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Exploring the Potential of 3D-printing in Biological Education: A Review of the Literature

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Abstract (227 words): Science education is most effective when it provides authentic experiences that reflect professional practices and approaches that address issues relevant to students' lives and communities. Such educational experiences are becoming increasingly interdisciplinary and can be enhanced using digital fabrication. Digital fabrication is the process of designing objects for the purpose of fabricating with machinery such as 3D-printers, laser cutters, and CNC machines. Historically, these types of tools have been exceptionally costly and difficult to access, however recent advancements in technological design have been accompanied by decreasing prices. In this review, we first establish the historical and theoretical foundations that support the use of digital fabrication as a pedagogical strategy to enhance learning. We specifically chose to focus attention on 3D-printing because this type of technology is becoming increasingly advanced, affordable, and widely available. We systematically reviewed the last 20 years of literature that characterized the use of 3D-printing in biological education, only finding a total of 13 articles that attempted to investigate the benefits for student learning. While the pedagogical value of student-driven creation is strongly supported by educational literature, it was challenging to make broad claims about student learning in relation to using or creating 3D-printed models in the context of biological education. Additional studies are needed to systematically investigate the impact of student-driven creation at the intersection of biology and engineering or computer science education.

Keywords: Life sciences; three-dimensional printing; learning; teaching; interdisciplinary

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Introduction

Digital fabrication in the form of 3D-printing has emerged as an innovative pedagogical approach to enhance Science, Technology, Engineering, and Mathematics (STEM) learning across a range of settings and for a variety of purposes. Evidence from the learning sciences suggests that individuals learn when they engage in the process of making through digital fabrication (Bevan 2017; Blikstein 2013; Papert and Harel 1991). Further, recent advances in fabrication technology accompanied by dropping prices have revolutionized what is possible to create in the modern world. Blikstein (2013) referred to this as the *democratization of invention* – any motivated individual can access the materials, tools, and expertise to create something of their own design. This revolutionary idea is the foundation of today's Maker Movement - a grassroots, Do-It-Yourself community of hobbyists, tinkerers, computer programmers, scientists, engineers, and artists (Resnick and Rosenbaum 2013; Martin 2015). This movement has spurred the creation of *educative making* as a pedagogical approach to support STEM learning in formal schooling (Bevan 2017). Previous research has positively connected educative making to learning gains in mathematics (Garneli et al. 2013), art (Peppler 2013), writing (Cantrill & Oh 2016), computing (Papert 1980), and spatial reasoning abilities (Leduc-Mills and Eisenberg 2011). It has also been associated with supporting development of twenty-first century skills, such as creative confidence (Barron and Martin 2016), self-efficacy and perseverance in problem-solving (Peppler and Hall

2016), resourcefulness (Sheridan and Konopasky 2016), and adaptive expertise (Martin and Dixon 2013).

Simultaneously, there have been increased calls for improving engineering and computer science education at a national level (Committee on STEM Education 2018; National Research Council [NRC] 2012; 2014). Digital fabrication is one effective approach that integrates engineering design and computing, providing an efficient mechanism to expose students to these disciplines. While many of these reform-based documents are specific to K-12 education, it follows that university-based educators should also heed calls to enhance their teaching through the inclusion of digital fabrication opportunities for college students. Brewer and Smith (2011), in their report identifying the actions necessary to improve biology education, emphasized the interdisciplinary nature of biology and noted that the most recent discoveries in the biological sciences have occurred only because there has been a blending of established disciplines. The future education of young scientists requires that long-standing divisions found in academic institutions begin to blur or even break down existing silos completely (NRC 2010). This change in education to focus attention more broadly on training our STEM workforces does not exclude our future physicians, as they also should be educated broadly with a focus on integrative and interdisciplinary courses (NRC 2009).

