learning is the reaction of some students to MCLEs as reported by the participants. Contrary to the popular belief that students will naturally be drawn to making, reports from both the literature and the participants in this study found that not all students are immediately comfortable with MCLEs and that some students are resistant to MCLEs because they do not reflect their expectations of what school learning experiences should be like (Becker & Jacobsen, 2023; Bower et al., 2020; Henderson et al., 2017; C.-Y. Lee et al., 2021). Matthew, Derek, and Bruce pointed out that students have schemas of how academic experiences should proceed and are resistant when they do not proceed as expected. For example, Derek noted how students expect teachers to provide them with instructions on every step of a project and are not accustomed to finding solutions on their own:

> [S]ome students come up to me and they say, "Mr. [Derek], I understand you're asking me to do this, but you haven't told us how." And I'm like, "How is your half of the deal. I can give you a little bit of how, but I told you how to make the motors move, I told you how you can glue things together, I showed you a few things. So if you want to make something move, you use the code and the wiring that you've been shown." And then there is a gap that [they] have to jump.

Matthew added that students are also not accustomed to multiple iterations of a project and that they can be resistant to repeating the process to refine their project. He explained:

> It's very common for students to do one go and be like, “Okay, I'm done. I'm done my project. “ And that's very much how they're trained to submit assignments in schools; I did my assignment, I get a grade and it is what it is. Whereas here, we're saying, “Okay, you did that, that's great. But how do you make it better?” And then understanding the nuances in there, that's a real challenge.”

Sophie and Sylvain pointed out that students are also accustomed to consuming knowledge, not producing knowledge. Sophie noted:

> [O]ur kids are very, very, very good at consuming. But it's hard for them at first to have open access at times to tech, but to be told, “No, you can't sit and watch YouTube or sit and watch some other guy make something, you need to be creating.”

Additionally, as Derek and Matthew pointed out, due to current emphases within schools, students are often less willing to engage in experiences such as MCLEs as they are perceived as less important to their academic development relative to core subjects. Matthew explained:

> [T]hat's a problem in the sense that […] it's competing against the sciences. […] People see it, and parents still see it, as you're making pretty chairs or home decor, not so much the problem-based thinking that is where design is sitting now in innovation. […] What that means is that students will maybe not put the amount of effort into this area that they would if it were, a core subject.

Finally, Charles and Sarah also pointed to students’ lack of skills to work independently on MCLEs as indicative of the types of learning that are prioritized or neglected in schools. Sarah explained:

> When I grew up, I made a lot of stuff. […] I made my own clothes, we did hand crafts, it's part of my culture and stuff. But the kids today, they don't. I have to teach it in school. […] They don't know how to use a ruler. They're not good at scissors, they'll get really frustrated. […] It would take them half an hour to cut out a shape that would take me maybe 30 seconds to cut out. […] They don't know measurements. They don't know how to draw something and figure out what the measurements are that you need. […] They don't have any fine motor skills. If I'm teaching them soldering, it takes a lot longer. […] It's really basic skills. […] So I have a class period teaching about how to measure things, or how to draw a box […] So it's really an issue for teachers because they have to teach way more than you and I might think.

Perceptions about maker-centered education and the role of the teacher

In addition to the already-mentioned factors that may cause teachers to resist integrating MCLEs into their teaching (e.g. lack of training, perceptions that integrating MCLEs adds to their teaching load, difficulty making connections to the required curriculum, etc.), 17 of the participants (81%) identified some additional challenges and enablers related to teacher perceptions about MCLEs, their own abilities and their role as a teacher in the context of MCLEs.

Similar to reports from the literature, some participants reported that teachers were often hesitant to integrate MCLEs into their teaching as they felt it was an add on and competed with their time to cover the required curriculum (Rosenfeld et al., 2019). Valentine and Sandy suggested that part of the problem is that some teachers perceive MCLEs as adding to the curriculum that they need to cover, instead of a means of covering already existing curricula. As previously mentioned, Valentine commented that she regularly has to broach this subject with teachers to clarify that it is not an add on and explain to them that "STEAM pedagogy is not an add on, it's a different way of approaching your curriculum." Lilliane and Samantha proposed that this may be due to teachers having difficulty understanding how to use MCLEs to address curriculum requirements, particularly, as Jocelyn pointed out, MCLEs are transdisciplinary and difficult to fit into undiscipline content driven curricula.

> [W]e have had difficulties in penetrating the curriculum. Although we're making a lot of inroads now, especially over the last few years, but I think it was difficult for people to understand what it was because it's amorphous in some sense, exploring knowledge across the disciplines. […] It's an interdisciplinary initiative, multidisciplinary, transdisciplinary, deeply disciplinary, what is it? So I think we suffered from a lack of definition, because it couldn't be found in, in some academic setting in ways that were, let's say, defined.

Matthew, Arjun, Jennifer, Alexandre, Lilliane and Michel suggested that many teachers are resistant because they are intimidated by the technology and how much there is to learn. Matthew recounted:

> The number one thing that teachers say […] is that they're intimidated. They feel like they just don't have much to offer because they don't know this. […] When they walk into the space it's got a lot more impact than I'm aware of. I'm comfortable around technology and a bunch of tools on the walls and materials everywhere because it gets me excited. […] I never thought that that would be intimidating. […] So the more I talk to teachers, the more they're saying they're intimidated.

Michel added that part of the issue may also be perceptions about what types of teachers integrate MCLEs into their teaching. He noted:

> I wonder if there's something to the image of a maker educator and a coding educator that itself is a barrier. Something about the identity or the vision coming from a novice looking at someone who's a maker educator, like, “Oh, my goodness, I'm never going to be that equipped. Look at what these people can do. They can do printing, coding, circuitry, all of these things. That's not going to be me.”

Furthermore, Alexandre, Michel, Arjun and Caroline pointed out that part of the intimidation may come from teachers’ misconceptions about what MCLEs involve. Alexandre and Arjun stated that they spend a lot of time demystifying MCLEs for teachers while Michel and Caroline noted that teachers misunderstand MCLEs as having to involve sophisticated high-tech digital fabrication tools. Michel mentioned that he frequently has to explain to teachers that:

> It doesn't have to be complicated. You could be doing making or coding, no-tech coding, or low-tech making, and that's fine. It doesn't have to be with a 3D printer, or it doesn't have to be Python. If that's your starting point, and that's where you're comfortable, fine.

Aside from the technology, Valentine and Arjun pointed out that some teachers are intimidated by the math, science and engineering that they think will be involved. Valentine noted:

> There is a notion with these tools and the notion of making and when you use the word engineering design, that it's math and science. We tried to dispel that so quickly. We try to dispel the fact that this word "engineering", it has a connotation. […] It carries a perception amongst teachers in elementary school, for the most part, again, I'm generalizing, but it's a bit of fear that [it] requires certain skills that you don't have.

In addition to being intimated by the technology and the perceived content knowledge they will be required to know, Matthew suggested that some teachers also lack the confidence to facilitate MCLEs:

> You get into a space and even if you're doing a canned project, you're going to have five hands go up saying, “Sir, or Ma'am, it's not working for me.” […] You’ve got to have the ability to deal with that kind of potential roadblocks there in the individual students. And if the teachers are comfortable with it, they'll go around and help. But oftentimes, teachers are given these spaces, but they don't have the confidence yet to help the students.

Sarah, Caroline and Michel explained that part of this may be due to the misconception that in order to engage in MCLEs they need to be experts in making. Emma and Caroline also noted that some teachers may be uncomfortable relinquishing some of the control in the classroom. Caroline explained:

> If you feel like you need to control everything, then it's really tough because you have to control every Lego brick and every piece and everything's got to go back the way it was. In that case, it's overwhelming. Everything that doesn't have a sheet of paper and a pencil is just too much. So I think that's part of it, to understand that you have to let go a little bit of the control. There will be a mess sometimes, but it's a little bit of managed chaos.

Sophie pointed out that, in some cases, the challenge is that some teachers’ perceptions about what learning looks like conflicts with what happens in the classroom when students are engaging in MCLEs:

> It's messy and there are a lot of teachers who are not comfortable with that. Noisy doesn't have to mean chaos. I always like to say there's a hum in the room, you know, there's a

> hum with the occasional scream of delight or frustration, but it's generally this hum. But there are a lot of teachers who believe that it should be much quieter in a learning space.

And as Caroline and Charles pointed out, for some of teachers, it simply came down to not wanting to deal with the mess and chaos. Caroline recounted an incident with one of the teachers she worked with:

> She wanted two of her colleagues to do it and they were like, "No way we're doing this with students. It's a mess, there's dye, I can't do it. Forget it."

Twelve participants (57%) stated the providing teachers with an opportunity to observe successful MCLEs in action is critical to overcoming misconceptions teachers may have about maker-centered education and how it helps students learn. Matthew, Charles, Bruce and Arjun stated that it is essential that teachers see MCLEs taking place in a classroom with real students so that teachers can see it work in an actual school context. Bruce explained:

> With making, and with digital fabrication specifically, in classrooms, there's no substitution for a teacher and administrator seeing it work. So having a model classroom. That really helped me when I was able to either teach a class in the library or come to a classroom and do a demo lesson, and show the teacher that this can work. Or when I had the mobile Fab Lab going out to high schools and partnering with teachers, partnering with schools, and coming in and showing them this can work. There's no replacement for that. There's nothing you can write on paper, there's no arguments, and it's disarming to arguments against it when you come in and the students learn and the students are more engaged. You can defeat a lot of these things that if you just wrote it down on a piece of paper and said, "Look, the research says this," you're going to have teachers saying, "No,

> you just can't get the kids to behave for that. They're just not old enough." But if they actually see it work, there's just no replacement.

Matthew, Charles, Bruce and Arjun all pointed out that this is most effective when teachers see their own students engaging in MCLEs. Matthew recounted an incident with a teacher he was working with:

> We were moving in time with her curriculum and the kids were making. They had learned how to draw, they'd learned how to document their work. It was a very successful project as far as I was concerned. At one time the bell rang, and she was like, "I can't believe it" I'm like, "What?" "They're not getting up." And I'm like, "Okay." She's like, "No, normally, when the bell rings, no matter what, the kids are running out of the class, but they're working." She had such a good experience that she was sold.

Sophie and Alexandre also argued that connecting teachers with other teachers who have successfully integrated MCLEs into their teaching but who are like them in their level of knowledge and skills with technology can be a particularly powerful way of convincing teachers. Alexandre explained:

> We have to show them people who have succeeded in doing it, […] other examples of teachers who were able to do it. It gives them reassurance and they need reassurance. But finding teachers who are like them because often when there are the teachers who are called geek teachers, their colleagues will say, "I'm not like them, I can't do that."

Discussion and Conclusion

Maker-centered learning experiences (MCLEs) are increasingly being integrated into schools (Blikstein, 2018; Halverson & Sheridan, 2014b) because of their potential to offer learners the opportunity to develop key skills and dispositions necessary for future civic and professional life (Blikstein, 2013; Halverson & Sheridan, 2014; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013). Given the disparate natures of the maker ethos and that of formal education, some challenges may be present when attempting to integrate maker activities into schools. Research in this area is limited, however, warranting further investigation.

Therefore, this study aimed to answer the following research questions:

1) What factors do experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered learning experiences into K-12 formal teaching?
    a. What are the perceived challenges faced by educators in K-12 formal education who have experience with maker-centered education, as they integrate maker-centered learning experiences into their teaching?
    b. What factors do educators in K-12 formal education, who are familiar with maker-centered education, perceive as facilitating the integration of maker-centered learning experiences into their teaching?

The results from the interviews with the 21 educators in this study revealed four overarching categories of challenges and enablers that may influence teachers' willingness and success integrating MCLEs into their teaching. These include 1) material, virtual and human resources, 2) educational operations and management, 3) training and professional development, and 4) perceptions about learning, teaching and maker-centered education. While many of these factors support existing reports in the literature, others appear to be newly identified, including enablers that may offer insight into how conditions can be improved to better support teachers as they integrate MCLEs into their teaching. In line with the literature, participants reported challenges related to space, equipment, time and scheduling, training and professional development, curriculum and standards, assessment, leadership, student expectations and capabilities, class size, teacher resistance, and funding. Challenge areas not previously well-explored in the literature were related to software and online tools, online resources, hiring regulations and position descriptions, and the influence unions have on what schools can ask of teachers.

In addition to the challenges revealed in this study, participants also identified enablers and provided recommendations that they perceive may circumvent at least some of the challenges. For example, participants reported that although dedicated makerspaces in schools can present some challenges, these spaces are ultimately enablers as they provide teachers with a space to develop and conduct projects that they could not do in a standard classroom. Participants also reported that the access to digital fabrication technology is becoming less problematic as equipment is becoming increasingly available at affordable prices and is often available through public institutions like libraries and community organizations like local makerspaces. Additionally, these technologies are becoming easier to use, enabling both teachers new to MLCEs and young students to engage in maker activities. Free online software, tools, and resources were also reported to be very helpful to teachers in the preparation of MCLEs, the facilitation of these activities, and the assessment of learning through MCLEs as a greater variety of MCLEs can be undertaken at no additional cost and they offload some of the cognitive strain on teachers. Support from online and local maker communities, publicly funded educational organizations, school boards, and specialized staff were also reported to be essential enablers for the preparation and facilitation of MCLEs. Finally, support from good leadership and flexibility in leadership, funding, and scheduling was reported to be of considerable help to teachers as it allowed them to attempt innovative approaches to teaching, like MCLEs, that were not regularly practiced in their local context.

The findings of this study reveal that integrating MCLEs into schools does have some challenges that impact teachers and need to be addressed to better enable teachers to effectively use MCLEs in their teaching practice. By better understanding the challenges and enablers that influence teachers as they integrate MCLEs into their classroom, education leaders and policy makers can more effectively make changes to improve the conditions in which teachers are working. This is essential if maker-centered education is to offer its full learning potential to students (Fulfilling the Maker Promise: Year One, 2017; Koole et al., 2020; Stornaiuolo & Nichols, 2021; Weiner et al., 2021).

Limitations

There are some limitations to this study. It study is an exploratory study intended to identify the potential challenges and enablers that influence teachers as they attempt to integrate MCLEs into their teaching practice. As the aim of the study was to discover the breadth of the potential challenges and enablers teachers may encounter, it was not possible to dive deeply into each of them. Further research investigating each of the identified challenges and enablers is required to deepen our understanding of the complexities of the environment in which teachers are working to effectively remove the barriers that teachers are encountering when integrating MCLEs into formal education settings.

Introduction to Manuscript 3

This dissertation thus far has explored the vast literature that is emerging on maker education and educator perceptions of the challenges and enablers that teachers encounter as they attempt to integrate maker-centered learning experiences into formal education settings. Among those challenges was a need to justify deviations from current practices with evidence that MCLEs do in fact lead to the learning and skills development touted by proponents of maker-centered education. Unfortunately, empirical evidence of the long-term value added of MCLEs is still limited (Duponsel & Davidson, in preparationa; Lindsey & DeCillis, 2017).

I was fortunate to be in an environment where I could tinker with interdisciplinary makers because of my research group (www.educationmakers.ca). Given the leadership of the Research Chair in Maker Culture and the institutional support of the university, Concordia University was named one of the best maker schools in the world (https://makezine.com/best-maker-schools-2021-from-make-and-newsweek/). This was possible because of the creation of multiple makerspaces on campus, mentorship and learning opportunities for students to engage in MCLEs so that they could enhance their learning and skills development, supplementing their learning from courses.

Throughout my journey as a doctoral student at Concordia University, I had a unique opportunity to engage in an MCLE of my own as an extracurricular experience. This manuscript, and the introduction prefacing it, provide some tangible evidence of the potential of MCLEs in formal education to contribute to student learning and skill development evidenced by the learning outcomes that have provided me with career opportunities that would not have been open to me otherwise.

The following preface to Manuscript 3 provides a description of the project, the learning outcomes I identified after having taken part in this MCLE, and the conditions I perceive made this MCLE possible in the context of my degree and university. The hope is that it will provide promising evidence of the potential learning outcomes of MCLEs and the value-added of maker-centered education when the necessary learning conditions are provided.

Description of the project

Context

This project was initiated in early summer of 2020 in response to the acute personal protective equipment (PPE) shortages that occurred during the first wave of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2, hereafter referred to as COVID-19). My supervisor, Dr. Ann-Louise Davidson (Professor, Department of Education, Concordia University) formed an interdisciplinary team of researchers from Education, Fine Arts, and Engineering with Professor Barbara Layne (Professor Emerita, Fibres and Material Practices, Studio Arts, Concordia University) and Dr. Ali Bahloul (Researcher, Institut de recherche Robert-Sauvé en santé et en sécurité du travail). The team collaborated to propose a MITACS project that would investigate the efficacy of community-developed alternatives to PPE. In response to the PPE shortages, many makers and maker communities began developing homemade alternatives to PPE that could be constructed using affordable and easily acquired materials (Ishack & Lipner, 2021a; Manero et al., 2020; Radfar et al., 2021). These efforts focused on helping frontline workers better protect themselves from exposure to COVID-19 (e.g. Armijo et al., 2021; Bharti & Singh, 2020; Erickson et al., 2020; Manero et al., 2020; Swennen et al., 2020), as well as finding more comfortable and sustainable options to disposable PPE (e.g. Aragaw, 2020; Beesoon et al., 2020; Lubrano et al., 2020; Patrício Silva et al., 2020). As such, this collaborative project had two primary objectives: 1) Investigate and test possible designs for PPE alternatives that would effectively protect frontline workers from the virus and, 2) investigate and test face mask designs using sustainable materials and designs that reduce discomfort such as breathing difficulties associated with mask wearing and fogging up of glasses.

The research was conducted at the Milieux Institute for Arts, Culture and Technology at Concordia University in partnership with l'Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) and the filtration lab in the Gina Cody School of Engineering. Two graduate interns were hired to undertake the project. Due to my experience with 3D printing and design and some prototyping that I had already independently done on PPE alternatives, I was hired to collaborate with the team to reach the first of the two above-mentioned objectives. A graduate student in Fine Arts was hired to investigate the second objective given her specialization in fibres and sustainable materials.

Throughout the project we collaborated with the researchers from the three disciplines as each provided us (the interns) with expert guidance in their respective areas of expertise (the design process and digital fabrication, fibres and materials, filtration efficiency testing and fit testing), none of which we were experts in. The team worked together on the project for one year.

Process

We took the Hasso Plattner Institute of Design at Stanford's (also known as the d.school) Design Thinking (d.school, 2010) approach to create our prototypes. This process consists of a five-phase cycle where prototypes are created through multiple iterations through the cycle of Empathize, Define, Ideate, Prototype, and Test. As much of the information gathered during the empathize phase of the process was pertinent to the research objectives of both interns, we conducted that phase together. The remaining phases were conducted separately but in collaboration with the research team.

In the Empathize phase, we gathered information about the needs related to masks and respirators for users both in the medical field and in the general public. We gathered information from both the scientific literature as well as from non-academic content on the Internet to gain a better understanding of what science indicated needed to be improved and what the public felt needed improvement. Our review of the scientific literature revealed that fit, filtration efficiency, and breathability of masks and respirators were the most crucial aspects of masks and respirators, while our review of non-academic sources online revealed that issues of comfort, fogging of glasses, and tenderness around the ears were of great importance to users. This phase of the project was primarily conducted during the first month of the internship, however, as the literature on these subjects was developing rapidly throughout the course of the internship, we continually consulted the literature for new findings that might influence our research decisions and prototype development.

In the Define phase, I isolated the factors that the scientific and non-academic literature identified as of greatest importance when developing masks and respirators. Together with the research team and experts from the Aerosol Filtration Lab, we identified fit, filtration efficiency, breathability, and comfort as the most important factors to consider as they are all crucial to the efficacy of a face mask in protecting the person wearing the mask from potential airborne contaminants.

In the Ideate phase, I explored already existing commercial products and open-source prototypes to modify or inspire new prototypes. I found that by the time we had started this project there already existed many commercial and open-source accessories for medical and procedural masks that were effective at improving breathability and some aspects of comfort (e.g. keeping the mask out of the mouth), but that only one (at the time) addressed the issue of fit (i.e. creating a good seal between the mask and the face preventing contaminated air from entering the mask). Given that PPE like N95 respirators are effective due to a combination of efficient filtration and good fit (Bahloul et al., 2021; O'Kelly et al., 2020), and that many procedural masks are made with excellent filtering materials (Whyte et al., 2022), I decided, with feedback from the team, to focus my efforts on creating a mask accessory that could improve mask fit so that procedural masks could work more like N95 respirators.

In the Prototype phase, I tested several 3D printing materials like thermoplastic elastomers, as well as other materials like skin-safe silicones and foams to create a mask accessory that would improve fit. Given that one of the overarching objectives of this project was to create easily accessible PPE alternatives, the designs needed to use materials that were easily accessible to the general public, and to use processes that did not require specialized equipment or knowledge to produce. Therefore, after some experimentation, I decided to use 3D printing due to is relative ease of access (through libraries and local makerspaces) and use of cost-effective and human safe printing materials.

Finally, in the Test phase, I tested my own prototypes subjectively for comfort, and objectively for their efficacy to create good fit when worn over a procedural mask. I tested fit using filtration testing equipment provided by IRSST in the Aerosol Filtration Lab. After having received training from a researcher at IRSST, I used a PortaCount (Model 8038) to test fit as it is among the most ecologically valid methods of testing fit (it tests respirators directly on people while performing various common movements) and it is the test typically used by medical professionals to assess N95 respirator fit.

Documentation

Although not an explicit phase of the design thinking cycle, as researchers, documentation of our findings is an important component of our work. Therefore, I have produced a few types of documents to outline our findings. I have reported the findings of this project in a paper submitted to the Journal of 3D Printing in Medicine, as well as presented a poster at the 20th Conference of the International Society for Respiratory Protection (Duponsel et al., 2022). I have also developed an open-source step-by-step post on Instructables guiding users through the process of 3D printing the frame and its proper use (https://www.instructables.com/Making-Better-Fitting-Facemasks-With-a-Quick-3D-Pr/). The Instructables page has nearly 6000 views and has been translated into Chinese for a Vietnamese audience (https://vmaker.tw/archives/53008).

The prototype and findings of this project have garnered considerable interest from the media. An article published at Concordia University (https://www.concordia.ca/news/stories/2021/07/26/surgical-masks-more-effective-if-worn-with-3d-printed-frame-concordia-phd-student-finds.html) caught the attention of the media and resulted in a CBC radio interview (https://www.cbc.ca/listen/live-radio/1-383-lets-go/clip/15857883-making-surgical-masks-more-effective-covid-19-infection), and a Global News interview (https://globalnews.ca/news/8147193/concordia-students-surgical-masks/). As a result of the media's interest in this project, I was awarded the Concordia University Communication Services Newsmaker of the Month in May of 2021.

Learning Outcomes

In addition to the tangible outcomes of this project (i.e., the prototype and the research data and reports), there have been several important outcomes related to knowledge and skill development and professional development.

The knowledge and skills developed in this project are varied and are related to interdisciplinary knowledge and skill development, design and prototyping, and designing of instructional guides. Having had no prior learning experiences related to aerosol filtration and mask efficiency, I learned a significant amount about the physics of filtration and the testing used to test filtration efficiency. I also learned about the factors considered when designing PPE like respirators such as fit, filtration efficiency, pressure drop, and dead spaces within the respirator, as well as safety regulations around PPE and 3D printing materials. Evidently, I would not have learned about any of these concepts within my own program of study.

Working with experts in a field completely different from my own also required some adaptation. The research and reporting practices and even terminology in physics and engineering versus education are quite different and required excellent communication skills among the team members to ensure that we understood each other correctly. Although I have worked in the medical field in the past, it was an experience in yet another approach to research that further broadened my capacity to work with experts from other disciplines.

In addition to the new knowledge I gained in aerosol filtration and PPE, this project also broadened my design capabilities. As a maker, I already have considerable experience prototyping devices for my own use, however, this project was the first time that I was prototyping a device that was intended to be used by others. This meant that I had to apply design principles that took the needs of others into consideration. This involved a lot of communication with the other test participant and several iterations with the design to ensure that the prototype was comfortable to wear and did not obstruct breathing or movement. The constraints of ensuring that the final design would be accessible to most users and needed to be skin and respiration safe added to the challenge and required me to keep these factors in mind when designing the prototypes. These challenges added a new dimension to my problem-solving strategies and creativity that I had not encountered in the past.

Another area where I further developed skills was in developing an instructional guide for the general public to create a mask frame for themselves. As a trained teacher and a part-time university instructor, I am accustomed to giving instructions and explaining concepts synchronously to learners. I am less accustomed, however, to providing asynchronous instructions to an audience where I cannot respond to inquiries with further clarifications. This required a shift in my approach when creating the Instructables page as I needed to take into consideration the characteristics of the platform that I was using and the type of user that would be following the instructions.

Finally, this project was beneficial for professional development reasons as it allowed me to diversify my network across disciplines through the research team and through exposure at a scientific conference in respiratory health. As networking is vital for professional success, this project offered me an invaluable opportunity to expand my network across multiple disciplines.

Enabling Conditions

There were many factors that contributed to the success of this project. While it is impossible for me to objectively assess all the influences within the system I am part of, the following is a brief analysis of the conditions that I believe made this project successful.

There were many material, human, and intellectual tools and resources that I was able to draw on that enabled the completion of this project. Apart from the everyday material tools that were needed for this project (e.g. computers), the specialized material tools needed to make the prototypes included access to a 3D printer, the various types of printing filaments, skin-safe silicone products, as well as the software required to design 3D models and prepare 3D prints. The 3D printers are available for student use at the makerspace at the Milieux Institute, and the 3D design and printing software are open source and free for download online. These open-source tools were critical for this project as paid versions are not only very costly, but also typically require specialized training in their use. The open-source versions are not as powerful, however, they are more user friendly and accessible to the novice and intermediate user. Open-source technology and software have been credited as one of the primary reasons why the Maker Movement is booming today (Clapp et al., 2017; Dougherty, Dale, 2013). The benefits of open-source technology were evident in this project. For the materials that needed to be purchased for this project, the funds that were provided by Mitacs were used to cover these costs. Again, without these funds, the project would not have been possible.

Given that some of the thermoplastic printing materials with which I experimented release harmful fumes when printing, I also needed access to an air filtration system, which was provided to me by the biolab at the Milieux Institute via their fume hood. Given that air filtration systems are very costly to install, the prototypes produced with those materials would not have been possible without the collaboration of the biolab due to the health measures in place at the time that prevented me from working at local makerspaces equipped with the appropriate air filtration units.

The material resources were not the only resources necessary for the success of this project. Although I have considerable prior experience with 3D design and printing, and prototyping, I had no prior knowledge in respiratory safety and aerosol filtration. As such, access to experts in these domains was crucial to my ability to carry out this project. Access to the online maker community was also important as there are always unexpected mechanical issues that arise with open-source 3D printers, for which the maker community can be extremely helpful in finding solutions. Finally, the availability of prototypes shared online by the maker community through websites like thingiverse.com allowed me to experiment with already existing ideas, which propelled the start of the project given my lack of experience in the field.

My prior experience in making and prototyping was crucial to the success of this project. Regardless of the material tools and human support available to me, without the prior opportunities I was granted to develop skills in making and prototyping through my academic supervisor, the Milieux Institute, and the local and international maker community, I would not have had the knowledge and skills to pursue this project to its end. As many makers suggest (e.g. Dougherty, Dale, 2013; Lindsey & DeCillis, 2017), successful making is not about the tools, but about the maker mindset, a set of attitudes that allow a person to problem-solve, tolerate error, learn from failure, and persevere until a solution is found. Without this mindset, I would not have been able to engage in a project I was almost entirely a novice to and yet achieve an outcome that has produced not only a useful prototype, but one that has contributed to scientific knowledge.

This project was possible due to the collaboration of many actors within my environment. The grant that was acquired to fund this project was prepared by the university faculty with the guidance of support staff from the Office of Research at the university. Once the project was funded, I worked extensively with the other intern on common objectives of the project. Even for objectives that we were responsible for separately, we met regularly to bounce ideas off of each other to generate new ideas we were not necessarily able to produce on our own. The research team of faculty from the university guided us throughout the experience, without over imposing their views so that we were able to problem-solve and design prototypes on our own. This is of particular importance as learning through making is suggested to be best achieved when students are given autonomy in their learning and design process (Clapp et al., 2017; Marsh et al., 2017; Petrich et al., 2016; Resnick & Rosenbaum, 2013). Finally, the expertise offered by the IRSST researchers guided us in our testing of various prototypes and in the preparation of the research documents at the culmination of the project. All of these actors were of great importance to the timely progression of this project. While it may have been possible to achieve without them, it may have taken significantly longer.

Of particular importance in enabling the success of this project revolved around policies that encouraged interdisciplinary research, flexibility of policies to respond to situational conditions (i.e. COVID health restrictions), and educational programs that encourage student independent learning.

There appear to be many policies in place at Concordia that encourage interdisciplinary student projects and research. The first is evidenced by the existence of the Milieux Institute for Arts, Culture and Technology. As its name suggests, the Milieux Institute is a research unit for graduate students in collaboration with faculty from a variety of departments that work at the intersection of design, art, culture, and technology and is described on the Concordia University (n.d.) website as "a platform for progressive imagining, critical thinking, creative experimenting and interdisciplinary training [emphasis added]". The Milieux Institute has eight research clusters that each has its own research mandate, however faculty and student members are encouraged to work across clusters. There are also multiple spaces at the Milieux Institute that are accessible to all students (given the necessary training), including MilieuxMake and the Speculative Life BioLab. MilieuxMake is a makerspace that intersects research and public spheres and offers students a unique space to work on projects that require design, construction, and digital fabrication tools. The Speculative Life BioLab is a hybrid research-creation bio-laboratory that encourages the "development and facilitation of conceptual and material-based exploration" (Milieux Institute, 2020, p. 9). As outlined above, access to MilieuxMake and the BioLab were essential to the success of this project.

Although the spaces at Milieux are open to all members, specialized training is necessary to safely access these spaces. While the training to access MilieuxMake is provided by the Milieux Institute, the training needed to enter the BioLab (WHMIS 1988 and 2015, Biosafety, and Hazardous Waste) and the Aerosol Filtration Lab (Radiation Safety) in the Engineering department is regulated by the Environmental Health and Safety Department at Concordia University. Environmental Health and Safety policies could limit the available training to students from specific departments, however, they do not, allowing students such as myself to receive the necessary training to access these spaces. This further encourages interdisciplinary learning experiences as it permitted me access to a space that I would not normally work in as a student from the Department of Education.

The culture of flexibility at both Concordia University and IRSST was also crucial for the success of this project. Although the makerspace and biolab at the Milieux Institute were essential for the project in the later stages, the initial health restrictions prevented me from working at the university. At this time, the project was able to progress due to the flexibility of the university that permitted me to borrow one of the 3D printers and work with it at home for the first few months of the project. Later, once the lockdowns had lifted, the university gave me special permission to work in the specialized spaces at the Milieux Institute due to the nature of the project, even though students were not permitted on campus at the time. IRSST also demonstrated flexibility in their policies that enabled the progression of the project as they permitted the research team to borrow the testing machine (PortaCount) and remove it from the IRSST premises for the purposes of testing the efficacy of the mask frames. Without the flexibility of these two institutions, the project could not have progressed in a timely manner given the health restrictions in place at the time.

Although the policies that encourage interdisciplinary research and flexibility were essential for its success, the project would not have been possible without the time and space within the graduate program to pursue such learning experiences. While professional degrees and graduate programs in other parts of the world may place a heavier emphasis on coursework, reducing the time and opportunities for students to engage in independent learning experiences like this project, my graduate program has limited course requirements, granting students much more time and opportunity for such experiences.

Historically, a graduate degree in Education may have been strictly focused on theory, but current trends in societal thinking have pushed for more practical experiences that develop 21st century skills in formal education. Therefore, granting agencies and formal education institutions are more willing to support these types of projects. Similarly, a recognition of the need to break down the boundaries between the disciplines and to collaborate more broadly on interdisciplinary studies has also encouraged greater support for these types of experiences. Finally, the shifts in the greater community to focus on issues of EDI and the Maker Movement’s emphasis on open source and Creative Commons licensing have led to greater support of research and student projects that tackle EDI issues, including projects like this one that had among its aims to produce an accessible option for PPE for all members of society.

Article presentation

The following article is an example demonstrating the possible scientific contributions students can make when given the opportunity and the right conditions to engage in interdisciplinary maker-centered learning experiences in formal education contexts. Although the team provided me guidance during this project, and I used the resources made available by the maker community, I worked primarily independently, including on the development of this article. This article is evidence of the powerful possibilities of maker learning experiences in formal education.

Manuscript 3: Improved mask frame design to increase surgical and procedural mask efficacy

Abstract

Aim: Test the efficacy of thermally fitted and semi-elastic 3D-printed mask frames to improve fit of certified procedural and surgical masks.

Materials and Method: 3D-printed mask frames designed to be thermally fitted to the user's face and with an elastic component to allow for jaw movement were tested over certified procedural and surgical masks using quantitative fit testing to determine if these designs create adequate seals between the mask and the user's face.

Results: Surgical and procedural masks successfully passed quantitative fit testing with both thermally fitted and semi-elastic mask frames. Semi-elastic mask frames were more effective than fully rigid frames at creating good fit.

Conclusions: Thermally fitted and semi-elastic mask frames worn over certified masks can create good fit.

Introduction

With the rapid spread of the SARS-COV-2 virus, shortages of personal protective equipment (PPE) left many medical professionals and frontline workers without adequate protection (Ishack & Lipner, 2021b). In response to this urgent need, many makers (also known as do-it-yourselfers) and researchers alike turned to 3D printing for temporary PPE alternatives due to its quick turn-around and ability to rapidly respond to time-sensitive needs (Ishack & Lipner, 2021a; Manero et al., 2020; Radfar et al., 2021; Tareq et al., 2021). As a result of these efforts, many prototypes ranging from face shields to fully 3D-printed respirators have been developed and distributed widely, with some organizations like the National Institute of Health creating online repositories providing designs for the public to use (*NIH 3D Printing Exchange - COVID 3D TRUST: Trusted Repository for Users and Suppliers through Testing*, n.d.). Despite a great enthusiasm for these temporary PPE alternatives, concerns nonetheless emerged about their efficacy and safety, particularly in the case of 3D-printed respirators, because these designs have not been rigorously tested as regulations require for use as PPE before implementation in medical contexts (Bharti & Singh, 2020; Duda et al., 2020).

Particulate filtering facepiece respirators (FFR; ex: N95 respirators) are worn over the nose and mouth and are designed to filter out potentially harmful airborne particles like dust, bacteria, pollen and infectious agents (*Respirator Fact Sheet| NPPTL | NIOSH | CDC*, 2020). To be effective, respirators need two components of function: good filtration performance (filter efficiency and pressure drop) and good fit (Bahloul et al., 2021; O'Kelly et al., 2021a). In contrast to respirators, medical masks have a primary purpose of providing source control (i.e. reduction of the release of infectious agents from the wearer; *CCOHS*, 2021).

Filtration

To function effectively, FFRs must filter out the most penetrating aerosols, while still allowing air to enter the FFR for breathing. Filtration can be accomplished through various mechanisms, such as through gravity sedimentation, interception, diffusion, inertial impaction, and electrostatic attraction (Bahloul et al., 2014). Additionally, the pressure drop across the respirator is an indicator of breathing resistance. Regardless of the mechanism of filtration, the degree to which an FFR is determined to eliminate potentially harmful particles corresponds to its efficiency. For example, an N95 respirator filters out 95% of potentially harmful particles, while an N99 respirator filters out 99% of harmful particles (*42 CFR Part 84 Respiratory Protection Devices*, 1995). FFRs are regulated by various bodies globally (ex: National Institute for Occupational Safety and Health – NIOSH – in the USA; European Committee for Standardization – CEN – in the European Union), and must be rigorously tested and certified for use in workplaces, including medical settings. In North America, performance is standardized via NIOSH certification and the Occupational Safety and Health Administration (OSHA) guidelines provides the fit factors that must be achieved by workers when using a respirator.

During the pandemic's first wave, governments had to manage as well as possible in order to limit the PPE shortage, especially respirators (Organisation for Economic Co-operation and Development, 2020). Healthcare workers were then able to use respirators approved under other certifications and equivalent to N95, such as KN95 and FFP2. However, recent studies have shown that successful fit tests appears to be lower for KN95 compared to N95 (Caoili et al., 2020; Mottay et al., 2021; O'Kelly et al., 2021a).

Additionally, at the start of the pandemic, many people began seeking other household materials that could be effective at filtering out harmful particles. For example, one trend that spread widely online was the idea of creating do-it-yourself (DIY) masks and respirators using vacuum bags as many of these bags use HEPA (high efficiency particulate air) filters, which, much like FFRs, filter air of dust, mold, bacteria, pollen, and airborne particles of approximately 0.3 microns (μm) (United States Environmental Protection Agency, 2021). HEPA filters used in devices like vacuum cleaners, however, are not designed for human respiration and safety concerns emerged as they may contain materials that are hazardous if inhaled (O'Kelly et al., 2020). In efforts to find other potentially safer options, studies were conducted investigating the filtration efficiency of other household materials like cotton, silk, coffee filters, and household filters (Hao et al., 2020; O'Kelly et al., 2020; Pei et al., 2020). These studies found that woven fabrics like cotton and t-shirt materials were not effective as aerosol filters even when multiple layers were present (Hao et al., 2020). Non-woven materials like coffee filters or household filters were found to be more efficient at filtering out aerosols, however, still not as good as N95 respirators and, once again, concerns were raised regarding their safety as manipulation of these materials can shed ultrafine fibres that can be harmful if inhaled (Hao et al., 2020).

One medical grade material that is more easily available is that of certified surgical masks. Although not necessarily designed with the intent of filtering out aerosols, certified surgical masks are often made with materials that are highly efficient particulate filters. ASTM Levels 1, 2, and 3 certified medical face masks are required to have a particle filtration efficiency of at least 95% and, while not required by the CEN, EN 14683 Type I, II, and IIR masks have also been shown to have good filtration efficiency (Whyte et al., 2022). However, it should be noted that there are some differences between the normative tests of N95 FFR and those for surgical masks.

Fit

The second essential component of the efficacy of FFRs is good fit. Good fit occurs when there are no gaps between the FFR and the user's face, therefore forcing all air entering the FFR to be passed through the filtering material of the respirator. Regardless of how efficient the filtering material of an FFR may be, if the fit is not good and gaps exist between the FFR and the face, hazardous particles will be able to enter through the gaps (Cooper et al., 1983; Reponen et al., 2011). As such, OSHA (*Occupational Safety and Health Standards: Personal Protective Equipment - Respiratory Protection*, n.d.) requires annual fit testing for all professionals working in contexts that require FFRs (standard 1910.134(f)(2)). A fit test is a test protocol conducted to verify that an FFR is both comfortable (i.e. not intolerable to wear) and provides the wearer with the expected protection.

Recognizing the need for well-fitting FFRs, many in the maker community focused their efforts on 3D-printed FFRs with the objective of creating a reusable alternative to the disposable FFRs that were in short supply (Ishack & Lipner, 2021a; Radfar et al., 2021; Swennen et al., 2020). Two literature reviews in previous issues of this journal (Ishack & Lipner, 2021a; Radfar et al., 2021) outline the various approaches that have been taken. Some early approaches involved retrofitting surgical helmets (Erickson et al., 2020) and snorkel masks (Germonpre et al., 2020) with 3D-printed parts to serve as PPE. The advantages of these approach are that these devices are already designed to create good seals on most faces, are safe for use against skin, and can be reused with simply a change of the filter. While they were found to be relatively effective in offering an acceptable level of protection to the user (Germonpre et al., 2020), they remain in limited supply and do not address the large-scale shortages in PPE that open-source DIY designs were attempting to resolve.

The majority of efforts in 3D-printed alternatives to FFRs consisted of 3D-printed FFRs where the body of the FFR was 3D-printed with a holder for a replaceable filter to be inserted (Gierthmuehlen et al., 2020; Swennen et al., 2020; Tino et al., 2020). While these designs closely resembled FFRs in appearance, thus far, the ones that have been tested have been found to be ineffective (Duda et al., 2020). In addition to being extremely uncomfortable, the rigid form of 3D-printed FFRs does not allow for movement when talking or moving the head, which results in gaps between the FFR and the face, allowing contaminated particles to enter the FFR (Duda et al., 2020). In efforts to improve fit and comfort, some used 3D scanning (Makowski & Okrasa, 2019) to create a design that was personalized to each user, while others used thermoplastic fitting (Duda et al., 2020) where the material was heated up and molded to the person’s face.

Unfortunately, neither process produced a 3D-printed FFR that provided adequate protection on measures of good fit (Duda et al., 2020; Makowski & Okrasa, 2019).

3D-printed mask frames as an alternative approach to creating DIY FFR using surgical masks

As previously mentioned, many certified surgical masks, and all ASTM certified surgical masks, are efficient particle filters and tend to be more readily available than FFRs. Unlike FFRs, surgical masks are not designed to create a good seal between the mask and the face, but rather to act as a physical barrier preventing large droplets emitted by the user entering the environment (O'Kelly et al., 2021b). As a result, aerosolized particles can enter the mask through gaps between the mask and the face, potentially exposing the user to aerosol transmissible diseases.

Mask frames are devices that are worn over masks in order to improve fit. Mask frames typically contour the mask near the outside edge of the mask to provide the largest filtration area possible. They can be semi-rigid, made of malleable materials that can be manipulated to conform to the face of the user, or rigid, made of materials that are pre-formed to contour around the nose and mouth. Research has found that mask frames can improve the fit of FFRs (McAvoy et al., 2021; Stemen et al., 2021), as well as certified surgical masks (Ahmed et al., 2021; Kongkiatkamon et al., 2022; J. Liu et al., 2021).

Although the research in this area is still very limited, some affordances and shortcomings of the tested mask frames have emerged that are related to how the mask frames are customized to individual faces and how mask frames perform when the face shape changes during activities such as talking. In order for a mask frame to effectively create good fit, the frame needs to be in contact with the face along the entirety of the frame's contour. This can be challenging given the wide range of face shapes of the various users. One approach to address this problem is to create personalized mask frames using 3D scans of users' faces. Three studies using this method have demonstrated positive outcomes with ASTM levels 1-3 surgical masks passing fit tests in the majority of cases when worn with a personalized mask frame but not when worn alone (Ahmed et al., 2021; Kongkiatkamon et al., 2022; J. Liu et al., 2021). While apparently effective, Stemen et al. (2021) point out, however, that creating personalized frames using 3D scans is both costly and time consuming and thus an unrealistic approach for large-scale use. Instead, Stemen et al. created a mask frame using the average surface contact area of six compliant N95 FFRs fitted on NIOSH headforms as the contour of FFRs has been carefully designed to fit most users. This approach resulted in passing fit scores for the majority of their test conditions, but still failed to produce a passing fit score for some users, which, as they point out, is also typical of N95 respirators given the impossibility of accommodating all face shapes.

In addition to the challenges of developing a mask frame that fits all face shapes, changes in facial shape during activities like talking and grimacing also pose a problem for FFRs and mask frames (Ahmed et al., 2021; Kongkiatkamon et al., 2022). Changing one's face can displace a rigid respirator or mask frame due to the movement of the jaw, potentially resulting in gaps being introduced between the face and the respirator (in fact, the purpose of the grimace exercise in the fit test is to intentionally break the face seal of the respirator to the face, hence it is not accounted for in the total fit calculation). In two studies (Ahmed et al., 2021; Kongkiatkamon et al., 2022), the quantitative fit test procedure that required talking was the most compromised fit factor score when a rigid mask frame was fitted over an ASTM certified mask, suggesting that this shortcoming needs to be addressed in order to create an effective mask frame.

The objectives of this study were to 1) determine if thermally molded mask frames could achieve a personalized and effective fit when worn over certified surgical and procedural masks and 2) determine if mask frames with an elastic component could effectively maintain good fit during activities like talking.

Method

Frame Design

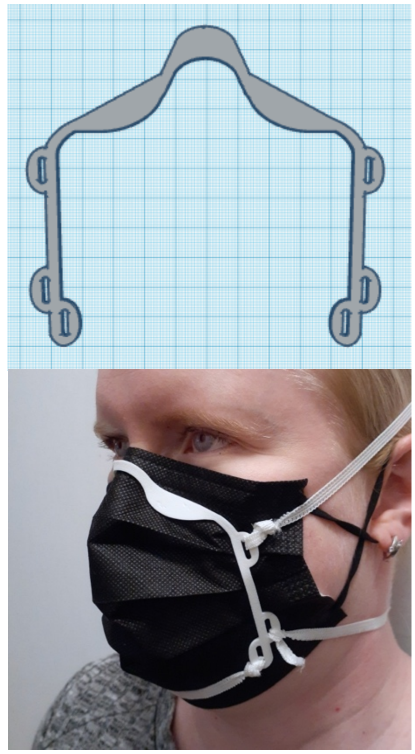
An iterative design process was used to develop 3 models of the mask frame. The first was a model of a mask frame (Figure 6a) designed by shiuan available on www.thingiverse.com, a website dedicated to shared user-created 3D designs. The model was selected because of its simplicity in design, as well as its ability to be heated and molded to the user's face, a technique that was found to be beneficial in adapting 3D-printed FFRs to different facial characteristics in previous research (Duda et al., 2020). Shiuan's original model, however, was completely rigid and did not allow for movements of the jaw, therefore we designed three models incorporating elastic sections into the model to allow for some movement of the face while maintaining rigidity in necessary locations, such as on the sides of the nose. Model A (Figure 6b) has a rigid nose piece and rigid sides but with an elastic section at the chin. Model B (Figure 6c) has a rigid nose piece and a rigid chin piece, but elastic sides attaching the nose piece to the chin piece. Model C (Figure 6d) has a rigid nose piece, but elastic sides and chin piece with 3D-printed clasps to attach the elastic on both sides of the chin. All frames have two headbands, allowing a better fit than ear loops (Figure 7). Other minor adjustments were made to reduce some of the unnecessary bulk of shiuan's design. All models were created in four sizes to accommodate different face sizes. Printing times range from 10-20 minutes, depending on the model and size of the frame.

Figure 6

Mask Frame Models

a. shiuan frame

b. Model A frame



c. Model B frame

d. Model C frame

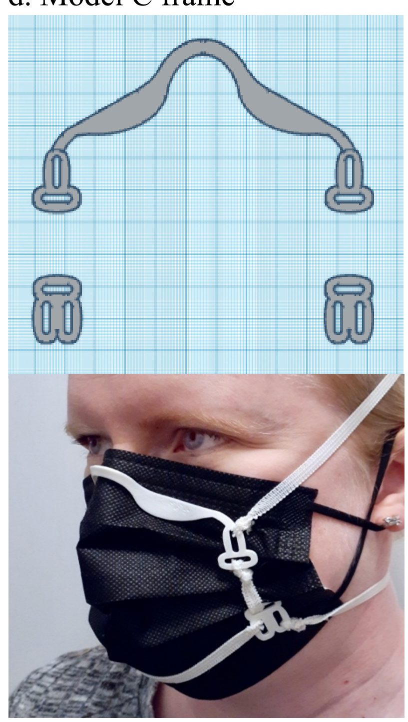


Figure 7

Mask Frame Fitted Over Mask With Head Straps

Design Software and Printer Settings

All software and equipment used to create the mask frame for this study were open-source. This was a deliberate choice as the intent was to find an alternative to FFRs in cases of shortages which members of the public could produce. An online computer-aided design (CAD) software called TinkerCAD was used to design the mask frame. Ultimaker Cura (version 4.9) was used to convert the Standard Tessellation Language (.STL) file generated by TinkerCAD into G-code, the computer numerical control (CNC) programming language used for our printers.

We used a Creality Ender 3-Pro V1 to print the mask frames. The Ender 3-Pro V1 has a build volume of 220x220x250mm and we used a 0.4mm nozzle. We used the standard settings provided by Cura for the Prusa i3 with a nozzle temperature of 210°C and a print bed temperature of 40°C. Our layer height was 0.2mm and our infill was set at 100% to maximize the strength of the frame.

Materials

We used Hatchbox 0.75mm diameter polylactic acid (PLA) filament. PLA is a sustainable thermoplastic aliphatic polyester derived from starches like corn, potato, tapioca roots, or sugarcane (Matbase, n.d.). PLA is widely used in the food industry to package sensitive foods (Bioplastic News, n.d.), and is also widely available for 3D printing. PLA has a glass transition temperature of 45-65°C (*Material Properties Database*, n.d.), making it ideal for safe thermoplastic fitting, a process described below.

Mask Frame Preparation for Use

For printing efficiency, the mask frames are printed flat. It is therefore necessary to mold the frames to the user's face (thermoplastic fitting) to ensure good fit. As the glass transition temperature of PLA is between 45-65°C, submerging the frames in recently boiled water is sufficient to soften the PLA without melting it to the point where it loses its shape. Once softened, the frames can then be molded to the user's face over a protective barrier, such as a cloth or mask. The process can be repeated until the frames have reached their desired shape.