However, many studies investigating educative making have occurred in selective spaces (e.g., high school robotics clubs) or with specialty groups (e.g., pre-professional students). We advocate that this pedagogical approach should be used in the context of formal classrooms and laboratories, places that are accessible to more individuals. Current evidence suggests that the United States will need 1 million *more* STEM professionals than it is expected to produce in the next decade (National Science Board 2020). Moreover, the diversity of the STEM workforce is still vastly unrepresentative of the United States population in terms of gender and ethnicity. For example, in 2017, only 29% of individuals in the STEM workforce identified as female (National Science Board 2020). Similarly, the number of underrepresented minorities (URM) in STEM careers continues to lag behind the overall population: only 13% of individuals who identified as Black, Hispanic, American Indian or Alaska Native were employed in a STEM career compared to 28% of the total US population (National Science Board 2020). Digital fabrication in the form of 3D-printing is one mechanism that holds promise for appealing to diverse groups of individuals. However, regardless of future career aspirations, it is imperative that *all* individuals have opportunities to gain technological fluency in the twenty-first century. This echoes past calls of increasing scientific literacy for the general populace to prepare well-educated citizens who are capable of understanding and interacting with scientific ideas in their everyday lives (DeBoer 2001).

To understand how and in what ways educative making has been used to support efforts in the context of biology education, we conducted a systematic literature review guided by the following question: *How is digital fabrication in the form of 3D-printing used to support biological education?* To answer this question, we first provide an overview of historical and theoretical views on learning that support the use of educative making before reviewing current literature. Indeed, there are decades of research across education and psychology that support the use of educative making to enhance learning. These historical and theoretical views on learning support our claim that *students should create in order to learn.* We argue that an understanding of these views is essential for all and should not be isolated to the domain of social scientists and educational researchers. We explicitly discuss these works in the context of a journal for scientists to label them and to provide resources and justification for those working to enhance their own teaching practices in an era of increased accountability and university budget cuts (e.g., Burke and Gordon 2020). Importantly, we need educators to be the voice for best practices as many of the pedagogical suggestions in this paper run counter to current demands to increase class enrollments and shift coursework online (e.g., Chirikov et al. 2020).

The drive to develop curriculum that engages students to create is not new and we can see it as early as 1762 when Jean-Jacques Rousseau (1712-1778) advocated for a new method of education (Martinez and Stager 2013). Rather than simply telling students what they need to know, Rosseau (1762) argued for a *student-centered* approach that valued the learner as a thinking being. This view runs counter to common lecture-based teaching methods that "tell" students what is important. Rousseau was one of the first to advocate for a student-centered teaching approach (Cremin 1964). These ideas were expanded by Friedrich Froebel (1782-1852), who developed "Froebel gifts" to aid in learning; objects such as geometric and pattern blocks (Martinez and Stager 2013). Using physical objects to support learning is still a common practice in teaching today; for example, consider an organic chemistry course that invites students to use three-dimensional models to support visualization of complex molecules. Additionally, Maria Montessori (1870-1952) worked to develop a "scientific pedagogy" of education, based on psychology and experimental methods (Montessori 2013). Like Froebel, Montessori saw the need to engage learners in sensory experiences to support their development.

Importantly, these ideas are viewed by some as foundational to today's Maker Movement that calls for student-driven creation of meaningful artifacts (Blikstein and Worsley 2016).

Further, John Dewey (1859-1952)'s focus on experiential learning also speaks to the value of educative making as a pedagogical approach. Dewey was an American philosopher and psychologist who is widely regarded as one of the most influential education reformists of the twentieth century (Cremin 1964). To Dewey, the school was seen as a lever of social change (Cremin 1964). This sentiment resonates with past calls to ensure all citizens are scientifically literate (DeBoer 1991), as well as current calls to broaden participation in the STEM workforce (National Science Board 2020). Dewey (1938) was a proponent of the "continuity of experience," positing that disconnected experiences between home and school can be disruptive to a learner's intellectual growth. The term *growth* is often associated with Dewey's educational philosophy, but Dewey (1938) believed that growth occurred through the purposeful progression of carefully selected *experiences*, designed to bring individuals to realize their full worth and potential in the world, or to reach self-realization. Educative making provides a mechanism to realize Dewey's radical visions for activity-driven lessons that are relevant to students' lives and the larger society. Recent technological advancements in fabrication technology have afforded new tools for student creation that instructors can use to enhance their teaching practices. Dewey's (1897; 1902; 1938) work is often cited as justification for *experiential learning* - the idea that students learn knowledge and skills from participating and reflecting on direct experiences situated in the world (not necessarily a classroom). William Heard Kilpatrick (1918), influenced by Dewey, argued that curriculum should engage students in meaningful activities that start with their own interests, rather than predetermined subject matter. This type of pedagogy has become known as *project-*