Once the frames are correctly shaped, elastic bands can be attached to the frame to form the elastic portions of the frame, as well as the loops that wrap around the head to secure the mask frame in place.

Testing Frame Efficacy

FFR efficacy relies on the combination of efficient filtration and good fit. Certified respirators have a known filtration efficiency but need to be fit-tested on each individual to ensure good fit (*Respiratory Protection Program Standards- Fit Testing Procedures*

(Mandatory), n.d.). Two industry-accepted methods are commonly used to test the fit of certified respirators: qualitative fit testing, which relies on the user's subjective detection of a taste or smell from particles introduced into the air around them, and quantitative fit testing, which uses machinery to measure the concentration of targeted particles in the ambient environment outside of the respirator relative to the concentration of these particles that enter into the respirator when worn (O'Kelly et al., 2021b). For certified respirators that have a known filtration efficiency, high concentrations of targeted particles inside the respirator indicate that undesirable particles are entering the respirator through gaps between the respirator and the face, or through defects in the respirator (O'Kelly et al., 2021b). The OSHA recommends that an FFRs is effectively protecting the wearer if the concentration of measured particles inside the respirator is 100 times fewer than the concentration of particles outside of the respirator (Appendix A to §1910.134—Fit Testing Procedures (Mandatory), 2004).

Quantitative fit testing was used to measure mask frame efficacy for this study. A TSI PortaCount Pro Respirator Fit Tester model 8038+ (PortaCount, TSI Inc., Shoreview, MN) was used to test fit using the OSHA protocol 29CFR1910.134 (Respiratory Protection Program Standards- Fit Testing Procedures (Mandatory), 2016). The PortaCount Pro was selected because it is capable of assessing FFRs with less than 99% filtration efficiency and provides a good estimate of workplace protection (Reponen et al., 2011). The PortaCount Pro measures particles with a minimum size of 0.02μm both inside and outside of the FFR at a sampling flow rate of 350cm^3/min. For FFRs with a filtration efficiency of 95% and above, the PortaCount generates a fit factor score ranging from 0 to 200+ (+/- 10% error) with higher scores indicating fewer target particles inside the FFR relative to outside the FFR (i.e. better fit). OSHA requires a minimum fit factor score of 100 for N95 respirators to be considered adequately protective (Reponen et al., 2011).

To generate an overall fit factor score, the Fit Test Mode of the PortaCount Pro tests fit during seven consecutive exercises for a duration of 60 seconds each (TSI Incorporated, 2015). These exercises include breathing normally, breathing heavily, moving head from side to side, moving head up and down, talking, bending over, and a second round of breathing normally. The PortaCount generates a fit factor for each exercise using the following formula:

$$FF = \frac{C_B + C_A}{2C_R}$$

where: FF = fit factor
C_B = particle concentration in the ambient sample before the respirator sample
C_A = particle concentration in the ambient sample after the respirator sample
$2C_R$ = particle concentration in the respirator sample.

The overall fit factor is then generated using the following formula:

$$Overall\ FF = \frac{n}{\frac{1}{FF_1} + \frac{1}{FF_2} + \cdots + \frac{1}{FF_n}}$$

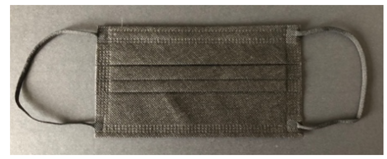
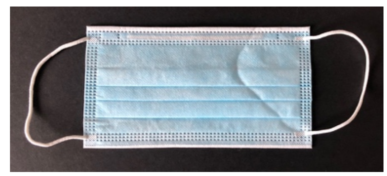
where: FF_x = fit factor for test cycle (exercise)
n = number of test cycles (exercises).

FFRs and Masks Tested

Three masks and one respirator were used to test the mask frames (Table 8). The participants were fit tested with each mask or respirator without a mask frame, as well as with a 3M model 8210 N95 respirator (no frame), to act as points of comparison. The total number of test conditions was thus 21 (4 masks x 4 frames + 4 masks without frames + 1 N95 respirator).

Table 8

FFRs and Masks Tested in the Study

Designation	Product Name	Certification	Description	Photo
PM	Thinka model TMP711-2	ASTM F2100-19 Level 1	procedural mask	
SM1	Canadian Red Cross model CRC-ELM-502R	EN 14683 Type IIR	surgical mask	
SM2	White Cross model F20-2-51J2	T/CNTAC 55-2020,T/CNITA 09104-2020	surgical mask	
KN95	Canadian Red Cross model HT-KN95S-10	GB2626-2006	KN95 respirator	
N95	3M model 8210	NIOSH 42 CFR 84	N95 respirator	

Test Participants

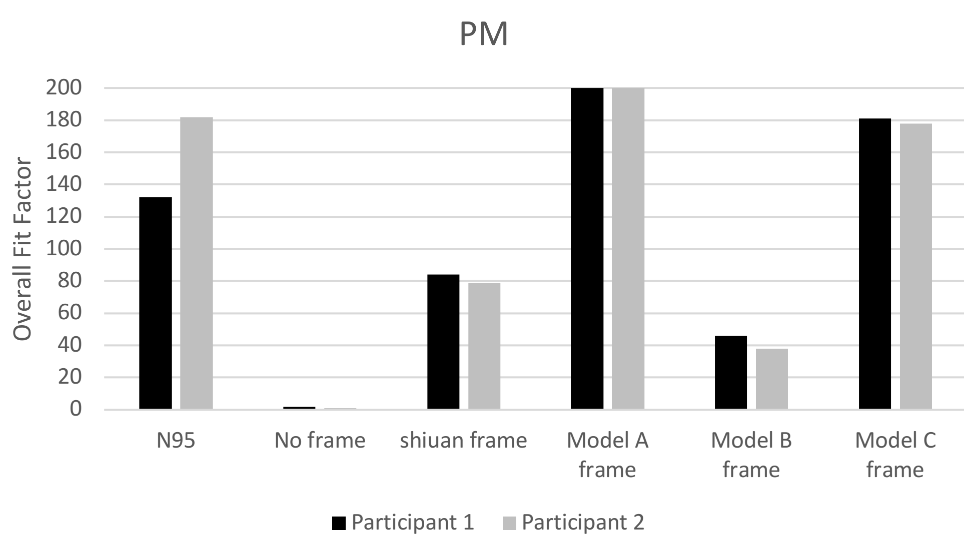
Two participants were tested under all 21 conditions. This study was intended to act as a proof of concept; therefore, it was necessary that all conditions were tested on the same individuals. The participants were both female, one with a narrow thin face (Participant 1), and one with a rounder fuller face (Participant 2) to test the performance of the frames with at least two face shapes. Both participants were female to avoid inconsistencies in test results due to facial hair. The research was conducted following the principles outlined in the Declaration of Helsinki for all human experimental investigations.

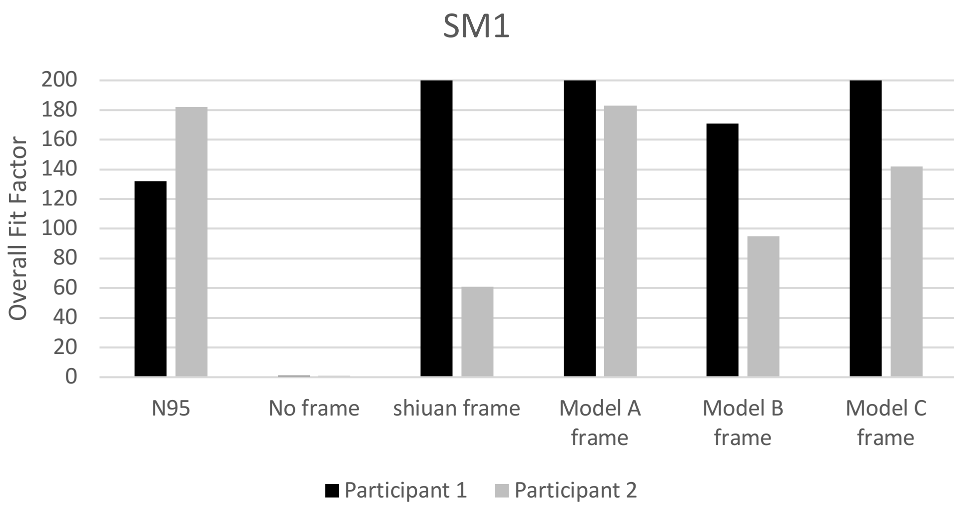
Results

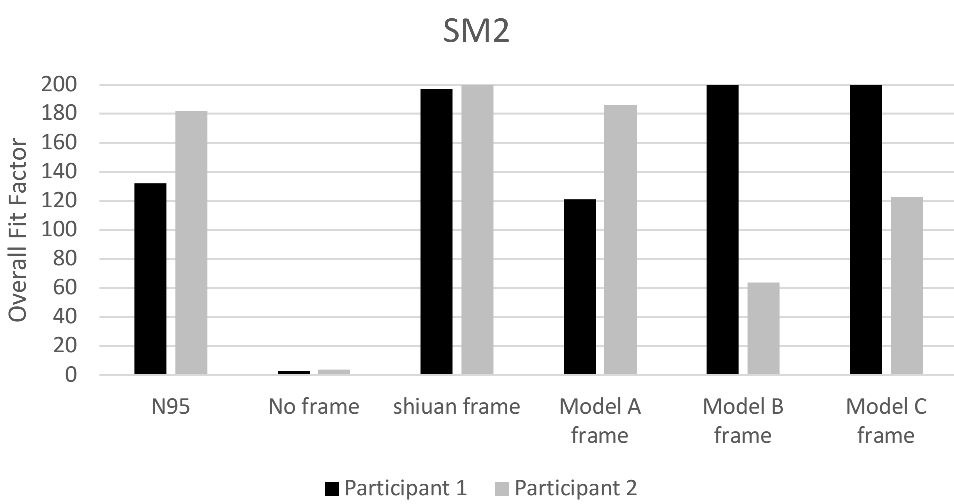
Using the N95 standard of a minimum fit factor score of 100 as the passing score, all masks and respirators were able to achieve passing fit scores for both participants with at least one of the mask frame models (Figure 8). With the exception of the 3M N95 respirator, all three masks and the KN95 respirator failed to adequately prevent target particles from entering the mask/respirator without a frame for both participants.

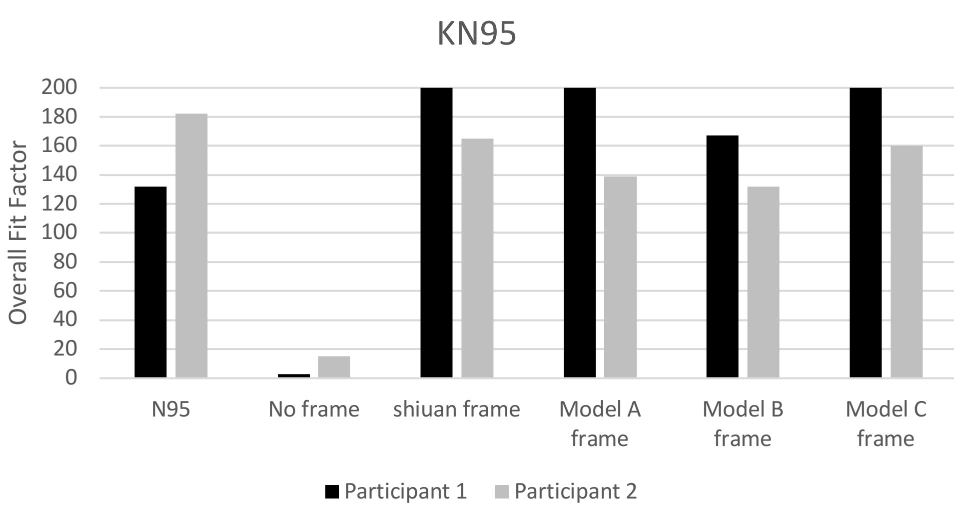
Figure 8

Overall Fit Factors




SM1
Overall Fit Factor
200
180
160
140
120
100
80
60
40
20
0
N95
No frame
shiuan frame
Model A frame
Model B frame
Model C frame
Participant 1
Participant 2


SM2
Overall Fit Factor
200
180
160
140
120
100
80
60
40
20
0
N95
No frame
shiuan frame
Model A frame
Model B frame
Model C frame
Participant 1
Participant 2


KN95
Overall Fit Factor
200
180
160
140
120
100
80
60
40
20
0
N95
No frame
shiuan frame
Model A frame
Model B frame
Model C frame
Participant 1
Participant 2

Mask frame Models A and C resulted in passing scores for both participants on all masks and the KN95 respirator. The original shiuan frame was effective for both participants when worn over SM2 and the KN95 respirator, but not when worn over PM (both participants) and SM1 (Participant 2). The Model B frame was effective for both participants on the KN95 respirator, but was not effective for either participant when worn over PM. The Model B frame showed mixed effectiveness when worn over the SM1 and SM2 as it was only effective for Participant 1.

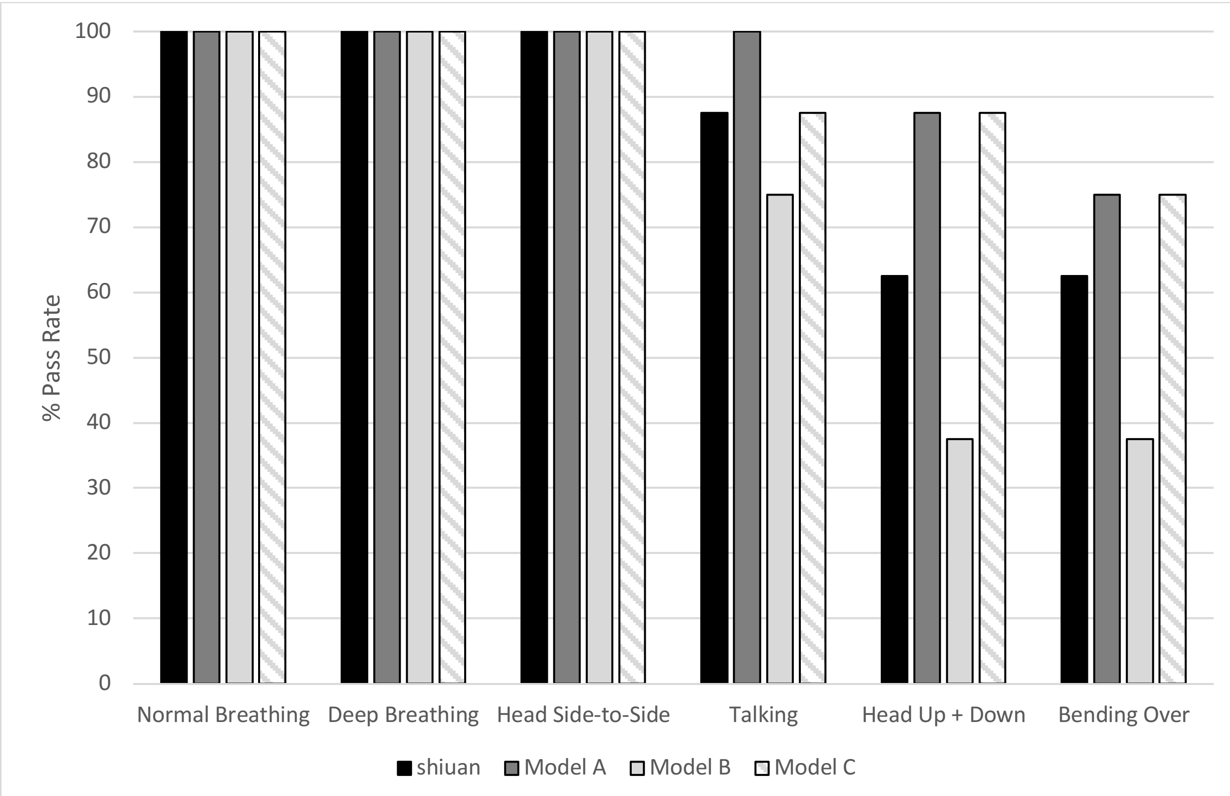
All models of mask frame received a passing fit factor score over all masks for both participants for the normal breathing, deep breathing and head moving side-to-side fit test tasks (Figure 9). For the talking test condition, the efficacy of the mask frames decreased slightly, with the greatest decrease in passing fit factors for the Model B frame (75% pass rate). The tasks that showed the greatest decreases in passing scores were for the tasks of moving the head up and down, and bending over. While models A and C were able to achieve a passing score 87.5% and 75% of the time on the head up and down and bending over tasks respectively, the original shiuan frame and Model B were only able to achieve passing scores 62.5% and 37.5% of the time respectively for both the head up and down and the bending over tasks.

Discussion

The aim of this study was to 1) determine if thermally molded mask frames could achieve a personalized and effective fit when worn over certified surgical and procedural masks and 2) determine if mask frames with an elastic component could effectively maintain good fit during activities like talking. It was hypothesized that thermally molded mask frames would be effective at creating good fit due to their personalized nature as a result of thermoplastic fitting. It was also

Figure 9

Passing Rates for Fit Test Tasks



hypothesized that mask frames with elastic components would better maintain good fit, particularly during tasks such as talking, given the mask could stretch and contract in response to movements of the jaw.

Quantitative fit test results indicated that thermally molded mask frames and mask frames with elastic components worn over certified surgical masks or KN95 respirators can produce fit factor scores comparable to N95 respirators. Some mask frames were found to be more effective than others, however. Mask frames with elastic chin pieces (Models A and C) were successful at passing all tested masks and the KN95 respirator on the fit test for both participants. Mask frames with rigid chin pieces (shiuan original frame and Model B), however, were not able to result in a passing fit factor score for either participant when used over the PM, and Model B failed for the participant with the fuller face with all masks except the SM2 and the KN95 respirator.

Although individual fit factors are not indicative of the overall fit of a respirator, an analysis of the various exercises during the fit test sheds some light as to where the frames with rigid chin pieces tend to fail. On test exercises that did not require movement of the jaw (talking) or up and down head movements (head up and down, bending over), 100% of exercises (48/48) resulted in a passing fit factor (excluding the final breathing exercise as displacement of the masks/respirators during movement exercises is not permitted to be rectified after the sequence of test exercises begins). On tests that required jaw and head up and down movements, only 60% of exercises (29/48) resulted in a passing fit factor. Participants reported that during these movements the rigid chin piece of the frame tended to be pushed upward by the bulk of the mask between the neck and the frame under the chin when moving the head down toward the chest, creating noticeable gaps between the mask and the face at the point of the nose. This was particularly true for the PM which uses a relatively rigid material compared to the other masks tested and did not conform as well to the face under the frame as the masks with more flexible materials. The vertical seam of the KN95 respirator caused a similar problem for the participant with the fuller face as the seam prevented the material from flexing, which caused the respirator to push up and create a gap at the nose.

In addition to their efficacy, frames with elastic elements were described as very comfortable by participants as the elastic components of the frame allowed the frame to adjust with movements of the jaw and head while keeping the mask flush against the face. Frames with rigid chins, however, tended to be painful at the bridge of the nose and under the chin, especially when talking and moving the head to look up, as the frame did not conform to the changes in the face shape during these exercises. Both participants noted very little impact of the mask frame on breathability and were able to wear the frames over the masks/respirators for a minimum of 15 minutes without experiencing difficulty breathing.

Thermally molded masks and masks with elastic components are effective at maintaining good fit even when talking. However, for tasks that involve movement of the head up and down and bending over, masks with rigid chin pieces demonstrate less efficacy at maintaining good fit. These findings suggest that while thermally fitted mask frames and elastic components to a mask frame are effective at creating good fit, the location of the elastic components impacts the efficacy of the frame.

Limitations

While this study demonstrates that thermally molded masks and masks with elastic components fitted over certified surgical or procedural masks or a KN95 respirators can produce quantitative fit results comparable to N95 respirators, these findings do not suggest that using a frame is an adequate alternative to N95 respirators. To begin with, only two participants were tested for this study. Although the participants differed in their face size and features, frames should be further tested on a much greater variety of face sizes and shapes. More importantly, however, the frame-over-mask combination should be more rigorously tested for performance and comfort over a much longer period of time as testing conditions do not reflect actual working conditions and each combination of frame and mask or respirator was worn for no longer than 15 minutes.

Conclusion

The findings of this study suggest that thermally molded mask frames and mask frames with elastic components worn over certified surgical masks or KN95 respirators can produce fit factor scores comparable to N95 respirators. While all frames were successful at creating a good seal on at least one mask or respirator, frames with elastic chin pieces were more successful at creating a good seal when worn over a surgical mask or KN95 respirator, as well as when they were fitted over masks with more flexible materials.

While not intended to act an alternative to N95 respirators, these findings suggest that there is potential for thermally molded mask frames and mask frames with elastic components fitted over a certified surgical or procedural mask or a KN95 respirator to effectively reduce the number of penetrating particles from reaching the user. In times of acute supply shortages of FFRs, using thermoplastic fitting and mask frames with elastic components worn over certified masks may provide a temporary protective option to frontline personnel as they work in contaminated environments.

General Conclusion

Summary of the thesis

This thesis aimed to analyze the challenges of integrating maker-centered learning experiences (MCLEs) into K-12 formal education and to document factors that help teachers integrate such activities in their teaching. Although some potential challenges for integrating MCLEs into formal education settings have been identified previously in the literature, few studies to date have investigated more deeply the challenges teachers encounter, as well as the enablers that are helping teachers integrate MCLEs into their classroom (see Manuscript 1). Given the stark differences between maker activities in grassroots maker environments and the constraints of formal education settings, questions arise as to the types of challenges that teachers are encountering as they attempt to integrate MCLEs into their teaching practices and meet education demands, as well as the factors that are enabling teachers to integrate MCLEs in schools.

Therefore, this thesis aimed to answer the following research questions:

1) What challenges are highlighted in current research literature regarding teachers' efforts to integrate maker-centered learning experiences into formal K-12 educational settings?
2) What factors do experienced maker-centered educators perceive influence teachers' ability to integrate maker-centered learning experience into K-12 formal teaching?
    a. What are the perceived challenges faced by educators in K-12 formal education who have experience with maker-centered education, as they integrate maker-centered learning experiences into their teaching?

b. What factors do educators in K-12 formal education, who are familiar with maker-centered education, perceive as facilitating the integration of maker-centered learning experiences into their teaching?

3) What are the potential learning outcomes of an interdisciplinary maker-centered learning experience in the context of higher education?

Research Question 1

To answer Research Question 1, a scoping review of the research literature from 2002 to 2022 was conducted. The review of the literature identified 350 articles that studied MCLEs in K-12 formal education settings. Of these studies, 10 investigated the challenges of integrating MCLEs into K-12 formal education settings as their primary research goal, while 26 studies investigated these factors as a secondary research aim. An additional 69 articles mentioned challenges associated with integrating MCLEs into school settings, though this topic was not among their explicitly stated research aims.

The analysis of the 105 articles that identified challenges associated with integrating MCLEs into K-12 formal education settings revealed 10 areas of challenges: space and equipment, time and scheduling, curriculum and assessment, training and professional development, teacher support, educational leadership, student expectations and capabilities, teacher resistance, education culture, and funds. Although nearly a third of the included articles reported challenges associated with MCLEs, most were reported in passing with few details to understand the causes and consequences of the challenges. Furthermore, the results revealed that, in the cases where challenges were reported, the nature of the challenges appeared to differ depending on whether the educators reporting the challenges were experienced in the integration of MCLEs in their classroom or not. Of the studies that explicitly investigated the challenges of integrating MCLEs into schools, only 12 involved teachers experienced with MCLEs. These findings suggested that further research involving experienced educators with MCLEs is needed to better identify the challenges teachers encounter integrating MCLEs into K-12 schools and to better understand the causes and consequences of these challenges. This justified the need to address the second research question in manuscript 2.

Research Question 2

To answer Research Question 2, a qualitative-interpretive study with 21 educators with experience integrating MCLEs into formal education settings was conducted to document and analyze their perceptions of the challenges and enablers teachers encounter when integrating MCLEs into their teaching practice. The findings revealed similar categories of challenges reported in the literature, however participants provided a greater depth of understanding about the causes and consequence of the previously reported challenges as well as identified some challenges not already reported in the literature. In line with the literature, participants reported challenges related to space, equipment, time and scheduling, training and professional development, curriculum and standards, assessment, leadership, student expectations and capabilities, class size, teacher resistance, and funding. Challenge areas not previously well-explored in the literature were related to software and online tools, online resources, hiring regulations and position descriptions, and the influence unions have on what schools can ask of teachers. This is likely due to the current educational context in Québec, Canada and the United States and the evolving phenomenon of maker education in schools.

In addition to the challenges revealed in this study, participants also identified enablers and provided recommendations that they perceive may circumvent at least some of the identified challenges. For example, participants reported that although dedicated makerspaces in schools can present some challenges, these spaces are ultimately enablers as they provide teachers with a space to develop and conduct projects that they could not do in a standard classroom. Participants also reported that the access to digital fabrication technology is becoming less problematic as equipment is becoming increasingly available at affordable prices and is often available through public institutions like libraries and community organizations like local makerspaces. Additionally, these technologies are becoming easier to use, enabling both teachers new to MLCEs and young students to engage in maker activities. Free online software, tools, and resources were also reported to be very helpful to teachers in the preparation of MCLEs, the facilitation of these activities, and the assessment of learning through MCLEs as a greater variety of MCLEs can be undertaken at no additional cost and they offload some of the cognitive strain on teachers. Support from online and local maker communities, publicly funded educational organizations, school boards, and specialized staff were also reported to be essential enablers for the preparation and facilitation of MCLEs. Finally, support from good leadership and flexibility in leadership, funding, and scheduling was reported to be of considerable help to teachers as it allowed them to attempt innovative approaches to teaching, like MCLEs, that were not regularly practiced in their local context. This further supports the need to connect to a community and to engage in professional development.

Research Question 3

The third research question addressed the "so what" of maker education. Evidence from this thesis and elsewhere (Fernandez et al., 2020; Godhe et al., 2019; Harron et al., 2022; Heilala et al., 2020; Justice, 2015; Powell, 2021; M. J. Song, 2021; Thompson, 2021) suggests that integrating maker-centered education into formal education requires additional effort and time from already overloaded teachers and education leaders, as well as physical and digital resources. Given the sparsity of evidence for the long-term benefits of maker-centered education, some may dismiss this approach as too much effort for the return. However, as I expressed in Ryan's story at the beginning of this thesis, learning experiences that go beyond the textbook can be life changing. This is why I decided to put myself through an MCLE as a doctoral student in education.

At that time, the COVID-19 pandemic was in full swing, the university had closed and all courses were online, both makerspaces we had created with Education Makers were shut down and my research came to a complete halt. As we did not have an appreciation yet of how long the pandemic would last, and given my experience with making, I decided to participate in a project that had the potential to be very helpful to frontline healthcare workers during the mask shortages of the initial waves of the pandemic. Although I had not planned to participate in a project of this nature as a part of my doctoral work, it was a fortuitous opportunity as it quickly became evident to me how the intersection of my experience and the outcomes of the project, along with the resulting output (the research paper), offer compelling evidence that these types of learning experiences have significant potential. My reflections on the experience and research output, particularly in Manuscript 3, suggest that MCLEs can indeed provide learners with a rich, multifaceted learning experience. These experiences touch on many of the critical skills, such as creativity, problem-solving, collaboration, and adaptability, that are increasingly recognized as essential for thriving in both professional and civic contexts in the 21st century. This research highlights the importance of interdisciplinary MCLEs and its potential to transform formal education into something far more dynamic and impactful. This finding in itself justifies the need for a better approach to support teachers who navigate the daily struggles in formal education, and to offer working conditions, a support structure and professional development opportunities that help overcome the challenges of integrating MCLEs. The next section discusses the implications and the contributions of this thesis.

Implications and Contributions of the Thesis

The results of this thesis reveal that there are many challenges that teachers encounter when integrating MCLEs into formal education settings. Gaining insight into the challenges and enablers encountered by teachers when integrating MCLEs into their teaching practice is essential for comprehending why some educators struggle with this integration or opt not to incorporate MCLEs into their teaching approaches. Historically, teachers have been held accountable for the shortcomings of educational initiatives (Karimi et al., 2017; Saunders, 2022). However, a nuanced understanding of the working conditions they face could not only divert undue blame from teachers, but also pave the way for creating improved conditions, thereby enhancing the prospects of successful maker-centered education program. Given the many aforementioned potential affordances of maker-centered education, it is critical that the barriers preventing teachers from integrating MCLEs into their teaching be identified and addressed so that students can benefit from these experiences.

The outcomes of this thesis contribute considerably to our grasp of educators' lived experiences and the conditions they identify as impeding or supporting their efforts to integrate MCLEs into their classrooms. The goal is to guide and inform education leaders, policymakers, and interested educators about the factors influencing teachers so that necessary improvements can be implemented. To accomplish this, a framework of guiding questions has been created to help educators and school leadership lay the groundwork for the development and implementation of a maker-centered education program (see below and Appendix A). Additionally, to assist education leadership above the school level, a list of recommendations has been made to guide them in their decisions that influences schools and their ability to create and sustain successful maker-centered education programs (see below). The following sections present the proposed framework of questions and the proposed recommendations.

Guiding Questions Framework for Developing a Maker-Centered Education Program

As the findings of this thesis have demonstrated, there are a multitude of elements to consider when planning and implementing a maker-centered education program. Launching a successful maker-centered education program requires more than enthusiasm (though enthusiasm is key!), it also demands a clear roadmap to navigate the complexities of planning, developing, implementing, and sustaining such an initiative. Given the insights that emerged from the findings of this thesis, it was possible to formulate a framework of guiding questions that can assist education leaders and educators in the design and implementation of a maker-centered education program.

The Guiding Questions Framework for Developing a Maker-Centered Education Program is designed to help educators and leaders lay the groundwork for their maker-centered education program by addressing questions in seven key challenge areas during four distinct phases of program development and implementation (see Figure 10 for an overview of the structure of the framework with the overarching questions for each category, and Appendix A for the full list of guiding questions). The seven key areas emerge from the primary challenge areas identified in the findings of this thesis and span across all four phases of the program development process. They include: 1) leadership, 2) curriculum and assessment, 3) space, 4) material resources, 5) virtual resources, 6) human resources and, 7) training and professional development. Questions related to time and scheduling, funding, and education regulations are integrated into each of the seven key areas as they are relevant to each.

Figure 10

Structural Overview of the Guiding Questions Framework for Developing a Maker-Centered Education Program

Guiding Questions Framework for Developing a Maker-Centered Education Program

	Leadership	Curriculum & Assessment	Space	Material Resources	Virtual Resources	Human Resources	Training & PD
Planning	Who will take the lead in developing and implementing the program?	What are the learning objectives of the program?	Where will the MCLEs take place?	What resources for materials and equipment are available to the school? What restrictions may limit what materials can be used?	What virtual resources are available to the school? What restrictions may limit what platforms or software can be used?	Who will be available to help with the planning of the program? What restrictions may limit who can participate?	What training and PD is needed for those developing the program?
Development	How will leadership encourage the school community to embrace the program?	How can the program be designed to create inclusive, engaging, and effective learning experiences that reach the identified program objectives?	What preparation does the space need to be ready for the program?	What materials will best suit the program's needs? What material preparation will be required?	What virtual resources will best suit the program's needs? What preparation of the virtual resources will be required?	Who will be involved in the development of the program?	What training and PD is needed for those implementing the program?
Implementation	How will leadership help make necessary adjustments as the program is first implemented?	How will the curriculum be rolled out and adjusted based on initial feedback?	How will the space be introduced to staff and students? How will the space be managed (scheduling, maintenance, etc.)?	How will staff and students be introduced to the materials and assisted during the initial phase?	How will staff and students be introduced to the virtual resources and assisted during the initial phase?	Who will implement the program? Who will support those who are implementing the program?	How will staff be supported in applying their training in the classroom or makerspace?
Continuation	How will leadership help ensure the continuation of the program?	How will the program and program objectives be periodically reviewed and updated?	What will the space need to accommodate the growth of the program?	How will the material resources be maintained and updated as the program continues?	How will the virtual resources be maintained and updated as the program continues?	How will the program's long-term staffing needs be met?	How will staff be supported in on-going training as new needs arise?

The four phases of program development include Planning, Development, Implementation and, Continuation. The Planning phase focuses on defining the objectives of the maker-centered education program, assigning responsibility for its planning, and identifying key resources and constraints. Clearly defined objectives align stakeholder efforts, while early identification of resources and constraints ensures the program is realistic, sustainable, and suited to the school's context. The answers to the questions in this phase will determine the direction of the subsequent phases of the program. The Development phase aims to advance the program more concretely given the objectives, resources, and constraints that were identified in the Planning phase. This phase addresses the logistical and practical aspects of readiness, from equipping spaces to empowering educators with the skills they need. The Implementation phase focuses on the launch of the program and developing contingency plans to address unforeseen issues that may arise during the initial implementation of the program. Finally, the Continuation phase focuses on developing strategies for the long-term success of the program. Participants in this study noted that maker-centered education programs are often initially successful but fail to be sustainable in the long-term. Strategies to mitigate foreseeable long-term challenges can help ensure the success and longevity of the program.

School leaders and educators are encouraged to review and address as many of the questions as possible before making any actionable decisions as many of the questions are interrelated. While it may not be necessary to have all questions answered before taking any steps toward developing and implementing a program, it is recommended that all questions are at least reviewed so that they can be kept in mind as decisions are made during the process. By methodically working through each phase and reflecting on the guiding questions in the seven key areas, educators and leaders can better anticipate challenges and leverage opportunities to best ensure the success of their program.

Recommendations to education leaders based on the results of the thesis

The following are recommendations based on the challenges identified by the scoping review as reported in Manuscript 1, the challenges, enablers, and recommendations identified by the 21 participants of the study reported in Manuscript 2, and my personal experience of engaging in an MCLE as reported in the introduction to Manuscript 3. While these recommendations are based on the findings of this thesis, leaders should keep in mind that each school and school district is unique and what may work for many contexts may not be universally appropriate. Critically assessing each context based on its unique needs is strongly recommended.

Dedicated makerspaces: When possible, insist on dedicated makerspaces in schools. A dedicated makerspace can offer teachers a place to engage in noisy or messy activities with students using technology that is not ideal or possible to install in every classroom. Dedicated makerspaces also provide more space for students to move around as they are engaging in MCLEs and, if equipped with adequate storage, saves time by allowing teachers and students to store projects in progress between working sessions. Dedicated makerspaces also offer teachers a common space to collaborate on interdisciplinary MCLEs.

Equipment: Provide school leadership and teachers with guidelines and assistance in purchasing equipment to avoid unnecessarily expensive purchases and to ensure that learning goals will be met. Encourage the selection of user-friendly equipment that does not require extended periods of time for fabrication. Opt to purchase the same equipment across the district to simplify training needs and to ensure that multiple educators are able to use and maintain the equipment. Provide the necessary training to ensure that teachers are able to use the equipment in their MCLEs. Develop a system of sharing equipment across schools so that funds can be more efficiently used and a greater variety of equipment can be available to all schools.

Specialized teachers/personnel: Hire specialized teachers or personnel to lead maker-centered programs, maintain the makerspace, and troubleshoot equipment. Specialized teachers/personnel can also assist in teacher training, as well as support teachers as they engage in MCLEs with their students. If it is not possible to hire such personnel for each school, hire at least one at the district level to consult with teachers as needed. Modify hiring requirements for these positions to allow candidates who do not necessarily have teaching certification so that more expertise in maker activities can be present in schools and can work alongside teachers to enhance student experiences and learning.

Time and scheduling: Provide teachers with time for professional development, planning, and collaboration with other teachers in order for them to design meaningful MCLEs. Schedule longer periods in student schedules for MCLEs so that teachers have more time with students to engage in MCLEs.

Curriculum and assessment: Modify curricula to include competency-based requirements. Provide explanations of the expectations of student learning with examples to assist teachers in interpreting the requirements of the curriculum. Provide teachers with training when changes are made to the curriculum so that they are better able to implement it. Align assessment measures with the curriculum requirements and provide teachers with assessment tools and training to ensure they are able to assess student learning from MCLEs. Modify reporting methods so that the types of learning exhibited through MCLEs can be conveyed to parents and future academic institutions.

Online resources: Curate a well-organized online platform where teachers can share MCLE ideas and resources using a systematic structure that includes aspects like targeted curriculum content so that teachers can more efficiently find ideas that match their teaching needs. By allowing teachers to populate the platform, it not only shares the work of creating the content of the platform, but potentially encourages hesitant teachers to attempt MCLEs knowing other teachers have already done so.

Communities of practice: Support the development of virtual or in-person communities of practice where teachers can share information and strategies, co-develop MCLEs, and offer each other general support. These communities can be very helpful to teachers, particularly when maker programs are in their infancy at a given school or when teachers are working alone at their school to integrate MCLEs into their teaching practice.

Training and professional development: Support teachers in their training and PD for MCLEs by providing them with the time to enhance their skills and by allowing teachers to take PD that goes beyond introductory workshops. Provide continual support after the training and PD so that teachers can improve their practice gradually. Encourage or require teacher training programs to include training on the use of MCLEs in schools so that future teachers are formed with the mindset of including MCLEs into their teaching practice right from the start of their career. Provide school principals and other education leaders with training and PD. Given their important role in ensuring the success of MCLE integration into their schools, it is essential to dispel among leadership misconceptions about maker-centered education and help them better understand the needs of teachers as they integrate these approaches into their teaching.

In-class support: Reduce the demands on teachers in class while engaging in MCLEs with students. If it is not possible to reduce the ratio of students to teachers by reducing class sizes, then increase the support in the classroom by hiring a technician or assistant. If that is not possible, enlist older students or students with experience with maker activities or with equipment to help teachers as part of their volunteering requirements. Allow teachers to have volunteers from the community with and without experience with making to help during MCLEs. Provide access to online platforms or equipment like iPads for the purposes of keeping traces of student learning to reduce the demands on teachers' time and attention when facilitating MCLEs so that they can focus on students' immediate needs and return to assessing students' learning at a later time.

Promote a school culture conducive to MCLEs: Promote a school culture that allows teachers to experiment with novel pedagogical approaches without the fear of failure. Encourage both teachers and students to learn from failure rather than fearing failure and encourage pedagogical approaches with open-ended problem solving of all kinds so that students learn to think critically and independently and not rely on step-by-step instructions from teachers. Provide students with more hands-on experiences that encourage the development of fine motor skills and other concepts like measurement. Encourage teachers to strive for continual improvement out of a desire to grow as a professional and not out of fear of accountability measures.

Funding: Provide schools with some flexibility in their attribution of funding to novel pedagogical approaches. Plan budgets to include funding for training and PD and to cover the costs of consumable materials. Provide teachers with opportunities to apply for special funding to try novel projects and inform teachers of their availability.

Try it out: One of the most effective ways to gain a deeper appreciation of the learning potential of MCLEs is to try engaging in one yourself. This will not only help you gain insight into the types of support teachers may need in the classroom when engaging in these types of activities with students, but also demonstrate to you the learning potential these experiences can offer.

Limitations of the thesis and future directions

This thesis was exploratory in nature and aimed to identify the potential challenges and enablers influencing teachers as they endeavor to incorporate MCLEs into their teaching practices, as well as provide further details regarding the causes and consequences of the various challenges. Due to the study's overarching focus on uncovering the broad spectrum of challenges and enablers, a comprehensive examination of each was not feasible with participants. Consequently, further research is necessary to delve into each identified challenge to deepen understanding of the complex environment within which teachers work. This understanding is crucial for effectively dismantling barriers hindering teachers from integrating MCLEs into formal education settings.

Participants were drawn exclusively from Canada and the USA and, therefore, cannot be generalized to all educational settings. Given the global variations in school systems and local educational practices, the findings may not be applicable to other contexts. To gain a more nuanced understanding and address challenges and enablers in specific education systems or schools, dedicated research should be conducted in each unique context.

Additionally, though this study provides insights from the perspective of educators in varying roles, these insights are drawn from multiple contexts where the interactions of the various influences in the environment may differ. As quoted in the introduction of this dissertation, "classrooms are geographically and institutionally bounded places with physical features, cultural histories, and social roles" (Kervin & Comber, 2021, p. 80). Research approaches that combine participant insight and researcher observations are needed to better understand the complexity of the interaction of the various elements in a system that are influencing teachers as they attempt to integrate MCLEs into formal education contexts. By studying systems using theoretical frameworks like Cultural Historical Activity Theory and its associated research methods, a far deeper understanding of how elements of a system are influencing teachers and how any changes to the system may impact their practice could be developed.

This research also focused on MCLEs that involved making physical artefacts. There is evidence, however, that MCLEs that result in virtual artefacts (e.g. video games, VR/AR, digital books, etc.) may also benefit student learning (e.g. Ou & Chen, 2024). The types of challenges and facilitators that teachers encounter when engaging in MCLEs that result in virtual artefacts may differ from those encountered when engaging in MCLEs that involve physical materials.

Further research in this area could provide valuable insights into the challenges and facilitators associated with this type of MCLE.

Finally, as the world transitions into the era of AI (Davies & Seitamaa-Hakkarainen, 2024) new technologies like artificial intelligence may impact how teachers design and facilitate MCLEs in their classroom (e.g. Ou & Chen, 2024). AI may pose new challenges, yet at the same time reduce some barriers that teachers may currently face. For example, AI may assist teachers in quickly designing MCLE activities, creating code snippets for projects, and designing sample projects, but it may pose challenges as students may begin to overly rely on AI for solutions, rather than developing their problem-solving skills. While AI can be a powerful tool and should be used as such, research should be conducted to ensure that AI supports learning, or is used as a tool for work, rather than overtaking it, even in the context of MCLEs.

Conclusion

In the years since working with Ryan and discovering the Maker Movement and maker-centered education, I have become more-and-more convinced of maker-centered education's value for student learning and personal growth. For three years during my doctoral program, I worked with Ann-Louise Davidson to build a makerspace and run a maker program at a local after-school community centre for youth in an underserved neighbourhood. Although not in a school setting, I saw how the youth engaged in critical thinking and creative problem solving with the projects we engaged in. I saw youth who said they hated math put math concepts into practice as we built a roof-top garden and designed and built safety boxes to prevent theft of the centre's game consoles. I saw them learn about electronics and copyright regulations as they built a gaming table from Ikea tables and Raspberry Pis. I saw them grapple with basic physics as they learned how to create 3D designs and successfully 3D print inventions to make them rich

(We're still working on the rich part!). But most importantly, I heard youth from a neighbourhood where people are accustomed to being called "the scum of society" (stated by an 11-year-old from the centre) shout with joy when they succeeded at a challenge and proclaim themselves as inventors. I heard youth who once said they had no idea what they wanted to be when they grew up state, "When I become an engineer, I'm going to redesign that." I heard young women exclaim, "I never thought girls could do that. I can build things too!"

The youth at this centre were fortunate to have the opportunity to engage in these experiences with us. While I think programs like this are excellent and hold tremendous value for the youth that have access to them, I believe the integration of this type of experience in schools would give all children and youth the opportunity to benefit from its many affordances. Maker-centered education is not just about using new technology to teach in old ways. When done properly (i.e. not reducing it to a step-by-step, follow-the-instructions construction activity), it is a fundamentally different approach to teaching that not only holds promise for helping students to build essential skills for current civic and professional conditions, but also to help them grow into adults with the dispositions needed to confidently build a better future.

Thanks to the convergence of several important technological and human developments (e.g. the internet, desktop manufacturing, open-source technology and software), maker-centred education combines in a unique way pedagogical approaches that avant-garde educators have long-fought for in education. I firmly believe in this approach, but for teachers to be able to successfully integrate it into their teaching practice, the barriers they encounter need to be addressed and removed. Only then can teachers truly provide students with the opportunity to experience all that making has to offer.

References

42 CFR Part 84 Respiratory Protection Devices. (1995).

Ackermann, E. (2001). Piaget's Constructivism, Papert's Constructionism: What's the difference? *Future of Learning Group Publication*, *5*(3), 438–449.

Agency by Design. (2015). *Maker Centered Learning and the Development of Self*. Harvard Graduate School of Education. https://pz.harvard.edu/sites/default/files/Maker-Centered-Learning-and-the-Development-of-Self_AbD_Jan-2015.pdf

Ahmed, A., Zhong, Z., Suprono, M., Savignano, R., Riter, H., Oyoyo, U., Wilson, A., Reece, R., Kim, J., Cho, E.-H., Handysides, R., Richardson, P., Caruso, J., & Li, Y. (2021). Enhancement of peripheral seal of medical face masks using a 3-dimensional–printed custom frame. *The Journal of the American Dental Association*, *152*(7), 542–550. https://doi.org/10.1016/j.adaj.2021.03.011

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in Mathematics Teaching and Learning: Evidence From Learners' and Teachers' Gestures. *Journal of the Learning Sciences*, *21*(2), 247–286. https://doi.org/10.1080/10508406.2011.611446

Alimisi, R., Loukatos, D., Zoulias, E., & Alimisis, D. (2020). Introducing the Making Culture in Teacher Education: The eCraft2Learn Project. In M. Moro, D. Alimisis, & L. Iocchi (Eds.), *Educational Robotics in the Context of the Maker Movement* (pp. 27–41). Springer International Publishing. https://doi.org/10.1007/978-3-030-18141-3_3

Andersen, H. V., & Pitkänen, K. (2019). Empowering educators by developing professional practice in digital fabrication and design thinking. *International Journal of Child-Computer Interaction*, *21*, 1–16. https://doi.org/10.1016/j.ijcci.2019.03.001

Andersen, R., Mørch, A. I., & Litherland, K. T. (2022). Collaborative learning with block-based programming: Investigating human-centered artificial intelligence in education. *Behaviour & Information Technology*, *41*(9), 1830–1847. https://doi.org/10.1080/0144929X.2022.2083981

Anderson, A., Goeke, M., Simpson, A., & Maltese, A. V. (2019). Where Should Learners Struggle? *Connected Science Learning*, *1*(12). https://www.nsta.org/connected-science-learning/connected-science-learning-october-december-2019/where-should-learners

Anderson, Chris. (2012). *Makers: The New Industrial Revolution*. Random House.

Appendix A to §1910.134—Fit Testing Procedures (Mandatory) (2004).

Aragaw, T. A. (2020). Surgical face masks as a potential source for microplastic pollution in the COVID-19 scenario. *Marine Pollution Bulletin*, *159*, 111517. https://doi.org/10.1016/j.marpolbul.2020.111517

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology: Theory and Practice*, *8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Armijo, P. R., Markin, N. W., Nguyen, S., Ho, D. H., Horseman, T. S., Lisco, S. J., & Schiller, A. M. (2021). 3D printing of face shields to meet the immediate need for PPE in an anesthesiology department during the COVID-19 pandemic. *American Journal of Infection Control*, *49*(3), 302–308. https://doi.org/10.1016/j.ajic.2020.07.037

Assaf, D., Buchner, J., & Jud, A. (2019). *Evaluating a makerspace visiting program for schools at a university of teacher education*. https://doi.org/10.1145/3335055.3335057

Avendano-Uribe, B. E., Ojeda-Ramírez, S., & Perez-Baron, J. (2022). Resourcefulness, narratives, and identity in science, technology, engineering, arts and mathematics education: A perspective of makerspaces for rural communities in Colombia. *Frontiers in Education*, *7*. https://doi.org/10.3389/feduc.2022.1055722

Bahloul, A., Brochot, C., & Layne, B. (2021). Leakage versus Material Filtration in Barrier Facemask Efficiency. *Health*, *13*(4), Article 4. https://doi.org/10.4236/health.2021.134035

Bahloul, A., Mahdavi, A., Haghighat, F., & Ostiguy, C. (2014). Evaluation of N95 Filtering Facepiece Respirator Efficiency with Cyclic and Constant Flows. *Journal of Occupational and Environmental Hygiene*, *11*(8), 499–508. https://doi.org/10.1080/15459624.2013.877590

Bailey, H. T. (1906). The Arts and Crafts in Public Schools. *Journal of Education*, *64*(5), 135–138. https://doi.org/10.1177/002205740606400502

Bardzell, J., Bardzell, S., Lin, C., Lindtner, S., & Toombs, A. (2017). HCI's Making Agendas. *Foundations and Trends® in Human–Computer Interaction*, *11*(3), 126–200. https://doi.org/10.1561/1100000066

Bazzini, L. (2001). From Grounding Metaphors to Technological Devices: A Call for Legitimacy in School Mathematics. *Educational Studies in Mathematics*, *47*(3), 259–271. https://doi.org/10.1023/A:1015143318759

Becker, S., & Jacobsen, M. (2019). "How Can I Build a Model if I Don't Know the Answer to the Question?": Developing Student and Teacher Sky Scientist Ontologies Through Making. *International Journal of Science and Mathematics Education*, *17*, 31–48. https://doi.org/10.1007/s10763-019-09953-8

Becker, S., & Jacobsen, M. (2022). Exploring design discourses and liminality as features of professional learning in an elementary makerspace. *Information and Learning Sciences*, *123*(5/6), 233–251. https://doi.org/10.1108/ILS-08-2020-0192

Becker, S., & Jacobsen, M. (2023). A year at the improv: The evolution of teacher and student identity in an elementary school makerspace. *Teaching Education*, *34*(0), 1–18. https://doi.org/10.1080/10476210.2021.1978968

Beesoon, S., Behary, N., & Perwuelz, A. (2020). Universal masking during COVID-19 pandemic: Can textile engineering help public health? Narrative review of the evidence. *Preventive Medicine*, *139*, 106236. https://doi.org/10.1016/j.ypmed.2020.106236

Bennett, D., & Monahan, P. (2013). NYSCI design lab: No bored kids. In M. Honey & Kanter, DE (Eds.), *Design, Make, Play: Growing the Next Generation of STEM Innovators* (pp. 34–49). Routledge.