based learning and is a current practice in many schools today, aligning well with educative making approaches. Students can engage in meaningful projects to fabricate objects that enhance their STEM learning.

Paulo Freire (1921-1997) is another significant figure often cited as justification for the Maker Movement (Blikstein 2013; Blikstein and Worsley 2016). To Freire (1970), education and social identity were intricately connected, and he believed it was through honest, trusting dialogue that people were better positioned to reflect upon and recognize the realities of their world and begin to formulate plans of action for liberation. This pedagogical approach is called *critical pedagogy* (Blikstein 2013). Freire advocated for “problem-posing education,” situated in local and personal problems, with the aim of allowing students to critically analyze the realities of their world and begin to conceptualize possibilities for creating change. A modern application of Freire’s ideas is found in Blikstein’s (2008) work with youth in an impoverished Brazilian city. Blikstein conducted a two-week workshop designed for students to select a personally relevant problem in their community and design a solution that involved technology. He found students took on a “re-purposing” culture, remixing and reusing old or defective technologies in novel ways. Further, Blikstein (2013) argued that educative making provides an opportunity to validate low-income students’ personal experiences: they may be able to leverage existing technical expertise situated within their community where manual, blue-collar work is more common. In short, technology has democratized and enhanced what individuals are capable of creating in the modern world.

The experiences students have in the classroom have been influenced by a number of theoretical perspectives on learning. Burrhus F. Skinner (1904-1990) was a prominent American psychologist and behaviorist who had a highly reductionist view of learning. According to Skinner, behavior is modified by consequences and learning involves reproducing behaviors that have positive outcomes while avoiding behaviors that have negative outcomes (Skinner 1974). Skinner (1984) argued that learning can be maximized through programmed instructional materials by teachers trained in behavioristic approaches. This approach, however, largely ignored the fact that internal thoughts and feelings influence an individual's actions (Deprato and Midgley 1992). Remnants of Skinner's learning theory of *behaviorism* are still evident in schooling practices today (e.g., awards and certificates to reward behavior; detention as a consequence to deter behavior; rigid and standardized curriculum), however scholars throughout the twentieth century pushed back on his reductionist conceptions of learning and development in favor of theoretical orientations that considered the individual as a thinking being, capable of acting in accordance with their free will.

Jean Piaget (1896-1980) was a Swiss psychologist who is credited with developing the fields of developmental psychology, cognitive theory, and evolutionary epistemology. Piaget considered learners as "active builders of knowledge" and this view forms the foundation of his learning theory of *constructivism* (Papert 1999). Constructivism is viewed as a theory of learning in contrast to Skinner's behaviorism (Fosnot and Perry 1996). Constructivism's implications for teaching and learning are significant. Piaget's (1980) theory of constructivism was focused on cognitive development and deep understanding; instead of viewing learning as a linear path, it was seen as complex and multi-faceted. Constructivism is often cited as theoretical justification for *active learning* approaches that call for instructors to provide opportunities for students to activate prior knowledge on a specific topic, stop and process new information in connection to their past experiences, and actively apply this new information to a relevant task. Again, educative making provides a mechanism to guide planning of relevant learning tasks connected to students' prior knowledge and lived experiences.