Bertrand, M. G., & Namukasa, I. K. (2020). STEAM education: Student learning and transferable skills. *Journal of Research in Innovative Teaching & Learning*, *13*(1), 43–56. https://doi.org/10.1108/JRIT-01-2020-0003

Bertrand, M. G., & Namukasa, I. K. (2022). Maker Education: Assessment, Documentation, and Sharing With a Wider Community. *International Journal of Online Pedagogy and Course Design*, *12*(3). https://doi.org/10.4018/IJOPCD.304083

Bevan, B. (2017). The promise and the promises of Making in science education. *Studies in Science Education*, *53*(1), 75–103. https://doi.org/10.1080/03057267.2016.1275380

Bevan, B., Gutwill, J. P., Petrich, M., & Wilkinson, K. (2015). Learning Through STEM-Rich Tinkering: Findings From a Jointly Negotiated Research Project Taken Up in Practice. *Science Education*, *99*(1), 98–120. https://doi.org/10.1002/sce.21151

Bevan, B., Ryoo, J. J., Vanderwerff, A., Wilkinson, K., & Petrich, M. (2020). "I See Students Differently": Following the Lead of Maker Educators in Defining What Counts as Learning. *Frontiers in Education*, *5*. https://www.frontiersin.org/articles/10.3389/feduc.2020.00121

Bharti, N., & Singh, S. (2020). COVID-19: The Use of 3D Printing to Address PPE Shortage during a Pandemic—A Safety Perspective. *ACS Chemical Health & Safety*, *27*(6), 335–340. https://doi.org/10.1021/acs.chas.0c00089

Bioplastic News. (n.d.). *Polylactic Acid or Polylactide (PLA)*. https://bioplasticsnews.com/polylactic-acid-or-polylactide-pla/

Blikstein, P. (2013). Digital Fabrication and 'Making' in Education: The Democratization of Invention. In Walter-Herrmann, J & Büching, C (Eds.), *FabLabs: Of Machines, Makers and Inventors* (pp. 203–222). Transcript Publishers.

Blikstein, P. (2018). Maker Movement in Education: History and Prospects. In M. J. de Vries (Ed.), *Handbook of Technology Education* (pp. 419–437). Springer International Publishing. https://doi.org/10.1007/978-3-319-44687-5_33

Blikstein, P., Kabayadondo, Z., Martin, A., & Fields, D. (2017). An Assessment Instrument of Technological Literacies in Makerspaces and FabLabs. *Journal of Engineering Education*, *106*(1), 149–175. https://doi.org/10.1002/jee.20156

Blikstein, P., & Valente, J. A. (2019). Authors' Response: Professional Development and Policymaking in Maker Education: Old Dilemmas and Familiar Risks. *Constructivist Foundations*, *14*(3), Article 3.

Blikstein, P., & Worsley, M. (2016). The Maker Movement: The last chance of progressive education? In Peppler, K. A., Halverson, Erica Rosenfeld, & Kafai, Y. B. (Eds.), *Makeology: Makerspaces as learning environments* (Vol. 2). Routledge.

Bolick, C. M., & Williams, W. A. (2021). Creative Citizens in the “Making”: Social Studies and Makerspaces. *Social Studies and the Young Learner*, *34*(2), 27–32.

Booth, A., Martyn-St James, M., Clowes, M., & Sutton, A. (2022). *Systematic Approaches to a Successful Literature Review* (3rd ed.). SAGE. https://www.torrossa.com/it/resources/an/5282271

Bosch, N. (2022). Design of the Participatory Learning Experience: Teachers’ new roles as designers of engaging design and maker-based learning experiences. *Interaction Design and Children*, 452–457. https://doi.org/10.1145/3501712.3535298

Bowen, G. A. (2009). Supporting a grounded theory with an audit trail: An illustration. *International Journal of Social Research Methodology*, *12*(4), 305–316. https://doi.org/10.1080/13645570802156196

Bower, M., Stevenson, M., Forbes, A., Falloon, G., & Hatzigianni, M. (2020). Makerspaces pedagogy – supports and constraints during 3D design and 3D printing activities in primary schools. *Educational Media International*, *57*(1), 1–28. https://doi.org/10.1080/09523987.2020.1744845

Braga, M., & Guttmann, G. (2019). The Knowledge Networks in a Makerspace: The Topologies of Collaboration. *International Journal of Science and Mathematics Education*, *17*(1), 13–30. https://doi.org/10.1007/s10763-019-09954-7

Brinkmann, S. (2018). The interview. In Denzin, NK & Lincoln, YS (Eds.), *Handbook of Qualitative Research* (5th ed., pp. 576–599). SAGE Publications.

Bull, G., Standish, N., Johnson, E., & Haj-Hariri, H. (2016). Educational Leadership and Planning for Digital Manufacturing in Schools. In R. Huang, Kinshuk, & J. K. Price (Eds.), *ICT in Education in Global Context: Comparative Reports of Innovations in K-12 Education* (pp. 173–194). Springer. https://doi.org/10.1007/978-3-662-47956-8_9

Campos, F., Soster, T., & Blikstein, P. (2019). Sorry, I Was in Teacher Mode Today: Pivotal Tensions and Contradictory Discourses in Real-World Implementations of School Makerspaces. *Proceedings of FabLearn 2019*, 96–103. https://doi.org/10.1145/3311890.3311903

Cao, F., Wu, S., & Stvilia, B. (2020). Library makerspaces in China: A comparison of public, academic, and school libraries. *Journal of Librarianship and Information Science*, *52*(4), 1209–1223. https://doi.org/10.1177/0961000620908657

Caoili, J. C., Vega, A., Santos, S., Bigalbal, J., & Cabujat, R. (2020). Fit testing of KN95 masks. *International Journal of Infection Control*, *16*(2), Article 2. https://doi.org/10.3396/ijic.v16i2.20359

Caratachea, M., & Monty Jones, W. (2024). Making in virtual reality environments: A case study of K-12 teachers’ perceptions on the educational affordances of virtual reality for maker-centered learning. *Educational Technology Research & Development*, *72*(1), 155–180. https://doi.org/10.1007/s11423-023-10290-5

Care, E., Kim, H., Vista, A., & Anderson, K. (2018). Education System Alignment for 21st Century Skills: Focus on Assessment. In *Center for Universal Education at The Brookings Institution*. Center for Universal Education at The Brookings Institution. https://eric.ed.gov/?id=ED592779

Castro-Alonso, J. C., Ayres, P., Zhang, S., de Koning, B. B., & Paas, F. (2024). Research Avenues Supporting Embodied Cognition in Learning and Instruction. *Educational Psychology Review*, *36*(1), 10. https://doi.org/10.1007/s10648-024-09847-4

Chen, C.-S., & Lin, J.-W. (2019). A Practical Action Research Study of the Impact of Maker-Centered STEM-PjBL on a Rural Middle School in Taiwan. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-019-09961-8

Chen, O., & Bergner, Y. (2021). "I know it when I see it": Employing reflective practice for assessment and feedback of reflective writing in a makerspace classroom. *Information and Learning Sciences*, *122*(3/4), 199–222. https://doi.org/10.1108/ILS-09-2020-0209

Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2017). *Maker-Centered Learning: Empowering Young People to Shape Their Worlds*. John Wiley & Sons.

Cohen, J., Jones, W. M., Smith, S., & Calandra, B. (2017). Makification: Towards a Framework for Leveraging the Maker Movement in Formal Education. *Journal of Educational Multimedia and Hypermedia*, *26*(3), 217–229.

Collins, C. E. (2018). *We Are All Makers: A Case Study of One Suburban District's Implementation of Makerspaces* [Ed.D., Northeastern University]. https://www.proquest.com/docview/2015177444/abstract/E9F4ABC9DE724168PQ/1

Cooper, D. W., Hinds, W. C., Price, J. W., Weker, R., & Yee, H. S. (1983). Common Materials for Emergency Respiratory Protection: Leakage Tests with a Manikin. *American Industrial Hygiene Association Journal*, *44*(10), 720–726. https://doi.org/10.1080/15298668391405634

Creese, B., Gonzalez, A., & Isaacs, T. (2016). Comparing international curriculum systems: The international instructional systems study. *The Curriculum Journal*, *27*(1), 5–23. https://doi.org/10.1080/09585176.2015.1128346

Creswell, J. W. (2012). *Educational Research* (4th ed.). Pearson.

Cross, A. (2017). Tinkering in k-12: An exploratory mixed methods study of makerspaces in schools as an application of constructivist learning [Ed.D., Pepperdine University]. In *ProQuest Dissertations and Theses*. https://www.proquest.com/docview/1906299377/abstract/203DF8860A89400CPQ/1

Das, M. (2020). FULL STEAM AHEAD: HANDS-ON ELEMENTARY EDUCATION and PERSISTENCE during COVID-19. *Proceedings of the ASME 2020 International Mechanical Engineering Congress and Exposition IMECE2020*, *9*. https://doi.org/10.1115/IMECE2020-24290

Daughrity, L. A. (2022). *A single case study of a makerbus in K-12 education.* (Vol. 83, p. No Pagination Specified). ProQuest Information & Learning.

Davidson, A.-L. (2018). How can makerspaces heighten student engagement? *EdCan Network*. https://www.edcan.ca/articles/makerspaces-heighten-student-engagement/

Davidson, A.-L., & Sanabria, J. (2018). Does your school have the maker fever?: An experiential learning approach to developing maker competencies. *The Medium*. https://medium.com/@annlouise.davidson/the-meaning-of-maker-culture-for-education-in-rural-areas-and-marginalized-neighbourhoods-bca667575e2f

Davies, S., & Seitamaa-Hakkarainen, P. (2024). Research on K-12 maker education in the early 2020s – a systematic literature review. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-024-09921-6

Davies, S., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2023). Idea generation and knowledge creation through maker practices in an artifact-mediated collaborative invention project. *Learning, Culture and Social Interaction*, *39*, 100692. https://doi.org/10.1016/j.lcsi.2023.100692

Davis, S. J., Scott, J. A., Wohlwend, K. E., & Pennington, C. M. (2021). Bringing Joy to School: Engaging K-16 Learners through Maker Literacies and Playshops. *Teachers College Record*, *123*(3). https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1349777&site=ehost-live&scope=sitehttp://dx.doi.org/10.1177/016146812112300309

Deci, E. L. & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior*. Plenum.

Denzin, N. K., & Lincoln, Y. S. (2018). Introduction: The discipline and practice of qualitative research. In Denzin, Norman K. & Lincoln, Yvonna S. (Eds.), *The SAGE Handbook of Qualitative Research* (5th ed., pp. 1–26). Sage Publications, Inc.

Digital action plan for education and higher education. (2018). Ministère de l'Éducation et de l'Enseignement supérieur (MEES). http://www.education.gouv.qc.ca/fileadmin/site_web/documents/ministere/PAN_Plan_action_VA.pdf

Dixon, C., & Martin, L. (2017). Make to Relate: Analyzing Narratives of Community Practice. *Cognition and Instruction*, *35*(2), 103–124. https://doi.org/10.1080/07370008.2017.1282484

Dougherty, Dale. (2013). The maker mindset. In M. Honey & Kanter, DE (Eds.), *Design, Make, Play: Growing the Next Generation of STEM Innovators* (pp. 7–11). Routledge.

Dougherty, Dale. (2016). *Dougherty, D. (2016). Free to make: How the maker movement is changing our schools, our jobs, and our minds*. North Atlantic Books.

Dousay, T. A. (2017). Defining and Differentiating the Makerspace. *Educational Technology*, *57*(2), 69–74.

Drodge, E. N., & Reid, D. A. (2000). Embodied Cognition and the Mathematical Emotional Orientation. *Mathematical Thinking and Learning*, *2*(4), 249–267. https://doi.org/10.1207/S15327833MTL0204_2

Duda, S., Hartig, S., Hagner, K., Meyer, L., Intriago, P. W., Meyer, T., & Wessling, H. (2020). Potential Risks of A Widespread Use of 3D Printing for The Manufacturing of Face Masks During the Severe Acute Respiratory Syndrome Coronavirus 2 Pandemic. *Journal of 3D Printing in Medicine*, *4*(3), 135–147. https://doi.org/10.2217/3dp-2020-0014

Duponsel, N., Brochot, C., Bahloul, A., Layne, B., & Davidson, A.-L. (2022). Improving surgical mask efficacy with 3D-printed frames. *Proceedings of the 20th Conference of the International Society for Respiratory Protection*. 20th Conference of the International Society for Respiratory Protection.

Duponsel, N., & Davidson, A.-L. (in preparationa). *Educator perceptions of the challenges and enablers for the integration of maker-centered learning experiences in K-12 formal education settings*.

Duponsel, N., & Davidson, A.-L. (in preparationb). *The challenges of integrating maker-centered learning experiences into K-12 formal education settings: A scoping review*.

Education Commission. (2016). *The learning generation: Investing in education for a changing world | VOCEDplus, the international tertiary education and research database*. Education Commission. https://www.voced.edu.au/content/ngv:81867

Erickson, M. M., Richardson, E. S., Hernandez, N. M., Bobbert, D. W., Gall, K., & Fearis, P. (2020). Helmet Modification to PPE With 3D Printing During the COVID-19 Pandemic at Duke University Medical Center: A Novel Technique. *The Journal of Arthroplasty*, *35*(7, Supplement), S23–S27. https://doi.org/10.1016/j.arth.2020.04.035

Eriksson, E., Heath, C., Ljungstrand, P., & Parnes, P. (2018). Makerspace in school—Considerations from a large-scale national testbed. *International Journal of Child-Computer Interaction*, *16*, 9–15. https://doi.org/10.1016/j.ijcci.2017.10.001

Fan, S.-C. (2022). An importance–performance analysis (IPA) of teachers' core competencies for implementing maker education in primary and secondary schools. *International Journal of Technology and Design Education*, *32*(2), 943–969. https://doi.org/10.1007/s10798-020-09633-7

Fancsali, C., Mirakhur, Z., Klevan, S., & Rivera-Cash, E. (2019). "Making" Science Relevant for the 21st Century: Early Lessons from a Research-Practice Partnership. *Proceedings of FabLearn 2019*, 136–139. https://doi.org/10.1145/3311890.3311910

Fattizzo, T., & Vania, P. (2021). Montessori Creativity Space: Making a Space for Creativity. In *Makers at School, Educational Robotics and Innovative Learning Environments* (Vol. 240, p. 117). https://doi.org/10.1007/978-3-030-77040-2_15

Fernandez, C., Hochgreb-Haegele, T., & Blikstein, P. (2020). Toward a sustainable model for maker education in public education: Teachers as co-designers in an implementation of educational makerspaces. *Proceedings of the FabLearn 2020 - 9th Annual Conference on Maker Education*, 46–53. https://doi.org/10.1145/3386201.3386218

Flick, U. (2018). Triangulation. In Denzin, N. K. & Lincoln, Yvonna S. (Eds.), *The SAGE Handbook of Qualitative Research* (5th ed., pp. 444–462). SAGE Publications.

Flores, C. (2016). Alternative Assessments and Feedback in a "Maker" Classroom. In P. Blikstein, S. Martinez, & H. Pang (Eds.), *Meaningful Making: Projects and Inspirations for Fab Labs and Makerspaces* (pp. 28–33). Constructing Modern Knowledge Press.

Forbes, A., Falloon, G., Stevenson, M., Hatzigianni, M., & Bower, M. (2021). An Analysis of the Nature of Young Students' STEM Learning in 3D Technology-Enhanced Makerspaces. *Early Education and Development*, *32*(1), 172–187.

Fox, S. (2014). Third Wave Do-It-Yourself (DIY): Potential for prosumption, innovation, and entrepreneurship by local populations in regions without industrial manufacturing infrastructure. *Technology in Society*, *39*, 18–30. https://doi.org/10.1016/j.techsoc.2014.07.001

Framework for 21st century learning definitions. (2019). Battelle for Kids. https://www.battelleforkids.org/insights/p21-resources/

Fulfilling the Maker Promise: Year One. (2017). Maker Ed & Digital Promise. https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=ED614385&site=ehost-live&scope=site

Fulfilling the Maker Promise: Year Two. (2018). *Digital Promise*. https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=ED614386&site=ehost-live&scope=site

Fyfe, E. R., McNeil, N. M., Son, J. Y., & Goldstone, R. L. (2014). Concreteness Fading in Mathematics and Science Instruction: A Systematic Review. *Educational Psychology Review*, *26*(1), 9–25. https://doi.org/10.1007/s10648-014-9249-3

Germonpre, P., Van Rompaey, D., & Balestra, C. (2020). Evaluation of Protection Level, Respiratory Safety, and Practical Aspects of Commercially Available Snorkel Masks as Personal Protection Devices Against Aerosolized Contaminants and SARS-CoV2. *International Journal of Environmental Research and Public Health*, *17*(12), Article 12. https://doi.org/10.3390/ijerph17124347

Gierthmuehlen, M., Kuhlenkoetter, B., Parpaley, Y., Gierthmuehlen, S., Köhler, D., & Dellweg, D. (2020). Evaluation and discussion of handmade face-masks and commercial diving-equipment as personal protection in pandemic scenarios. *PLOS ONE*, *15*(8), e0237899. https://doi.org/10.1371/journal.pone.0237899

Giusti, T., & Bombieri, L. (2020). Learning inclusion through makerspace: A curriculum approach in Italy to share powerful ideas in a meaningful context. *The International Journal of Information and Learning Technology*, *37*(3), 73–86. https://doi.org/10.1108/IJILT-10-2019-0095

Glaser, B. G., & Strauss, A. L. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Aldine Publishing Company.

Glesne, C. (2011). *Becoming Qualitative Researchers: An Introduction* (4th ed.). Pearson Education.

Godhe, A.-L., Lilja, P., & Selwyn, N. (2019). Making sense of making: Critical issues in the integration of maker education into schools. *Technology, Pedagogy and Education*, *28*(3), 317–328. https://doi.org/10.1080/1475939X.2019.1610040

Grand-Clement, S., Devaux, A, Belanger, J, & Manville, C. (2017). Digital Learning: Education and Skills in the Digital Age. In *RAND Europe*. RAND Europe. https://www.rand.org/pubs/conf_proceedings/CF369.html

Gutwill, J. P., Hido, N., & Sindorf, L. (2015). Research to Practice: Observing Learning in Tinkering Activities. *Curator: The Museum Journal*, *58*(2), 151–168. https://doi.org/10.1111/cura.12105

Hachey, A. C., An, S. A., & Golding, D. E. (2022). Nurturing Kindergarteners' Early STEM Academic Identity Through Makerspace Pedagogy. *Early Childhood Education Journal*, *50*(3), 469–479. https://doi.org/10.1007/s10643-021-01154-9

Halpern, E.S. (1983). *Auditing naturalistic inquiries: The development and application of a model.* Indiana University.

Halverson, E. R., & Sheridan, K. (2014a). The Maker Movement in Education. *Harvard Educational Review*, *84*(4), 495–504. https://doi.org/10.17763/haer.84.4.34j1g68140382063

Halverson, E. R., & Sheridan, K. M. (2014b). The Maker Movement in Education. *Harvard Educational Review*, *84*(4), 495–504.

Hansen, A. K., McBeath, J. K., & Harlow, D. B. (2019). No Bones about It: How Digital Fabrication Changes Student Perceptions of Their Role in the Classroom. *Journal of Pre-College Engineering Education Research*, *9*(1), 95–116.

Hao, W., Parasch, A., Williams, S., Li, J., Ma, H., Burken, J., & Wang, Y. (2020). Filtration performances of non-medical materials as candidates for manufacturing facemasks and respirators. *International Journal of Hygiene and Environmental Health*, *229*, 113582. https://doi.org/10.1016/j.ijheh.2020.113582

Harron, J. R., Jin, Y., Hillen, A., Mason, L., & Siegel, L. (2022). Maker Math: Exploring Mathematics through Digitally Fabricated Tools with K–12 In-Service Teachers. *Mathematics*, *10*(17), Article 17. https://doi.org/10.3390/math10173069

Hartikainen, H., Ventä-Olkkonen, L., Kinnula, M., & Iivari, N. (2023). "We were proud of our idea": How teens and teachers gained value in an entrepreneurship and making project. *International Journal of Child-Computer Interaction*, *35*, 100552. https://doi.org/10.1016/j.ijcci.2022.100552

Hatch, M. (2014). *The maker movement manifesto*. McGraw-Hill.

Heilala, V., Saarela, M., Reponen, S., & Kärkkäinen, T. (2020). Let Me Hack It: Teachers' Perceptions About 'Making' in Education. In A. El Moussati, K. Kpalma, M. Ghaouth Belkasmi, M. Saber, & S. Guégan (Eds.), *Advances in Smart Technologies Applications and Case Studies* (pp. 509–518). Springer International Publishing. https://doi.org/10.1007/978-3-030-53187-4_55

Henderson, T. G., Vogel, P., & Campagna, M. (2017). MakerSpace to Capstone: Plans and Progress Towards a Integrated K-12 Design Thinking and STEAM Curriculum. *International Journal of Designs for Learning*, *8*(1), 22–38.

Heredia, S. C., & Tan, E. (2021). Teaching & learning in makerspaces: Equipping teachers to become justice-oriented maker-educators. *Journal of Educational Research*, *114*(2), 171–182. https://doi.org/10.1080/00220671.2020.1860871

Herro, D., Quigley, C., & Abimbade, O. (2021). Assessing elementary students' collaborative problem-solving in makerspace activities. *Information and Learning Sciences*, *122*(11/12), 774–794. https://doi.org/10.1108/ILS-08-2020-0176

Hira, A., & Hynes, M. M. (2018). People, Means, and Activities: A Conceptual Framework for Realizing the Educational Potential of Makerspaces. *Education Research International*, *2018*, e6923617. https://doi.org/10.1155/2018/6923617

Honey, M., & Kanter, D. E. (Eds.). (2013). *Design, Make, Play: Growing the Next Generation of STEM Innovators*. Routledge.

Hughes, J. M. (2017). Digital making with "At-Risk" youth. *The International Journal of Information and Learning Technology*, *34*(2), 102–113. https://doi.org/10.1108/IJILT-08-2016-0037

Hughes, J., & Morrison, L. (2018). The Use of E-Textiles in Ontario Education—ProQuest. *Canadian Journal of Education*, *41*(1), 256–384.

Hughes, J., Morrison, L., & Robb, J. (2022). Making STEAM-Based Professional Learning: A Four-Year Design-Based Research Study. *Canadian Journal of Learning and Technology*, *47*(3). https://doi.org/10.21432/cjlt27915

Hughes, J., Robb, J. A., Hagerman, M. S., Laffier, J., & Cotnam-Kappel, M. (2022). What makes a maker teacher? Examining key characteristics of two maker educators. *International Journal of Educational Research Open*, *3*. https://doi.org/10.1016/j.ijedro.2021.100118

Hughes, J., Thompson, S., & Morrison, L. (2022). Inquiry-Based Learning Through Making. In J. Hughes (Ed.), *Making, Makers, Makerspaces: The Shift to Making in 20 Schools* (pp. 21–33). Springer International Publishing. https://doi.org/10.1007/978-3-031-09819-2_2

Humburg, M., Tan, V., Maltese, A. V., Simpson, A., & Danish, J. A. (2021). Making for learning: How graduate students discuss and design for maker-focused pedagogy. *Information and Learning Sciences*, *122*(3/4), 147–170. https://doi.org/10.1108/ILS-08-2020-0191

Hunsinger, J., & Schrock, A. (2016). The democratization of hacking and making. *New Media & Society*, *18*(4), 535–538. https://doi.org/10.1177/1461444816629466

Ioannou, A., & Gravel, B. E. (2024). Trends, tensions, and futures of maker education research: A 2025 vision for STEM+ disciplinary and transdisciplinary spaces for learning through making. *Educational Technology Research and Development*, *72*(1), 1–14. https://doi.org/10.1007/s11423-023-10334-w

Ishack, S., & Lipner, S. R. (2021a). Use of 3D Printing to Support COVID-19 Medical Supply Shortages: A Review. *Journal of 3D Printing in Medicine*, *5*(2), 83–95. https://doi.org/10.2217/3dp-2020-0031

Ishack, S., & Lipner, S. R. (2021b). Use of 3D printing to support COVID-19 medical supply shortages: A review. *Journal of 3D Printing in Medicine*, *5*(2), 83–95. https://doi.org/10.2217/3dp-2020-0031

Ito, M, Baumer, S, Bittanti, M, Boyd, D, Cody, R, Herr-Stephenson, B, & Tripp, L. (2010). *Hanging out, messing around, and geeking out: Kids living and learning with new media*. MIT Press.

Iwata, M., Pitkänen, K., Laru, J., & Mäkitalo, K. (2020). Exploring Potentials and Challenges to Develop Twenty-First Century Skills and Computational Thinking in K-12 Maker Education. *Frontiers in Education*, *5*. https://www.frontiersin.org/articles/10.3389/feduc.2020.00087

Jaatinen, J., & Lindfors, E. (2019). Makerspaces for Pedagogical Innovation Processes: How Finnish Comprehensive Schools Create Space for Makers. *Design and Technology Education*, *24*(2). https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1221415&site=ehost-live&scope=site

Jin, Y., Martin, L., Stephens, S., & Carrier, A. M. (2020). Drive Student Success: Designing a MakerBus to Bring Standard-Based Making and Technology Activities into K-12 Schools. *International Journal of Designs for Learning*, *11*(2), 130–141.

Jocius, R., Albert, J., Andrews, A., & Blanton, M. (2020). A study in contradictions: Exploring standards-based making in elementary classrooms. *The Journal of Educational Research*, *113*(5), 396–403. https://doi.org/10.1080/00220671.2020.1838409

Jones, W. M., Smith, S., & Cohen, J. (2017). Preservice Teachers' Beliefs About Using Maker Activities in Formal K-12 Educational Settings: A Multi-Institutional Study. *Journal of Research on Technology in Education*, *49*(3–4), 134–148. https://doi.org/10.1080/15391523.2017.1318097

Jun, W. (2018). A Study on Development of Selection Standards of Maker Education Teaching Aids. *2018 International Conference on Information and Communication Technology Convergence (ICTC)*, 273–278. https://doi.org/10.1109/ICTC.2018.8539704

Justice, S. B. (2015). *Learning to teach in the digital age: Digital materiality and maker paradigms in schools* [Ed.D.C.T., Teachers College, Columbia University]. https://www.proquest.com/docview/1690497932/abstract/8FE74E3F08FF4951PQ/1

Kafai, Y. B., & Vasudevan, V. (2015). Constructionist gaming beyond the screen: Middle school students' Crafting and computing of touchpads, Board games, And controllers. *WiPSCE '15*, *09-11-November-2015*, 49–54. https://doi.org/10.1145/2818314.2818334

Kafai, Y., Fields, D., & Searle, K. (2014). Electronic Textiles as Disruptive Designs: Supporting and Challenging Maker Activities in Schools. *Harvard Educational Review*, *84*(4), 532–556. https://doi.org/10.17763/haer.84.4.46m7372370214783

Karimi, A., Worthy, P., McInnes, P., Bodén, M., Matthews, B., & Viller, S. (2017). The community garden hack: Participatory experiments in facilitating primary school teacher's appropriation of technology. *Proceedings of the 29th Australian Conference on Computer-Human Interaction*, 143–151. https://doi.org/10.1145/3152771.3152787

Kendrick, M., Namazzi, E., Becker-Zayas, A., & Tibwamulala, E. N. (2020). Closing the HIV and AIDS "Information Gap" Between Children and Parents: An Exploration of Makerspaces in a Ugandan Primary School. *Education Sciences*, *10*(8), 193. https://doi.org/10.3390/educsci10080193

Kervin, L., & Comber, B. (2021). Re-configuring the early childhood classroom as a multimodal makerspace. In *Maker literacies and maker identities in the digital age: Learning and playing through modes and media.* (pp. 74–93). Routledge/Taylor & Francis Group. https://doi.org/10.4324/9781003049241-5

Kim, J.-Y., Chung, H., Jung, E. Y., Kim, J.-O., & Lee, T.-W. (2020). Development and Application of a Novel Engineering-Based Maker Education Course for Pre-Service Teachers. *Education Sciences*, *10*(5), Article 5. https://doi.org/10.3390/educsci10050126

Kim, J.-Y., Murai, Y., & Chang, S. (2021). Implementation of embedded assessment in maker classrooms: Challenges and opportunities. *Information and Learning Science*, *12*(3–4), 292–314. https://doi.org/10.1108/ILS-08-2020-0188

Kim, Y. J., Murai, Y., & Chang, S. (2020, January 19). *Embedded Assessment Tools for Maker Classrooms: A Design-Based Research Approach*. https://doi.org/10.35542/osf.io/4h3n7

Kjartansdóttir, S. H., Hjartarson, T., & Pétursdóttir, S. (2020). Of Women Tech Pioneers and Tiny Experts of Ingenuity. *Frontiers in Education*, *5*. https://www.frontiersin.org/articles/10.3389/feduc.2020.00160

Koh, K., Ge, X., & Petrella, J. B. (2022). Librarian-Teacher Co-Teaching and the Role of School Librarians in Facilitating Inquiry and Maker Learning. *School Library Research*, *25*. https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1348949&site=ehost-live&scope=site

Kohn, A. (2010, January). Getting rid of grades: Case studies. *Alfie Kohn*. https://www.alfiekohn.org/blogs/getting-rid-grades-case-studies/?print=print

Kongkiatkamon, S., Wongkornchaowalit, N., Kiatthanakorn, V., Tonphu, S., & Kunanusont, C. (2022). Quantitative Fit Test of a 3D Printed Frame Fitted Over a Surgical Mask: An Alternative Option to N95 Respirator. *International Journal of Dentistry*, *2022*(1), 1270106. https://doi.org/10.1155/2022/1270106

Koole, M., Anderson, K., & Wilson, J. (2020). Unleashing the Learners: Teacher Self-Efficacy in Facilitating School-Based Makerspaces. *In Education*, *26*(1), 63–84. https://doi.org/10.37119/ojs2020.v26i1.452

Koole, M., Epp, J., Anderson, K., Hepner, R., & Hossain, M. (2017). Designing a Makerspace for Pre- and In-Service Teachers. *International Journal of Designs for Learning*, *8*(1). https://doi.org/10.14434/ijdl.v8i1.22703

Kumpulainen, K., & Kajamaa, A. (2021). The sociomaterial ecology of emotions in a school's makerspace. In *Maker literacies and maker identities in the digital age: Learning and* *playing through modes and media.* (pp. 149–166). Routledge/Taylor & Francis Group. https://doi.org/10.4324/9781003049241-9

Kumpulainen, K., & Kajamaa, A. (2022). The transformative potential of school-based makerspaces: Novel designs in educational practice. In *Digital learning and collaborative practices: Lessons from inclusive and empowering participation with emerging technologies.* (pp. 175–184). Routledge/Taylor & Francis Group.

Kurti, R. S., Kurti, D. L., & Fleming, L. (2014). The philosophy of educational makerspaces: Part 1 of making an educational makerspace. *Teacher Librarian*, *41*(5), 8–11.

Kuznetsov, S., & Paulos, E. (2010). Rise of the expert amateur: DIY projects, communities, and cultures. *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, 295–304. https://doi.org/10.1145/1868914.1868950

Lacy, J. E. (2017). *A case study of a high school fab lab.* (Vol. 78, p. No Pagination Specified). ProQuest Information & Learning.

Lahana, L. I. (2016). The Tech Cafe, a Social Action Makerspace: Middle School Students as Change Agents [ProQuest LLC]. In *ProQuest LLC*. https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=ED589865&site=ehost-live&scope=sitehttp://gateway.proquest.com/openurl?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&res_dat=xri:

Lakind, A., Willett, R., & Halverson, E. R. (2019). Democratizing the Maker Movement: A Case Study of One Public Library System's Makerspace Program. *Reference & User Services Quarterly*, *58*(4), 235–245.

LaMore, R., Root-Bernstein, R., Root-Bernstein, M., Schweitzer, J. H., Lawton, J. L., Roraback, E., Peruski, A., VanDyke, M., & Fernandez, L. (2013). Arts and Crafts: Critical to Economic Innovation. *Economic Development Quarterly*, *27*(3), 221–229. https://doi.org/10.1177/0891242413486186

Laprade, M. (2021). *Constructionism 3.0: The emergence of digital fabrication learning in K-12 educational technology: A four-decade narrative history of objects-to-think-with*. https://www.academia.edu/72254431/Constructionism_3_0_The_emergence_of_digital_fabrication_learning_in_K_12_educational_technology_A_four_decade_narrative_history_of_objects_to_think_with

Lee, C. E., Arnett, H., Samuel, N., Bievenue, L., Ginger, J., & Israel, M. (2020). Towards an Inclusive Model of Makerspace Educator Professional Development: Implications for Students with Disabilities and At-Risk. *FabLearn '20*, 102–105. https://doi.org/10.1145/3386201.3386209

Lee, C.-Y., Peng, L.-W., & Klemm, A. (2021). Effective Makerspaces in STEAM Secondary Education: What Do the Professionals Think? *Excellence in Education Journal*, *10*(2), 35–50.

Lee, C. eun, Samuel, N., Israel, M., Arnett, H., Bievenue, L., Ginger, J., & Perry, M. (2020). Understanding Instructional Challenges and Approaches to Including Middle School Students with Disabilities in Makerspace activities: A cross-case analysis. *Proceedings of the FabLearn 2020 - 9th Annual Conference on Maker Education*, 26–33. https://doi.org/10.1145/3386201.3386208

Leinonen, T., Virnes, M., Hietala, I., & Brinck, J. (2020). 3D Printing in the Wild: Adopting Digital Fabrication in Elementary School Education. *International Journal of Art and Design Education*, *39*(3), 600–615. https://doi.org/10.1111/jade.12310

Leonard, S. N., Repetto, M., Kennedy, J. P., Tudini, E., & Fowler, S. (2022). Designing Maker initiatives for educational inclusion. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-022-09754-1

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. SAGE.

Lindsey, B., & DeCillis, M. D. (2017). *The maker movement and k-12 education: Current status and opportunities for engagement in California*. California Council on Science and Technology. https://ccst.us/wp-content/uploads/2017K12makers-1.pdf

Liu, J., Ma, J., Ahmed, I. I., & Varma, D. K. (2021). Effectiveness of a 3D-printed mask fitter in an Ophthalmology setting during COVID-19. *Canadian Journal of Ophthalmology*, *57*(3), 161–166. https://doi.org/10.1016/j.jcjo.2021.03.004

Liu, S., & Li, C. (2023). Promoting design thinking and creativity by making: A quasi-experiment in the information technology course. *Thinking Skills and Creativity*, *49*, 101335. https://doi.org/10.1016/j.tsc.2023.101335

Locke, A. (2024, March 18). Makerspace slated to close due to budget cuts. *The Cardinal TImes*. https://cardinaltimes.org/23232/news/makerspace-slated-to-close-due-to-budget-cuts/

Lockley, J. (2016). Teachers Designing Classroom Curriculum through the Lens of Cultural-Historical Activity Theory. In D. S. P. Gedera & P. J. Williams (Eds.), *Activity theory in education: Research and practice* (pp. 183–198). Sense Publishers. https://brill.com/display/book/edcoll/9789463003872/BP000013.xml

Love, T. S. (2022). Examining the Influence That Professional Development Has on Educators' Perceptions of Integrated STEM Safety in Makerspaces. *Journal of Science Education and Technology*, *31*(3), 289–302. https://doi.org/10.1007/s10956-022-09955-2

Lubrano, C., Matrone, G. M., Forro, C., Jahed, Z., Offenhaeusser, A., Salleo, A., Cui, B., & Santoro, F. (2020). MRS Communications. *MRS Bulletin*, *45*(10), 864–865. https://doi.org/10.1557/mrs.2020.261

Maker Faires at a Glance. (2024). Maker Faire. https://makerfaire.com/?utm_source=make&utm_medium=universalnav&utm_campaign=makerfaire&utm_content=launch

Makowski, K., & Okrasa, M. (2019). Application of 3D scanning and 3D printing for designing and fabricating customized half-mask facepieces: A pilot study. *Work*, *63*(1), 125–135. https://doi.org/10.3233/WOR-192913

Manero, A., Smith, P., Koontz, A., Dombrowski, M., Sparkman, J., Courbin, D., & Chi, A. (2020). Leveraging 3D Printing Capacity in Times of Crisis: Recommendations for COVID-19 Distributed Manufacturing for Medical Equipment Rapid Response. *International Journal of Environmental Research and Public Health*, *17*(13), Article 13. https://doi.org/10.3390/ijerph17134634

Marsh, J., Kumpulainen, K., Nisha, B., Velicu, A., Blum-Ross, A., Hyatt, D., Jónsdóttir, S., Levy, R., Little, S., Marusteru, G., Ólafsdóttir, M., Sandvik, K., Scott, F., Thestrup, K., Arnseth, H. C., Dýrfjörð, K., Jornet, A., Kjartansdóttir, S. H., Pahl, K., … Thorsteinsson, G. (2017). *Makerspaces in the early years: A literature review*. University of Sheffield.

Marshall, J. A., & Harron, J. R. (2018). Making Learners: A Framework for Evaluating Making in STEM Education. *Interdisciplinary Journal of Problem-Based Learning*, *12*(2).

https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1182524&site=ehost-live&scope=sitehttps://doi.org/10.7771/1541-5015.1749

Martin, L. (2015). The Promise of the Maker Movement for Education. *Journal of Pre-College Engineering Education Research (J-PEER)*, *5*(1), 30–39. https://doi.org/10.7771/2157-9288.1099

Martinez, S. L., & Stager, G. S. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Constructing Modern Knowledge Press.

Matbase. (n.d.). *Material Properties Database*. https://web.archive.org/web/20120210194852/http://www.matbase.com/material/polymers/agrobased/polylactic-acid-pla/properties

Material Properties Database. (n.d.). Matbase. https://web.archive.org/web/20120210194852/http://www.matbase.com/material/polymers/agrobased/polylactic-acid-pla/properties.

Mays, N., Roberts, E., & Popay, J. (2001). Synthesising research evidence. In N. Fulop, P. Allen, A. Clarke, & N. Black (Eds.), *Studying the organisation and delivery of health services: Research methods*. Routledge.

McAvoy, M., Bui, A.-T. N., Hansen, C., Plana, D., Said, J. T., Yu, Z., Yang, H., Freake, J., Van, C., Krikorian, D., Cramer, A., Smith, L., Jiang, L., Lee, K. J., Li, S. J., Beller, B., Huggins, K., Short, M. P., Yu, S. H., … LeBoeuf, N. R. (2021). 3D Printed frames to enable reuse and improve the fit of N95 and KN95 respirators. *BMC Biomedical Engineering*, *3*(1), 10. https://doi.org/10.1186/s42490-021-00055-7

McKay, C., Banks, T. D., & Wallace, S. (2016). Makerspace Classrooms: Where Technology Intersects With Problem, Project, and Place-Based Design in Classroom Curriculum. *International Journal of Designs for Learning*, *7*(2). https://doi.org/10.14434/ijdl.v7i2.20267

Mehrotra, A., Giang, C., El-Hamamsy, L., Guinchard, A., Dame, A., Zahnd, G., & Mondada, F. (2021). Accessible Maker-Based Approaches to Educational Robotics in Online Learning. *IEEE Access*, *9*, 96877–96889. IEEE Access. https://doi.org/10.1109/ACCESS.2021.3094158

Mehto, V., Riikonen, S., Kangas, K., & Seitamaa-Hakkarainen, P. (2020). Sociomateriality of collaboration within a small team in secondary school maker-centered learning project. *International Journal of Child-Computer Interaction*, *26*. https://doi.org/10.1016/j.ijcci.2020.100209

Milara, I. S., Pitkänen, K., Laru, J., Iwata, M., Orduña, M. C., & Riekki, J. (2020). STEAM in Oulu: Scaffolding the development of a Community of Practice for local educators around STEAM and digital fabrication. *International Journal of Child-Computer Interaction*, *26*. https://doi.org/10.1016/j.ijcci.2020.100197

Milara, I. S., Pitkänen, K., Niva, A., Iwata, M., Laru, J., & Riekki, J. (2019). The STEAM path: Building a Community of Practice for local schools around STEAM and Digital Fabrication. *Proceedings of the FabLearn Europe 2019 Conference*, 1–3. https://doi.org/10.1145/3335055.3335072

Milieux Institute. (2020). *Milieux Institute for Arts, Culture and Technology Annual Report 2019-2020*. Concordia University. https://milieux.concordia.ca/wp-content/uploads/2022/11/Milieux-2019-2020-Annual_Report-X.pdf

MIT Fab Lab. (2012). *The Fab Charter*. https://fab.cba.mit.edu/about/charter/

Moorefield-Lang, H. (2014). Makers in the library: Case studies of 3D printers and maker spaces in library settings. *Library Hi Tech*, *32*(4), 583–593. https://doi.org/10.1108/LHT-06-2014-0056

Morado, M. F., Melo, A. E., & Jarman, A. (2021). Learning by making: A framework to revisit practices in a constructionist learning environment. *British Journal of Educational Technology*, *52*(3), 1093–1115.

Morse, J. (2018). Reframing rigor in qualitative inquiry. In N. K. Denzin & Y. S. Lincoln (Eds.), *The SAGE Handbook of Qualitative Research* (5th ed., pp. 796–817). SAGE Publications.

Mottay, L., Roux, J. le, Perumal, R., Esmail, A., Timm, L., Sivarasu, S., & Dhea, K. (2021). KN95 filtering facepiece respirators distributed in South Africa fail safety testing protocols. *South African Medical Journal*, *111*(3), Article 3.

Murai, Y., Kim, Y. J., Chang, S., & Reich, J. (2022). Principles of assessment in school-based making. *Learning: Research and Practice*. https://doi.org/10.1080/23735082.2022.2107695

Murai, Y., Kim, Y. J., Martin, E., Kirschmann, P., Rosenheck, L., & Reich, J. (2019). Embedding assessment in school-based making: Preliminary exploration of principles for embedded assessment in maker learning. *FL2019: Proceedings of FabLearn 2019*, 180–183. https://doi.org/10.1145/3311890.3311922

Nemorin, S., & Selwyn, N. (2017). Making the best of it? Exploring the realities of 3D printing in school. *Research Papers in Education*, *32*(5), 578–595. https://doi.org/10.1080/02671522.2016.1225802

Ng, O.-L., Liu, M., & Cui, Z. (2023). Students' in-moment challenges and developing maker perspectives during problem-based digital making. *Journal of Research on Technology in Education*, *55*(3), 411–425. https://doi.org/10.1080/15391523.2021.1967817

Niemeyer, D. J., & Gerber, H. R. (2015). Maker culture and Minecraft: Implications for the future of learning. *Educational Media International*, *52*(3), 216–226. https://doi.org/10.1080/09523987.2015.1075103

NIH 3D Printing Exchange—COVID 3D TRUST: Trusted Repository for Users and Suppliers through Testing. (n.d.). National Institute of Health. Retrieved November 3, 2024, from https://3d.nih.gov/collections/covid-19-response

Norouzi, B., Kinnula, M., & Iivari, N. (2021). Digital fabrication and Making with children: Scrutinizing adult actors' strategies and challenges in mediating young people's activities. *International Journal of Child-Computer Interaction*, *28*, 1–15. https://doi.org/10.1016/j.ijcci.2021.100267

Novotny, K. (2019). Maker's Mind: Interdisciplinarity, Epistemology, and Collaborative Pedagogy. *Journal of Interdisciplinary Studies in Education*, *8*(1), 45–62.

Occupational Safety and Health Standards: Personal Protective Equipment—Respiratory Protection. (n.d.). https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.134.

O'Connor, C. (2017). Embodiment and the Construction of Social Knowledge: Towards an Integration of Embodiment and Social Representations Theory. *Journal for the Theory of Social Behaviour*, *47*(1), 2–24. https://doi.org/10.1111/jtsb.12110

O'Connor, C., & Joffe, H. (2020). Intercoder Reliability in Qualitative Research: Debates and Practical Guidelines. *International Journal of Qualitative Methods*, *19*, 1609406919899220. https://doi.org/10.1177/1609406919899220

OECD. (2016). *Innovating Education and Educating for Innovation: The Power of Digital Technologies and Skills*. Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/education/innovating-education-and-educating-for-innovation_9789264265097-en

O'Kelly, E., Arora, A., Pirog, S., Ward, J., & Clarkson, P. J. (2021a). Comparing the fit of N95, KN95, surgical, and cloth face masks and assessing the accuracy of fit checking. *PLoS ONE*, *16*(1 January), 1–14. https://doi.org/10.1371/journal.pone.0245688

O'Kelly, E., Arora, A., Pirog, S., Ward, J., & Clarkson, P. J. (2021b). Comparing the fit of N95, KN95, surgical, and cloth face masks and assessing the accuracy of fit checking. *PLOS ONE*, *16*(1), e0245688. https://doi.org/10.1371/journal.pone.0245688

O'Kelly, E., Pirog, S., Ward, J., & Clarkson, P. J. (2020). Ability of fabric face mask materials to filter ultrafine particles at coughing velocity. *BMJ Open*, *10*(9), e039424. https://doi.org/10.1136/bmjopen-2020-039424

Organisation for Economic Co-operation and Development. (2020). *The face mask global value chain in the COVID-19 outbreak: Evidence and policy lessons*. https://www.oecd.org/coronavirus/policy-responses/the-face-mask-global-value-chain-in-the-covid-19-outbreak-evidence-and-policy-lessons-a4df866d/

Otero, N., & Blikstein, P. (2016). Barcino, Creation of a Cross-Disciplinary City. *Proceedings of the The 15th International Conference on Interaction Design and Children*, 694–700. https://doi.org/10.1145/2930674.2935996

Ou, Q., & Chen, X. (2024). Investigation and analysis of maker education curriculum from the perspective of artificial intelligence. *Scientific Reports*, *14*(1), 1–14. https://doi.org/10.1038/s41598-024-52302-1

Papavlasopoulou, S., Giannakos, M. N., & Jaccheri, L. (2017). Empirical studies on the Maker Movement, a promising approach to learning: A literature review. *Entertainment Computing*, *18*, 57–78. https://doi.org/10.1016/j.entcom.2016.09.002

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books, Inc.

Papert, S. (1991). Situating constructionism. In S. Papert & I. Harel (Eds.), *Constructionism* (pp. 1–12). MIT Press.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. Basic Books.

Patrício Silva, A. L., Prata, J. C., Walker, T. R., Campos, D., Duarte, A. C., Soares, A. M. V. M., Barcelò, D., & Rocha-Santos, T. (2020). Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. *Science of The Total Environment*, *742*, 140565. https://doi.org/10.1016/j.scitotenv.2020.140565

Pei, C., Ou, Q., Kim, S. C., Chen, S.-C., & Pui, D. Y. H. (2020). Alternative Face Masks Made of Common Materials for General Public: Fractional Filtration Efficiency and Breathability Perspective. *Aerosol and Air Quality Research*, *20*(12), 2581–2591. https://doi.org/10.4209/aaqr.2020.07.0423

Penuel, W. R., & Fishman, B. J. (2012). Large-scale science education intervention research we can use. *Journal of Research in Science Teaching*, *49*(3), 281–304. https://doi.org/10.1002/tea.21001

Peterson, L., & Scharber, C. (2018). Learning about Makerspaces: Professional Development with K-12 Inservice Educators. *Journal of Digital Learning in Teacher Education*, *34*(1), 43–52.

Petrich, M., Bevan, B., & Wilkinson, K. (2016). Tinkering With MOOCs and Social Media. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology: Makerspaces as learning environments* (Vol. 1, pp. 175–189). Routledge. https://www-taylorfrancis-com.lib-ezproxy.concordia.ca/chapters/edit/10.4324/9781315726519-16/tinkering-moocs-social-media-mike-petrich-bronwyn-bevan-karen-wilkinson

Petrich, M., Wilkinson, K., & Bevan, B. (2013). It looks like fun, but are they learning? In M. Honey & D. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 50–69). Routledge.