Seymour Papert (1928-2016) is considered the "father" of today's current Maker Movement (Martinez and Stager 2013). In his seminal book, *Mindstorms: Children, Computers, and Powerful Ideas,* Papert (1980) advocated for learners to program the computer, as opposed to the computer programming the child. Having worked with Piaget during the 1960s, Papert was greatly influenced by his work and used Piaget's theory of constructivism to formulate a new theory of learning, *constructionism*. This theory suggests that people learn best when making an artifact for public consumption (Papert and Harel 1991). In contrast to constructivism, Papert's (1991) theory of constructionism can apply to both a teaching and learning perspective. Individuals learn best when they are constructing, but educators can also use this to guide their instructional design and teaching. Importantly, constructionism, as a theory of teaching, contrasts transmission models of instruction—students who are simply told how to solve a problem, rather than experiencing how to solve a problem, often fall short of meaningful learning that is assimilated.

The act of creating an object through digital fabrication in the form of 3D-printing holds great promise for learning. Historical and theoretical views have encouraged learning through creation for hundreds of years, yet recent advancements in technology have revolutionized what individuals are capable of creating in the modern world. Many K-12 schools and universities are adding spaces on campus to create, sometimes referred to as makerspaces, fabrication labs, or design studios. However, many of these spaces are still reserved for select courses (e.g., studio art; engineering) and are not used in an interdisciplinary manner across courses. Moreover, specific types of content areas, such as life science, are less represented in the research literature. To understand how and in what ways student-driven creation using 3D-printing has been incorporated in biological education efforts, we conducted a systematic literature review spanning the years 2000 to early 2020 and discuss the sparsity of efforts to integrate these in a systematic manner. We conclude with recommendations for educators and directions for future research.

Research Methods

The following overarching question guided our literature review: *How is digital fabrication in the form of 3D-printing used to support biological education?* While we recognize there are other tools that can support active construction (i.e., CNC machines, laser cutters), we specifically focused attention on the 3D-printer as a tool of construction because of its increasing use in university settings accompanied by decreasing prices (Barrett et al. 2015). Further, we specifically limited our search to studies that investigated student or teacher outcomes connected to 3D-printing in the context of life science or biology education across the schooling experience (K-12; undergraduate; and graduate studies) to document promising pedagogical practices and identify gaps for future research at the intersection of biology and engineering or computer science education.

Data Collection

We first specified a set of appropriate search engines and search terms in consultation with our project team and university librarian. Our team specifically included a faculty member with expertise in biology (Lent) and STEM education (Hansen), as well as student researchers.

Ultimately, we included the following online databases in our search due to their focus on science and/or education research: 1) Association for Computing Machinery Digital Library (ACM), 2) Wiley Online Library, 3) EBSCO Education Source, 4) Springer Online, 5) ScienceDirect, and 6) The National Science Teaching Association (NSTA). We avoided database aggregators (i.e. Web of Science, Google Scholar) due to the varying criteria for inclusion in these types of databases. The key search terms used were “3D printing” AND “Biology OR Life Science” AND “Education OR Teaching OR Learning,” as well as derivatives of these terms. Our search was also limited from the years 2000-2020 because access to 3D-printing technology has increased in this time frame due to dropping prices and technological advancements. It is important to note that this search was conducted at the beginning of 2020, so only articles published in January or February 2020 were included in the review. This yielded a total of 454 articles across the various search engines.

Data Analysis

Next, as a team, we evaluated each paper based on Kitchenham’s (2004) predetermined quality criteria to determine suitability for inclusion in this review. Specifically, we ensured each article was unbiased, internally valid, and externally valid. A study was considered *unbiased* if the authors identified sufficient details about the overall research aims, participants, data collection methods and analysis, as well as findings and implications connected to relevant past studies. A study was considered *internally valid* if the overall design was likely to minimize systematic error within the study. Finally, a study was considered *externally valid* if the effects observed were likely applicable outside of the study. In short, we included empirical articles with sound research designs and potentially generalizable results.