Petrovich, M. E., Barany, A., Shah, M., & Foster, A. (2022). Identity exploration for maker educators: Constructing meaning in after-school environmental science. *Journal of Research on Technology in Education*, *54*(4), 535–556. https://doi.org/10.1080/15391523.2021.1885530

Powell, S. C. (2021). *Maker Education Initiators and Innovators* [Ed.D., Northeastern University]. https://www.proquest.com/docview/2565999117/abstract/AE4DA266E7B3475EPQ/1

Québec Education Program. (2001). Ministère de l'Éducation. https://www.quebec.ca/en/education/preschool-elementary-and-secondary-schools/quebec-education-program

Radfar, P., Bazaz, S. R., Mirakhorli, F., & Warkiani, M. E. (2021). The Role of 3D Printing in the Fight Against Covid-19 Outbreak. *Journal of 3D Printing in Medicine*, *5*(1), 51–60. https://doi.org/10.2217/3dp-2020-0028

Rafalow, M. (2016). Tinkering online: Digital supports for making and sharing. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology: Makerspaces as learning environments* (Vol. 1, pp. 158–174). Routledge. https://www-taylorfrancis-com.lib-ezproxy.concordia.ca/chapters/edit/10.4324/9781315726519-15/tinkering-online-matt-rafalow

Ramey, K. E., & Stevens, R. (2019). Interest development and learning in choice-based, in-school, making activities: The case of a 3D printer. *Learning, Culture and Social Interaction*, *23*, 100262. https://doi.org/10.1016/j.lcsi.2018.11.009

Reponen, T., Lee, S.-A., Grinshpun, S. A., Johnson, E., & Mckay, R. (2011). Effect of Fit Testing on the Protection Offered by N95 Filtering Facepiece Respirators Against Fine Particles in a Laboratory Setting. *The Annals of Occupational Hygiene*, *55*(3), 264–271. https://doi.org/10.1093/annhyg/meq085

Resnick, M., Eidman-Aadahl, E., & Dougherty, D. (2016). Making-writing-coding. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology: Makers as learners* (Vol. 2, pp. 229–240). Routledge.

Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In M. Honey & D. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 163–181). Routledge.

Respirator Fact Sheet| NPPTL | NIOSH | CDC. (2020). Centres for Disease Control. https://www.cdc.gov/niosh/npptl/topics/respirators/factsheets/respfact.html

Respirators Versus Surgical Masks Versus Non-medical Masks. (2021). Canadian Centre for Occupational Health and Safety. https://www.ccohs.ca/oshanswers/prevention/ppe/surgical_mask.html

Respiratory Protection Program Standards- Fit Testing Procedures (Mandatory). (n.d.). https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.134AppA

Respiratory Protection Program Standards- Fit Testing Procedures (Mandatory) (2016).

Riikonen, S. M., Kangas, K., Kokko, S., Korhonen, T., Hakkarainen, K., & Seitamaa-Hakkarainen, P. (2020). The Development of Pedagogical Infrastructures in Three Cycles of Maker-Centered Learning Projects. *Design and Technology Education*, *25*(2), 29–49.

Riikonen, S., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2020). Bringing Maker Practices to School: Tracing Discursive and Materially Mediated Aspects of Student Teams' Collaborative Making Processes. *International Journal of Computer-Supported Collaborative Learning*, *15*(3), 319–349.

Rodriguez, S., Smith, S., & Harron, J. (2021). Analyzing the Development of Science and Mathematics Teachers' Maker-Centered Philosophy and Instructional Practices. *Contemporary Issues in Technology and Teacher Education (CITE Journal)*, *21*(1). https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1288194&site=ehost-live&scope=sitehttps://citejournal.org/volume-21/issue-1-21/science/analyzing-the-development-of-science-and-mathematics-teacher

Rosenfeld, S., Yayon, M., Halevi, R., & Blonder, R. (2019). Teachers as Makers in Chemistry Education: An Exploratory Study. *International Journal of Science and Mathematics Education*, *17*(1), 125–148. https://doi.org/10.1007/s10763-019-09989-w

Ryan, R. M., & Deci, E. L. (2017). *Self-Determination Theory: Basic Psychological Needs in Motivation, Development, and Wellness*. Guilford Publications.

Saari, H., Åkerman, M., Kieslinger, B., Myllyoja, J., & Sipos, R. (2021). How Open Is the Maker Movement? Integrative Literature Review of the Openness Practices in the Global Maker Movement. *Sustainability*, *13*(24), Article 24. https://doi.org/10.3390/su132413559

Saavedra, J. (2020, April 13). *Our education system is losing relevance. Here's how to update it*. World Economic Forum. https://www.weforum.org/stories/2020/04/our-education-system-is-losing-relevance-heres-how-to-update-it/

Salas-Valdivia, L., & Gutierrez-Aguilar, O. (2021). Appropriation of the Maker methodology to stimulate Invisible Learning in high school students in times of Covid-19. *2021 XVI Latin American Conference on Learning Technologies (LACLO)*, 372–375. https://doi.org/10.1109/LACLO54177.2021.00045

Salo, L., Ansolahti, A., Korhonen, T., & Juurola, L. (2021). Supporting teachers' maker education in the 2020's: Educating resilient makers starts from early childhood. *Proceedings of the FabLearn 2020 - 9th Annual Conference on Maker Education*, 106–109. https://doi.org/10.1145/3386201.3386212

Saunders, G. L. (2022). *Making Them Gifted: How Elementary Makers' Spaces Reveal Giftedness* [Ed.D., University of Southern California]. https://www.proquest.com/docview/2670031202/abstract/FC422464C64E40BEPQ/1

Schad, M., & Jones, W. M. (2020). The Maker Movement and Education: A Systematic Review of the Literature. *Journal of Research on Technology in Education*, *52*(1), 65–78. https://doi.org/10.1080/15391523.2019.1688739

Schlegel, R. J., Chu, S. L., Chen, K., Deuermeyer, E., Christy, A. G., & Quek, F. (2019). Making in the classroom: Longitudinal evidence of increases in self-efficacy and STEM possible selves over time. *Computers & Education*, *142*, 103637. https://doi.org/10.1016/j.compedu.2019.103637

Schouweiler, J. (2020). *Middle School Teachers Stem Career Awareness: A Case Study on Makerspaces* [Ed.D., University of Massachusetts Lowell]. https://www.proquest.com/docview/2414767592/abstract/9D9AE6C448874FCBPQ/1

Seidman, I. (2019). *Interviewing as qualitative research* (5th ed.). Teachers College Press.

Sheffield, R., & Koul, R. (2021). Investigating learning in a STEM makerspace: India case study. *Journal of Physics: Conference Series*, *1882*(1), 012141. https://doi.org/10.1088/1742-6596/1882/1/012141

Sheridan, K., Halverson, E. R., Litts, B., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the Making: A Comparative Case Study of Three Makerspaces. *Harvard Educational Review*, *84*(4), 505–531. https://doi.org/10.17763/haer.84.4.brr34733723j648u

Sheridan, K., & Konopasky, A. (2016). Designing for resourcefulness in a community-based makerspace. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology: Makerspaces as Learning Environments* (Vol. 1, pp. 30–46). Routledge.

Shively, K., Stith, K., & DaVia Rubenstein, L. (2021). Ideation to implementation: A 4-year exploration of innovating education through maker pedagogy. *Journal of Educational Research*, *114*(2), 155–170. https://doi.org/10.1080/00220671.2021.1872472

Singh, R., & Kim, Y. J. (2019). Systematic Approach to Develop Sustainable Makerspaces in Resource-Constrained Schools. *Proceedings of FabLearn 2019*, 164–167. https://doi.org/10.1145/3311890.3311917

Siung, J., Sola, P. G., & Sunderland Bowe, J.-A. (2021). The Creative School. In M. Ioannides, E. Fink, L. Cantoni, & E. Champion (Eds.), *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection* (pp. 725–733). Springer International Publishing. https://doi.org/10.1007/978-3-030-73043-7_64

Sivek, S. C. (2011). "We Need a Showing of All Hands": Technological Utopianism in MAKE Magazine. *Journal of Communication Inquiry*, *35*(3), 187–209. https://doi.org/10.1177/0196859911410317

Smith, R. C., Iversen, O. S., & Veerasawmy, R. (2016). Impediments to digital fabrication in education: A study of teachers' role in digital fabrication. *International Journal of Digital Literacy and Digital Competence*, *7*, 33–49. https://doi.org/10.4018/IJDLDC.2016010103

Smith, W., & Smith, B. C. (2016). Bringing the Maker Movement to School. Fourth Grade Students Create Projects to Illustrate the Transfer and Transformation of Energy. *Science and Children*, *54*(1), 30–37.

Smolarczyk, K., & Kröner, S. (2021). Two decades in the making: A scoping review on research on digital making and its potential for digital empowerment in non-formal settings. *Journal of Research on Technology in Education*, *55*(3), 459–476. https://doi.org/10.1080/15391523.2021.1974987

Somanath, S., Oehlberg, L., Hughes, J., Sharlin, E., & Sousa, M. C. (2017). "Maker" within Constraints: Exploratory Study of Young Learners using Arduino at a High School in

India. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 96–108. https://doi.org/10.1145/3025453.3025849

Song, L. (2018). Improving Pre-Service Teachers' Self-Efficacy on Technology Integration through Service Learning. *Canadian Journal of Action Research*, *19*(1), 22–32.

Song, M. J. (2021). Teacher professional development in integrating digital fabrication technologies into teaching and learning. *Educational Media International*, *58*(4), 317–334. https://doi.org/10.1080/09523987.2021.1989766

Soomro, S. A., Casakin, H., Nanjappan, V., & Georgiev, G. V. (2023). Makerspaces Fostering Creativity: A Systematic Literature Review. *Journal of Science Education and Technology*, *32*(4), 530–548. https://doi.org/10.1007/s10956-023-10041-4

Spark & Sustain: How all of the world's school systems can improve learning at scale. (2024). McKinsey & Company. http://ceros.mckinsey.com/mck-spark-and-sustain-exhibit

Spieler, B., Schifferle, T. M., & Dahinden, M. (2022). Exploring Making in Schools: A Maker-Framework for Teachers in K12. *6th FabLearn Europe / MakeEd Conference 2022*, 1–6. https://doi.org/10.1145/3535227.3535234

Stemen, D., Ge, M., Hwang, D., Qaddoumi, B., Roden, M., Nanda, N., & Ference, E. (2021). Frame to Improve the Fit of N95 Filtering Face Mask Respirators. *Journal of Occupational and Environmental Medicine*, *63*(6), e362. https://doi.org/10.1097/JOM.0000000000002223

Stevens, G., Boden, A., & von Rekowski, T. (2013). Objects-to-think-with-together. In Y. Dittrich, M. Burnett, A. Mørch, & D. Redmiles (Eds.), *End-User Development* (pp. 223–228). Springer. https://doi.org/10.1007/978-3-642-38706-7_17

Stevenson, M., Bower, M., Falloon, G., Forbes, A., & Hatzigianni, M. (2019). By Design: Professional Learning Ecologies to Develop Primary School Teachers' Makerspaces Pedagogical Capabilities. *British Journal of Educational Technology*, *50*(3), 1260–1274.

Stoltenberg, L., Krenz, P., & Redlich, T. (2024). Prosuming for a sustainable future? Effects of different forms of participatory value creation with respect to sustainability. *Discover Sustainability*, *5*(1), 100. https://doi.org/10.1007/s43621-024-00279-2

Stornaiuolo, A., & Nichols, T. P. (2021). Makerspaces in K-12 schools: Six key tensions. In *Maker literacies and maker identities in the digital age: Learning and playing through modes and media.* (pp. 117–132). Routledge/Taylor & Francis Group. https://doi.org/10.4324/9781003049241-7

Strycker, J. (2015). Makerspaces: The Next Iteration for Educational Technology in K-12 Schools. *Educational Technology*, *55*(3), 28–32.

Student Growth through Design-Centered Learning: Report from the Learning Studios Pilot. (2017). In *Digital Promise Global*. Digital Promise Global. https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=ED611799&site=ehost-live&scope=site

Susmitha, V., Akshay, N., Vennila, V., Muraleedharan, A., Nair, R., Velayudhan, A., Alkoyak Yildiz, M., & Bhavani, R. R. (2018). All Aboard for the Joy of Making! Teaching User Centered Design and Tinkering to Middle School Children in India. *2018 IEEE Tenth International Conference on Technology for Education (T4E)*, 33–40. https://doi.org/10.1109/T4E.2018.00015

Swennen, G. R. J., Pottel, L., & Haers, P. E. (2020). Custom-made 3D-printed face masks in case of pandemic crisis situations with a lack of commercially available FFP2/3 masks.

International Journal of Oral and Maxillofacial Surgery, *49*(5), 673–677. https://doi.org/10.1016/j.ijom.2020.03.015

Tan, M., Lee, S.-S., & Ng, Z. Y. (2017). Social influences on student perceptions of failure in learning design processes: Instructional implications. *Learning: Research and Practice*, *3*(2), 130–147. https://doi.org/10.1080/23735082.2017.1351577

Tanenbaum, T. J., Williams, A. M., Desjardins, A., & Tanenbaum, K. (2013). Democratizing technology: Pleasure, utility and expressiveness in DIY and maker practice. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2603–2612. https://doi.org/10.1145/2470654.2481360

Tareq, Md. S., Rahman, T., Hossain, M., & Dorrington, P. (2021). Additive manufacturing and the COVID-19 challenges: An in-depth study. *Journal of Manufacturing Systems*, *60*, 787–798. https://doi.org/10.1016/j.jmsy.2020.12.021

Tech Model Railroad Club. (n.d.). Massachusetts Institute of Technology. Retrieved November 3, 2024, from http://tmrc.mit.edu/

The Maker Movement in Education: Designing, Creating, and Learning Across Contexts. (2014). *Harvard Educational Review*, *84*(4), 492–494. https://doi.org/10.17763/haer.84.4.b1p1352374577600

Thompson, K. (2021). *Making Space in the Curriculum: Examining Purpose in a Middle School Makerspace* [Ph.D., Boston College]. https://www.proquest.com/docview/2535880458/abstract/26A91F312F3D49CFPQ/1

Tillman, D. A., An, S. A., Cohen, J. D., Kjellstrom, W., & Boren, R. L. (2014). Exploring Wind Power: Improving Mathematical Thinking through Digital Fabrication. *Journal of Educational Multimedia and Hypermedia*, *23*(4), 401–421.

Timotheou, S., & Ioannou, A. (2021). Learning and innovation skills in making contexts: A comprehensive analytical framework and coding scheme. *Educational Technology Research and Development*, *69*(6), 3179–3207. https://doi.org/10.1007/s11423-021-10067-8

Tino, R., Moore, R., Antoline, S., Ravi, P., Wake, N., Ionita, C. N., Morris, J. M., Decker, S. J., Sheikh, A., Rybicki, F. J., & Chepelev, L. L. (2020). COVID-19 and the role of 3D printing in medicine. *3D Printing in Medicine*, *6*(1), 11. https://doi.org/10.1186/s41205-020-00064-7

Tofel-Grehl, C., Fields, D., Searle, K., Maahs-Fladung, C., Feldon, D., Gu, G., & Sun, C. (2017). Electrifying Engagement in Middle School Science Class: Improving Student Interest Through E-textiles. *Journal of Science Education and Technology*, *26*(4), 406–417. https://doi.org/10.1007/s10956-017-9688-y

Togou, M. A., Lorenzo, C., Cornetta, G., & Muntean, G.-M. (2020). Assessing the Effectiveness of Using Fab Lab-Based Learning in Schools on K–12 Students' Attitude Toward STEAM. *IEEE Transactions on Education*, *63*(1), 56–62. IEEE Transactions on Education. https://doi.org/10.1109/TE.2019.2957711

Torkington, S. (2016, September 2). *The jobs of the future – and two skills you need to get them*. World Economic Forum. https://www.weforum.org/stories/2016/09/jobs-of-future-and-skills-you-need/

Torralba, J. (2019). A mixed-methods approach to investigating proportional reasoning understanding in maker-based integrative steam projects. *FL2019: Proceedings of FabLearn 2019*, 81–88. https://doi.org/10.1145/3311890.3311901

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K., Colquhoun, H., Kastner, M., Levac, D., Ng, C., Sharpe, J. P., Wilson, K., Kenny, M., Warren, R., Wilson, C., Stelfox, H. T., & Straus, S. E. (2016). A scoping review on the conduct and reporting of scoping reviews. *BMC Medical Research Methodology*, *16*(1), 1–10. https://doi.org/10.1186/s12874-016-0116-4

Trust, T., Maloy, R. W., & Edwards, S. (2018). Learning through Making: Emerging and Expanding Designs for College Classes. *TechTrends*, *62*(1), 19–28. https://doi.org/10.1007/s11528-017-0214-0

TSI Incorporated. (2015). *PortaCount® Pro 8030 and PortaCount® Pro+ 8038 Respirator Fit Testers Operation and Service Manual*.

Tucker, M. S. (2011). *Surpassing Shanghai: An agenda for American education built on the world's leading systems*. Harvard Education Press.

Turner, V. A. (2022). *Educator and administrator perceptions of student learning in K-12 makerspaces.* (Vol. 83, p. No Pagination Specified). ProQuest Information & Learning.

United States Environmental Protection Agency. (2021). *What is a HEPA filter?* https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1

Unterfrauner, E., Voigt, C., Schrammel, M., & Menichinelli, M. (2018). The Maker Movement and the Disruption of the Producer-Consumer Relation. In S. Diplaris, A. Satsiou, A. Følstad, M. Vafopoulos, & T. Vilarinho (Eds.), *Internet Science* (pp. 113–125). Springer International Publishing. https://doi.org/10.1007/978-3-319-77547-0_9

Veldhuis, A., Xiao, D., Bekker, T., & Markopoulos, P. (2022). *Model-based support for authoring Design-based Learning and Maker Education materials in elementary education*. https://doi.org/10.1145/3535227.3535230

Vongkulluksn, V. W., Matewos, A. M., & Sinatra, G. M. (2021). Growth Mindset Development in Design-Based Makerspace: A Longitudinal Study. *Journal of Educational Research*, *114*(2), 139–154.

Vossoughi, S., & Bevan, B. (2014). *Making and tinkering: A review of the literature*. Report commissioned by the NRC Committee of Successful Out-of-School STEM Learning. https://informalscience.org/research/making-and-tinkering-review-literature/

Vossoughi, S., Hooper, P. K., & Escudé, M. (2016). Making Through the Lens of Culture and Power: Toward Transformative Visions for Educational Equity. *Harvard Educational Review*, *86*(2), 206–232. https://doi.org/10.17763/0017-8055.86.2.206

Walan, S., & Gericke, N. (2022). Transferring makerspace activities to the classroom: A tension between two learning cultures. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-022-09799-2

Waldman-Brown, A., & Adebola, S. O. (2015). DEMOCRATISING TECHNOLOGY: THE CONFLUENCE OF MAKERS AND GRASSROOT INNOVATORS. *Proceedings for the International Conference on Creativity and Innovations at Grassroots*. International Conference on Creativity and Innovations at Grassroots, Ahmedabad, India.

Wardrip, P. S., & Brahms, L. (2016). Taking making to school: A model for integrating making into classrooms. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology: Makerspaces as Learning Environments* (Vol. 1, pp. 97–106). Routledge.

Weiner, S., Jordan, S. S., & Lande, M. (2021). What to “make” of school: Revealing the conflicting institutional logics of grassroots making and formal education. *Journal of Research on Technology in Education*, *53*(3), 264–278. https://doi.org/10.1080/15391523.2020.1767526

Weng, X., Chiu, T. K. F., & Jong, M. S. Y. (2022). Applying Relatedness to Explain Learning Outcomes of STEM Maker Activities. *Frontiers in Psychology*, *12*. https://www.frontiersin.org/articles/10.3389/fpsyg.2021.800569

Weng, X., Chiu, T. K. F., & Tsang, C. C. (2022). Promoting student creativity and entrepreneurship through real-world problem-based maker education. *Thinking Skills and Creativity*, *45*. https://doi.org/10.1016/j.tsc.2022.101046

Whyte, H. E., Montigaud, Y., Audoux, E., Verhoeven, P., Prier, A., Leclerc, L., Sarry, G., Laurent, C., Le Coq, L., Joubert, A., & Pourchez, J. (2022). Comparison of bacterial filtration efficiency vs. Particle filtration efficiency to assess the performance of non-medical face masks. *Scientific Reports*, *12*(1), 1188. https://doi.org/10.1038/s41598-022-05245-4

Wilkerson, G. (2024, January 30). Makerspace engineering workshop closed in December despite student petition to save it. *The Daily Gamecock*. https://www.dailygamecock.com/article/2024/01/makerspace-engineering-workshop-closed-in-december-despite-student-petition-to-save-it-news-wilkerson

Wilson, J., & Gobeil, M. (2017). Guitars and Makerspace: Examining the Experience of First Nations Students. *Canadian Journal of Learning and Technology*, *43*(3). https://lib-ezproxy.concordia.ca/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ1166010&site=ehost-live&scope=site

Wong Shui Huen. (2020). 素養導向為學校核心價值的 設計思考：創客教育與 教師專業學習社群. (Reflections on the Design of Literacy-Oriented School Core Values: Creative Education and Professional Learning Communities for Teachers). *Journal of Education Research (1680-6360)*, *313*, 35–46.

Yamagata-Lynch, L. C. (2010). *Activity systems analysis methods: Understanding complex learning environments*. Springer.

Yin, Y., Hadad, R., Tang, X., & Lin, Q. (2020). Improving and Assessing Computational Thinking in Maker Activities: The Integration with Physics and Engineering Learning. *Journal of Science Education and Technology*, *29*(2), 189–214. https://doi.org/10.1007/s10956-019-09794-8

Zhang, H. (2021). The Construction of Innovative Education Curriculum System for High School Students: Based on the Practice of "Workshop + Project" Innovative Education Curriculum of Zhengzhou No. 12 Middle School, China. *Science Insights Education Frontiers*, *9*(2), 1265–1281.

Appendix A: Guiding Questions Framework for Developing a Maker-Centered Education Program

Implementing a maker-centered education program can transform learning by providing students with hands-on, creative experiences that foster problem-solving, critical thinking, and collaboration. Establishing a successful maker-centered program requires thoughtful planning and support from school leaders to ensure it aligns with educational goals and provides teachers with the resources and guidance they need. The Guiding Questions Framework for Developing a Maker-Centered Education Program (see Table A1) is designed to help educators and leaders lay the groundwork for their maker program by addressing questions in seven key challenge areas during four distinct phases of program development and implementation. The seven key areas emerge from the primary challenge areas identified in the research literature. They include: 1) leadership, 2) curriculum and assessment, 3) space, 4) material resources, 5) virtual resources, 6) human resources and, 7) training and professional development. Questions related to time and scheduling, funding, and education regulations are integrated into each of the seven key areas as they are relevant to each. The four phases include Planning, Preparation, Implementation and, Continuation:

Phase 1 - Planning: The Planning phase focuses on defining the objectives of the maker-centered education program, assigning responsibility for its planning, and identifying key resources and constraints. Clearly defined objectives align stakeholder efforts, while early identification of resources and constraints ensures the program is realistic, sustainable, and suited to the school's context. The answers to the questions in this phase will determine the direction of the subsequent phases of the program.

Phase 2 - Preparation: The Preparation phase aims to develop the program more concretely given the objectives, resources, and constraints that were identified in the Planning phase. This phase addresses the logistical and practical aspects of readiness, from equipping spaces to empowering educators with the skills they need.

Phase 3 - Implementation: The Implementation phase focuses on the launch of the program and developing contingency plans to address unforeseen issues as they arise during the initial implementation of the program.

Phase 4 - Continuation: The Continuation phase focuses on developing strategies for the long-term success of the program. Many maker-centered education programs are initially successful but fail to be sustainable in the long-term. Strategies to mitigate foreseeable long-term challenges can help ensure the success and longevity of the program.

School leaders and educators are encouraged to review and address as many of the questions as possible before making any actionable decisions as many of the questions are interrelated. While it may not be necessary to have all questions answered before taking any steps toward developing and implementing a program, it is recommended that all questions are at least reviewed so that they can be kept in mind as decisions are made during the process. By methodically working through each phase and reflecting on the guiding questions in the seven key areas, educators and leaders can better anticipate challenges and leverage opportunities to best ensure the success of their program.

Table 1A

Guiding Questions Framework for Developing a Maker-Centered Education Program

<table>
<tr><th colspan="2">Guiding Questions Framework for Developing a Maker-Centered Education Program</th></tr>
<tr><td colspan="2">Leadership</td></tr>
<tr><td>Planning</td><td>Who will take the lead in developing and overseeing the program? (Ideally this would be at least two people to share the load and to ensure the longevity of the program should one person need to leave.)
What roles will leadership play in supporting the program’s design, implementation, and long-term sustainability?
What governance structures will be put in place to guide decision-making for the program?
How will leadership ensure that decisions are transparent, inclusive, and aligned with the program’s goals?
Who will be responsible for resolving conflicts or addressing challenges during the program’s development?
How will responsibilities be distributed among school leadership, staff, and the organizing committee?
Who else will be involved in the planning of the program?
When will the organizing personnel be able to plan and prepare?
Is there a budget to hire someone specifically for this task?
What regulations, if any, govern who can take on these tasks and responsibilities?
How will leadership ensure that all voices, including those of underrepresented groups, are included in the planning process?
What accountability measures will leadership put in place to ensure the program remains on track during development and implementation?</td></tr>
<tr><td>Development</td><td>How will leadership ensure buy-in and support from key stakeholders, including staff, parents, and the broader school community?
What strategies will leadership use to encourage stakeholder participation and enthusiasm for the program?
How will leadership address potential resistance or skepticism from stakeholders?
How will the leadership of the school and the organizing team prepare educators for implementation of the program?
What steps will leadership take to address any resistance or hesitancy from educators?
What approaches can be used to dispel misconceptions about maker-centered education that may be held by some educators?
What approaches can be used to help educators who may feel intimidated by maker-centered educational approaches and the fabrication technology commonly used in making?
What approaches can be used to help educators appreciate the value maker-centered education can have for teaching and learning?
How can the leadership promote a culture of making in the school?</td></tr>
</table>

Implementation	Who will be responsible for making key decisions during the early stages of the program (e.g., program adjustments, resource allocation)? • What processes will be in place to ensure that decision-making is collaborative and inclusive? • What mechanisms will leaders use to regularly monitor and evaluate the program's progress during its initial implementation? How will leadership foster a culture of innovation, experimentation, and creativity among staff and students during the program's rollout? • What steps will leadership take to create a supportive environment where staff and students feel comfortable trying new approaches and learning from mistakes? • How will staff be supported in managing student engagement, behaviour, and participation in the program? How will leadership communicate program updates, successes, and challenges to stakeholders (e.g., staff, students, parents, community partners)? How will leadership support staff in managing the workload and challenges of implementing the program? • Will there be regular meetings or feedback sessions with staff and educators? • How will leadership ensure flexibility in adapting the program based on initial feedback and outcomes? What steps will leadership take to recognize and celebrate staff efforts and successes during the program's launch? Are there opportunities for leadership to showcase the program to the broader community to build awareness and support? How will leadership collect and analyze feedback from staff, students, and parents about the progression of the program? • What processes will leadership use to act on feedback and make iterative improvements? What metrics or benchmarks will leadership use to assess whether the program is meeting its initial objectives?
Continuation	What strategies will leadership use to ensure the program remains sustainable beyond the initial implementation? • How will leadership ensure the program remains aligned with the school's long-term vision and educational goals? • What strategic plans will be developed to expand or adapt the program to meet future needs and opportunities? • How will leadership identify and respond to emerging trends and technologies in maker-centered education? How will leadership ensure sustained funding for the program, including materials, staffing, and professional development? • Are there plans to pursue additional funding opportunities, such as grants, partnerships, or donations? • What strategies will be used to allocate resources efficiently and maintain a balanced budget over the long term? How will leadership continue to promote the program to staff, students, parents, and the broader community? • What steps will leadership take to maintain enthusiasm and engagement in the program over time? • How will leadership advocate for the program at district, state, or national levels to ensure ongoing support? How will leadership evaluate the program's impact and success on an ongoing basis (e.g., student outcomes, staff feedback)? • What metrics can be used to assess the long-term impact of the program (e.g. student academic performance, student career outcomes)? • How will the data for these long-term metrics be gathered? • What processes will be in place to identify areas for improvement and implement changes based on evaluations? • How will leadership involve staff, students, and stakeholders in the evaluation and improvement process?

Guiding Questions Framework for Developing a Maker-Centered Education Program

Curriculum & Assessment

Planning

What are the objectives of the program?

- Is the program intended to be extra-curricular or integrated into the school day for credit?
- Is the program in response to curriculum requirements?
    - If yes, what are these requirements?
- Is the program intended to be used as a teaching approach to support existing curriculum content? Or is it intended to have learning objectives of its own?
    - If it is intended to have learning objectives of its own:
        - What specific skills or competencies will be targeted?
        - How will these skills or competencies be assessed?
        - How will these skills or competencies be reported?

Are their constraints related to curriculum that may affect how the program is implemented? (e.g. regulations on teaching time per subject)

If the program is to be embedded during the school day, when in the students' schedule will MCLEs take place?

- Is there a possibility of scheduling in double-periods (two consecutive periods with the same teacher) to give teachers more time for more complex MCLEs?
- Is there a possibility to reserve a number of days during the school year dedicated to MCLEs and other activities that could benefit from longer periods of time?

Are there existing maker-centered curricula that the program can use?

- Are there funds to purchase such a curriculum if a fee is associated with it?

Development

What types of projects or challenges will best support the desired learning outcomes? (e.g. open-ended explorations, inquiry-based projects, industry-aligned challenges)

How will the program support diverse learner interests and promote equity?

- Are there opportunities for students to pursue their own interests and passion projects within the program?
- Will it include strategies for engaging underrepresented groups or providing differentiated support?
- How will the program ensure that all students, including those from diverse backgrounds and abilities, feel included and supported in the curriculum?
- How will the curriculum be designed to engage and inspire students who may not initially see themselves as "makers"?

Are there opportunities to create cross-disciplinary collaboration among educators (e.g., integrating STEM with art or humanities)?

What support will teachers need to implement the curriculum effectively?

- What resources (e.g., instructional guides) are available to help educators develop MCLEs that support their teaching objectives?
- How will teachers be encouraged to share best practices and challenges they encounter while delivering the curriculum?

<table>
<tr>
<td>Development</td>
<td>In the case where knowledge and skills developed through MCLEs is to be assessed, what methods will be used to assess student learning and growth in the program (e.g., portfolios, project outcomes, peer reviews)?

How will assessment focus on process-oriented skills like problem-solving, creativity, and collaboration rather than just final products?
How will assessment rubrics and tools be designed to ensure that they are clear, fair, and aligned with the program's learning objectives?
How will formative assessments (e.g., ongoing feedback during projects) be integrated into the program to guide student learning?
What summative assessments (e.g., project presentations, written reflections) will be used to evaluate overall student achievement?
How will feedback be provided to students in a constructive and meaningful way to encourage improvement and learning?
Will students have opportunities to self-assess and reflect on their work and learning process?
How will student work and progress be documented (e.g., journals, digital portfolios, videos)?
</td>
</tr>
<tr>
<td>Implementation</td>
<td>How will the curriculum be rolled out during the initial stages of the program?

How can projects and activities be designed to introduce students to the makerspace (if applicable), tools, and resources in a gradual and structured way?

What opportunities will students have to share their projects with peers, parents, or the wider community (e.g., exhibitions, showcases)?
How will the curriculum and assessment strategies be evaluated at the end of the first implementation phase?

What processes will be in place to gather feedback from teachers and students about the curriculum's strengths and areas for improvement?
How will the curriculum and assessment methods be adjusted based on student feedback, interests, and challenges during the initial implementation?

Are there mechanisms for teachers to modify activities or assessments to better suit the needs of their students?

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<tr>
<td>Continuation</td>
<td>How will the objectives of the program be periodically reviewed to ensure it remains relevant, engaging, and aligned with educational goals?

Are there opportunities to integrate new maker technologies or methods into the program as they become available?
How will the program be adapted to address feedback from students, staff, and other stakeholders?

Will there be opportunities to offer more advanced or specialized maker activities for students who want to deepen their skills?

Are there plans to develop advanced or specialized tracks for students who demonstrate a strong interest in maker activities?

Are there opportunities to document and share the curriculum as a model for other schools or programs?</td>
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Guiding Questions Framework for Developing a Maker-Centered Education Program	
Space	
Planning	Where will the maker-centered learning activities take place in the school? • Is there available space in the school that can serve as a dedicated makerspace? If there is a space that can be dedicated to maker-centered activities: • Can the space accommodate a variety of activities, including those that are noisy or messy? • Can the space accommodate equipment that has special requirements like ventilation (if applicable)? • Will the space provide enough room for the safe movement of users while tools and equipment are in use (e.g. powered tools)? • Does the space have adequate storage for unfinished projects to reduce setup time for teachers and students? If a dedicated space is not available: • How will maker-centered learning activities take place? (e.g. in regular classrooms, in a shared space for a variety of activities including MCLEs.) What funds are available for the preparation of a physical space for the program?
Development	What is required for the set-up of the space? • What structural changes need to be made to the space (e.g. ventilation ducts, sound-proofing)? • What furniture will be conducive to the types of activities that will take place in the space? • How will the layout be designed to accommodate various activities, tools, and equipment while ensuring safety and accessibility? • What signs and safety reminders need to be visible for users in the space? • What adaptations or modifications are needed to ensure the makerspace is accessible to all students, including those with disabilities or special needs? (e.g., adjustable tables, labeled tools, visual aids)? How can an effective system for organizing and storing tools, materials, and student projects be developed? • How will storage areas be labeled and designed for easy access while maintaining safety? • How will in-progress projects be stored securely without disrupting other activities? What is the projected timeframe for the set-up of the space? Is there a way to pilot the space before it is fully opened for use?

<table>
<tr>
<td>Implementation</td>
<td>How will the makerspace be scheduled to accommodate different classes, projects, and extracurricular activities?

What policies will govern the use of the makerspace (e.g., booking procedures, time limits, equipment usage rules)?
Are there designated open hours or times for students to use the makerspace outside of regular class periods?

How will staff and students be introduced to the space?

How will staff and students be trained on safety protocols, including the use of tools and emergency procedures?

What systems can be put in place to monitor and supervise student use of the makerspace to ensure safety and proper tool usage, especially in the initial implementation when familiarity with these tools may be limited?
Are there clear protocols for staff to follow if students encounter difficulties or safety issues in the makerspace?

How will staff manage large groups or multiple projects simultaneously in the space?
What instructions or guides can be made available to help students and staff navigate the makerspace and its tools?

Who will maintain the space and make sure it is ready for the next group of users?

Will there be a dedicated person for this?
If each educator is responsible for this after they have finished using the space, what common rules will be established regarding what the space's "ready" state is?

How will leadership ensure that the space remains compliant with local health and safety regulations?
How will feedback from students and staff be collected to evaluate the makerspace's effectiveness during the initial implementation?

What systems will be in place to address issues or make adjustments to the makerspace as needed?

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<tr>
<td>Continuation</td>
<td>What routine maintenance procedures are needed to keep the space in optimal condition?

Who will be responsible for overseeing maintenance and ensuring compliance with safety standards?

How will the school ensure the makerspace remains a dynamic and evolving environment for learning and innovation?

Will there be regular reviews to identify areas for improvement or new opportunities for the makerspace?
How will the school assess the layout of the makerspace for functionality and efficiency?
How will the makerspace be adapted for changes in program offerings?
Is there room for expansion of the space if needed?

How will funding be allocated to maintain, upgrade, and expand the makerspace?

Are there opportunities for additional funding, such as grants, donations, or partnerships, to support the makerspace's future needs?
What contingency plans are in place to address unexpected costs related to the makerspace?

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<tr><th colspan="2">Guiding Questions Framework for Developing a Maker-Centered Education Program</th></tr>
<tr><th colspan="2">Material Resources</th></tr>
<tr><td>Planning</td><td>What regulations, if any, govern the type of materials and equipment that can be purchased and where they can be purchased?
Are there suppliers and vendors schools are or are not permitted to purchase from?
What regulations, if any, govern what types of equipment and material students are permitted to use?
What funds are available for the purchase of equipment and materials?
How will leadership prioritize purchases if budget constraints arise?
What other sources of material resources may exist?
Can equipment and tools be loaned from a local library or makerspace?
Can partnerships with local businesses, suppliers, or community organizations help secure discounted or donated materials?
Are there opportunities to engage the community in material sourcing, such as material drives or shared resources?</td></tr>
<tr><td>Development</td><td>What materials and equipment does the school already have available for the program?
What specific tools, machines, and consumables are essential for achieving the program's goals (e.g., 3D printers, laser cutters, sewing machines)?
Are the materials and equipment that are being considered accessible and usable for students of all skill levels, abilities, and age groups?
How do the materials and equipment that are being considered support diverse learning approaches and creativity?
Is the equipment that is being considered widely used and has a large online community of support available to educators and students in the case of trouble-shooting needs?
What are the safety concerns related to the equipment being considered?
How will safety data sheets (SDS) be made available and accessible to all users?
Are there specific storage requirements for certain materials (e.g., flammable or hazardous items)?
Are there specific infrastructure requirements (e.g., power supply, ventilation, fireproof storage) for certain materials or equipment?
Are there service contracts or partnerships with vendors to assist with equipment maintenance?
What criteria will be used to select durable, high-quality equipment and materials?
What is the expected lifespan of the equipment, and how will this influence procurement decisions?
What service contracts or warranties for high-value equipment are available and needed?</td></tr>
</table>

Implementation	How will students and staff be introduced to the available materials and their appropriate uses? • What resources or guides can be made available to help staff and students learn how to use materials effectively in projects? • Who will be available to help with troubleshooting equipment error, especially during the initial phases of implementation when educators are still getting used to the equipment? Is there a system for monitoring and maintaining tools and equipment (e.g., regular inspections, service contracts)? How will materials and equipment be allocated across different classes, projects, or activities? • What guidelines need to be developed for students and staff on how to request or reserve specific materials or tools? • What mechanisms will be in place to ensure equitable access to high-demand or limited materials and equipment? How will consumable materials be restocked and monitored to ensure availability for student projects? • Is there a plan for tracking and managing the cost of consumable materials during the program's initial implementation? • Are there contingency plans if additional material resources are needed unexpectedly? How will feedback be collected from students and staff regarding the adequacy and quality of materials provided?
Continuation	What routine maintenance procedures are needed to keep tools and equipment in optimal condition? • Who will be responsible for overseeing maintenance and ensuring compliance with safety standards? • Are there plans to repair or replace outdated or broken equipment and tools? o Is there a budget reserved for this purpose? How will the school ensure an ongoing supply of consumables during the program's operation? • What funds will be reserved for these expenses? • How will excess or unused materials be managed to minimize waste or repurposed for future use? How will the program adapt material needs as participation grows or project complexity increases? Are there plans to diversify the types of materials available as the program evolves? How will feedback from staff and students about the quality and availability of materials be collected and acted upon? Will there be regular reviews of material usage to identify inefficiencies or opportunities for improvement?

Guiding Questions Framework for Developing a Maker-Centered Education Program	
Virtual Resources	
Planning	What regulations, if any, govern what type of virtual tools and software students are permitted to use? • Are there any district, state, or national regulations regarding the use of specific virtual tools or platforms? • What data privacy laws (e.g., COPPA, FERPA, GDPR) need to be considered when considering virtual resources? • Who is responsible for managing data security and addressing any breaches? What funds are available for up-front costs associated with the purchase of software licences? • Are there educational licenses, discounts, or grants available for software or online platforms? • Are funds available for hardware upgrades if required? What existing virtual tools or resources are already available to the school or district, and how can they be leveraged for the program? • Are there open-source or free alternatives that meet the program's needs?
Development	What types of software or virtual tools are essential to support the program's goals (e.g., CAD software, coding platforms, project management tools)? How will the virtual tools that are being considered align with and support the planned curriculum and assessment methods? • Are there specific features of the software that can enhance learning outcomes (e.g., collaboration tools, simulations, or analytics)? • Are there specific skills (e.g., coding, design, digital collaboration) that virtual tools should help students develop? • How will virtual resources support creativity and innovation in student projects? • Can the virtual resources facilitate collaboration with external experts, community members, or other schools? • Are there online platforms or forums where students and educators can share their work or gain inspiration from others? Are the virtual resources being considered compatible with the school's existing hardware and IT infrastructure? • What hardware requirements (e.g., computer specifications, internet bandwidth) are necessary to run the software effectively? • How will the virtual resources be integrated into the school's network and systems? What are the costs associated with acquiring or subscribing to virtual resources, and how will these fit into the program's budget? How will students and educators access the virtual resources (e.g., individual accounts, shared logins)? • Are the virtual resources being considered easily accessible from both school and home environments? • What measures will be taken to ensure equitable access for all students, including those who may lack internet or hardware at home? • How will data privacy and security be managed for student and staff accounts?

Implementation	How will login credentials and access permissions be distributed to all users? What support will be available to staff and students as they familiarize themselves with the materials and equipment? • Are there user guides, tutorials, or help documents that can be made available to staff and students? • Who will be available to help with troubleshooting software problems, especially during the initial phases of implementation when educators are still getting used to the software? What mechanisms will be in place to address feedback and make improvements to virtual tools and their usage? • How will feedback about the effectiveness and usability of virtual resources be collected from staff and students? Are there contingency plans if additional virtual resources are needed unexpectedly?
Continuation	What mechanisms can be put in place to provide ongoing technical support for troubleshooting and resolving issues with virtual resources? How will licenses or subscriptions for virtual resources be managed, renewed, or updated over time? • What processes will be put in place to track software licenses, subscriptions, and renewal dates? • Can open-source or free alternatives replace any paid virtual tools without compromising quality? • How will updates or changes to virtual resources be communicated to staff and students? • Is there a budget reserved for this purpose? Are there plans to expand or diversify virtual tools and platforms to meet future program needs? • How will new virtual tools and platforms be evaluated and integrated into the program as technology evolves? How will usage of virtual resources be monitored and evaluated for effectiveness and relevance to the program? • What metrics will be used to evaluate the impact of virtual resources on learning outcomes and program success? Can these resources and insights be shared with other schools or programs looking to implement similar initiatives? • What system for documenting the virtual tools used in the program, their purposes, and best practices for implementation can be implemented?

<table>
<tr><th colspan="2">Guiding Questions Framework for Developing a Maker-Centered Education Program</th></tr>
<tr><th colspan="2">Virtual Resources</th></tr>
<tr><td>Planning</td><td>Who has existing expertise in maker-centered education, or at the very least, making, that can offer guidance to the team throughout the development of the program?
• Is there someone within the school district that is already involved in maker-centered education?
• Is there someone at a local library or a community makerspace that has experience with MCLEs or making?
• Is there an educational organization that has services related to the planning and integration of a maker-centered education program?
    o If so, are there fees associated with their services?
    o Are there funds available for such services?
Will additional staff be hired, or will existing staff take on new responsibilities?
• Does the school have funds to hire a specialized educator or maker expert ?
    o If so, for what role will they be hired?
        ▪ To run and maintain the makerspace and equipment?
        ▪ To assist educators with MCLEs?
        ▪ To teach courses specifically on design and maker-related processes?
        ▪ For all of the above?
Are there regulations that govern who can be involved in the program and its development (e.g. volunteers, industry professionals)?</td></tr>
<tr><td>Development</td><td>What specific roles are needed to support the program (e.g., program coordinator, educators, technicians, volunteers)?
• Who will prepare the space?
• Who will prepare the material and equipment?
• Who will set up the software and prepare the accounts for online platforms?
• What qualifications, skills, and experiences are required for these roles?
• How will roles and responsibilities be defined and communicated clearly to all team members?
• How will collaboration between makerspace staff and classroom teachers be facilitated? (if applicable)
Can volunteers (e.g., parents, community members, or local university students) play a role in supporting the program?
• How will volunteers be recruited, trained, and managed?
• What roles can the volunteers fulfill?
• Are there opportunities to involve industry professionals or experts as guest instructors, mentors, or consultants?
What qualifications, skills, and experience are necessary for staff and volunteers to fulfill their roles effectively?</td></tr>
</table>

Implementation	Who will be responsible for overseeing the program's day-to-day operations? • How can clear points of contact for addressing issues related to materials, virtual tools, or student concerns be established? How will the program's schedule be designed to accommodate staff availability and ensure smooth operation? • How will we manage staff workloads to ensure they are not overwhelmed by the program's demands? • How will staffing schedules be managed to ensure adequate supervision and support during all makerspace activities? • Are there procedures for managing sick leave, emergencies, or unexpected staff absences? o Can volunteers, community members, or external experts fill gaps in staffing, if needed? How will staff collaborate and communicate to ensure the program runs smoothly (e.g., regular meetings, digital communication tools)? • How will interdisciplinary collaboration between teachers (e.g., STEM and art educators) be encouraged and supported? • What opportunities will staff have to share feedback, ideas, and challenges with leadership and each other? How will volunteers and external experts be integrated into the program? • Who will be responsible for volunteer coordination? • What processes need to be in place to ensure volunteers and external contributors understand program goals and adhere to safety and operational standards? How will feedback from staff be collected to evaluate the program's staffing structure and effectiveness? • What systems will be in place to act on staff feedback and make necessary adjustments to roles, training, or resources?

Continuation	How will leadership plan for long-term staffing needs as the program grows and evolves?
	• How will the program address potential staff turnover or changes in team composition over time?
	    o What succession planning is in place to ensure program continuity in case of leadership or staffing changes?
	    o How will the program document staff expertise, workflows, and best practices to ensure knowledge transfer to future team members?
	• How will the program recruit and onboard new staff as needed, particularly those with specialized maker education skills?
	Will there be opportunities for staff to take on leadership roles within the program (e.g., mentorship, curriculum design, or community outreach)?
	What metrics or feedback mechanisms will be used to assess the effectiveness of the human resource structure of the program?
	• How will feedback from staff about their roles, workload, and experiences be collected and acted upon?
	• How will staff workloads be monitored to ensure staff is not overworked to prevent burnout?
	• How can the school determine whether staffing levels are sufficient to meet the program's current and future needs?
	As students gain experience over time, will there be opportunities for students to assist in the program by mentoring their peers or younger students in maker activities?
	How can the program maintain and expand its network of volunteers, community members, and external experts?
	• Are there opportunities to engage alumni or parents as volunteers or mentors?
	• What processes will be in place to ensure volunteers are effectively trained, supported, and integrated into the program?
	• How can the school show its appreciate for the volunteers?
	Can lessons learned from staffing the program be shared with other schools or programs to build a broader community of practice?

Guiding Questions Framework for Developing a Maker-Centered Education Program	
Virtual Resources	
Planning	What, if any, training and professional development does the organizing team need to best be able to plan a successful program? (This can include information seeking through visits at other schools with existing programs in addition to formal training.) What regulations, if any, govern what types of training can be done and who can receive training? What funds are available for training and professional development of this nature?
Development	What are the current skill levels of staff, and what gaps need to be addressed to prepare them for the program? • For equipment and tool use? • For software and online tools? • For making as a pedagogical approach? • For making connections with the curriculum? • For assessing learning that occurs as a result of making? (If applicable) Where are professional development opportunities, certifications, or workshops available for staff? • What is the format of the available training (e.g., in-person workshops, online courses, hybrid models)? • When are these professional development opportunities offered? • Will provisions like replacement teachers be required? Are there staff members with prior maker education or technical expertise who can serve as mentors or trainers? What external resources (e.g., online tutorials, maker education communities) can staff access for self-directed learning? What opportunities are there for staff to network with other educators or join professional communities focused on maker-centered education? What funds are available for training and professional development?
Implementation	How will staff be supported in addressing challenges or gaps in their knowledge as they arise? • What opportunities for ongoing professional development during the implementation phase will be available? • Will there be refresher sessions or additional training opportunities for staff who need extra support? • What will be the best format for ongoing training during the implementation phase (e.g., workshops, online courses, mentoring)? How will staff be supported in applying their training to real-world classroom and makerspace scenarios? • Will there be real-time support from those who offered the training? • Will external experts or consultants be brought in for advanced or specialized training? Will there be opportunities for staff to learn from each other through peer mentoring or collaborative teaching sessions? • How will staff collaborate and share insights or challenges with colleagues during the implementation phase? What training, if any, will volunteers need?

Continuation	How will professional development be embedded into the program's long-term plan? • What opportunities will be provided for ongoing professional development (e.g., advanced workshops, conferences, online courses)? • How can the school ensure differentiated training opportunities to support both beginners and advanced users of the makerspace, maker pedagogies, etc.? • How will staff stay updated on new technologies, tools, and best practices in maker-centered education? • What systems will be put in place to ensure that new staff members receive adequate training in the future? • What portion of the program's budget will be allocated to ongoing training and professional development? • Are there grants, sponsorships, or partnerships available that are specifically geared toward more advanced professional development activities? How will leadership ensure that safety training is continuously reinforced and updated as needed? How will leadership identify and address gaps in staff knowledge or skills over time? • What processes will be in place to evaluate and improve training based on staff experiences and outcomes? Are there plans to develop a professional learning community among staff to support ongoing growth and collaboration? • How will leadership encourage staff to take leadership roles in professional development, such as mentoring peers or leading workshops? • What opportunities will there be for staff to take leadership roles in professional development (e.g., leading workshops, sharing best practices) as they accumulate knowledge in the area? • What strategies will be used to build a culture of continuous learning and experimentation among staff? Could partnerships with universities, businesses, or professional organizations that can provide training or mentorship programs be developed? How can leadership recognize and celebrate staff participation in training and professional development? • Are there incentives, certifications, or other rewards for staff who complete advanced training or contribute significantly to the program?