In our evaluation, we only included peer-reviewed studies in the form of journal articles or conference proceedings that had an explicit connection to biology or life science. The studies we included represented a variety of research methodologies, ranging from qualitative case studies with limited numbers of participants to quasi-experimental methods seeking to test specific interventions and simultaneously control extraneous variables. Additionally, we included studies that focused attention on any type of student or educator, ranging from K-12 schools to pre-professional, graduate programs. Most excluded articles were removed due to their lack of focus on students, teachers, or learning. A large number of studies were also excluded for failing to focus attention on the life sciences specifically. Recall that our goal was to review studies that investigated the benefits of incorporating 3D-printing for the learning or teaching process in the life sciences. Our team met on a weekly basis over the course of 6 months to evaluate the 454 articles included in the review. Discussion was used to reach consensus if opinions differed about whether to include an article in the review. In total, we found 13 articles that met our criteria (see Table 1).

Results

The following section provides an overview of the 13 studies that met our criteria for inclusion (see Appendix A). First, we describe the type of research (quantitative, qualitative, or mixed methods), the disciplinary content focus area, and the participants involved in the studies. Then, we provide an overview of how 3D-printing was used to enhance teaching or learning, as well as data collection methods for assessing the learning experience. Finally, we discuss the overall significance of these findings and conclude with recommendations for future research.

Type of Research

We used Creswell's (2009) descriptions of research designs to classify the studies included in this review as quantitative, qualitative, or mixed methods. According to Creswell (2009), *quantitative* studies seek to examine relationships among variables, most often through instruments designed to measure specific constructs and generate numerical data for statistical analysis; whereas *qualitative* studies seek to explore and understand participants' perceptions or experiences in a particular setting about a social or human problem, most often through interviews, focus groups, or researcher observations that are analyzed inductively to generate descriptive themes that reflect the complexity of the situation. Finally, *mixed methods* studies use both quantitative and qualitative data. For example, a mixed methods study might involve collecting quantitative survey data using Likert-scale responses, but supplement the quantitative data with qualitative data such as participant interviews or observations.

The majority of studies included in our review reported quantitative (6) or mixed methodologies (5), with fewer studies (2) reporting qualitative research designs. Of the quantitative studies, most (5 out of 6) reported using Likert-scale survey instruments: half of these studies (3) used a survey to evaluate the students' overall *experience or satisfaction* after using or making 3D-printed models, whereas the remaining half (3) used surveys to assess changes in students' *conceptual understanding* of course content after using 3D-printed models. Similarly, all of the mixed methods studies also administered surveys to evaluate participants' overall satisfaction before and/or after using 3D-printed models; yet these studies included additional types of qualitative data (e.g., focus groups, student work samples, observations). Finally, both qualitative studies primarily relied on observations of students working with 3D-printed materials.

Context: Subjects & Students

All studies included in the review related to biology or life science education, more broadly. A closer inspection of the specific disciplinary content areas revealed greater diversity in foci. Most studies investigated 3D-printing in the context of anatomy (4) or molecular biology and biochemistry (3) courses. Other studies focused attention on 3D-printing in the context of environmental science (1), physical therapy (1), veterinary medicine (1), dentistry (1), biomechanics (1), and general STEM coursework (1). Most studies investigated 3D-printing in the context of undergraduate coursework (6) or graduate coursework (4). Fewer studies (2) investigated the use of 3D-printed materials with K-12 students. Finally, only 1 pilot study included participants from multiple age demographics (high school and undergraduate).

Data Collection Techniques

The most common type of data collected across all 13 studies included in this review was survey responses from participants. However, most studies (11) only used surveys to evaluate the user's experience after using 3D-printed materials, not to assess their learning. Of these studies, over half (6) used a Likert-scale survey that was designed by the authors; only 2 of these studies explicitly mentioned the additional inclusion of qualitative, open-ended questions. The remaining studies that used surveys (5) were also designed by the authors, but did not use a Likert-scale design. Less than half (5) of these studies reported on measures taken to validate the survey instruments. Only 3 studies included in this review administered a pre/post conceptual assessment to measure changes in students' learning as a result of using or making 3D-printed materials.

Other types of data collection were less common across the studies. Specifically, only 3 studies reported using observations of participants engaged in learning activities. Similarly, only 2 studies conducted focus groups for participants to elaborate on their experiences or survey responses. Only 2 studies used student work samples as evidence of learning. Finally, only 2 studies included course grades as a measure to evaluate students' learning outcomes.

What was printed? How was it used?

In order to evaluate the breadth of purposes for using 3D-printed materials to enhance biological education, we also analyzed what each study printed and how they used the created artifacts. The majority of studies (6) printed models of bones, organs, or specific features of the human body (e.g., Pterygopalatine fossa; teeth) for use in anatomy or health science courses. Three studies investigated the use of 3D-printed models of complex molecules or proteins for use in biochemistry coursework; two of these studies also included a digital interface to use in conjunction with the physical models. An additional two studies focused attention on 3D-printing objects for special populations of students, specifically printing assistive technologies for physical therapy and printing tactile images of two-dimensional photographs for use in undergraduate STEM laboratory courses by students who are blind or visually impaired (BVI). Finally, 2 studies investigated the use of 3D-printing for K-12 students. One of these studies investigated 3D-printing using plastic salvaged from the ocean to expose children to environmental science and sustainability concepts. The remaining study reported using 3D-printed materials in a STEM outreach event facilitated by undergraduate students to excite younger students about the study of biomechanics.

Impact on Learning

Only 4 studies specifically measured changes in students' conceptual understanding related to course content after using 3D-printed materials: all of these studies reported an increase in conceptual gains when students were allowed to use printed models. However, most studies included in this review (8) only reported findings related to student satisfaction using 3D-printed materials. In these cases, all 8 reported positive student perceptions. One study was unique in that it sought to measure young students' self-identity as a scientist and engineer, attitudes toward engineering, and attitudes toward biomechanics after participation in an outreach activity using 3D-printed materials; results indicated significant gains in all three areas that were assessed.

Discussion

This paper provides a systematic review of the literature investigating the potential of 3D-printing for teaching and learning in biological education throughout the twenty-first century (2000 - 2020). Only 13 of the 454 articles reviewed met our criteria for inclusion (see Appendix A). The main reason most articles were excluded (411 of the 454) was because they were not education focused (i.e. related to educational research) or related to biological or life sciences. Of the remaining 30 excluded articles, 15 were not related to 3D-printing and 15 were not empirical or student-centered studies. All included articles used 3D-printing in the context of biology or life science settings and attempted to evaluate the impact on students. The type of students varied across studies, ranging from elementary school children to graduate students pursuing professional degrees in health science fields. The most common methods of investigation were quantitative, with many studies reporting the use of Likert-scale surveys. However, most survey instruments were designed by the authors of each study and fewer yet reported their procedures for survey validation. Further, most surveys were used to evaluate the students' satisfaction using 3D-printed materials rather than conceptual changes in their understanding of course content. Most studies used 3D-printed models for the study of human anatomy (e.g., bones, teeth, organs) or the study of molecular biology (e.g., proteins, complex molecules).

In general, all studies reported positive student outcomes connected to using 3D-printed materials. However, due to the limited nature of data collected and analyzed across the studies, it is challenging to make broad claims about student learning in relation to using or creating 3D-printed models in the context of biological education. Many studies failed to collect multiple types of data to triangulate their findings. One study emerged as a notable exception. Howell et al. (2019) included three types of data (satisfaction surveys, conceptual assessments, and focus groups) in their analysis to generate evidence-based claims about student learning in relation to using 3D-printed materials in combination with interactive learning modules. This was the only study that reported using three types of data in their analysis and was thus able to make more robust claims about the value of 3D-printing for learning. Future studies should use mixed methods research designs that investigate the impact on student or teacher learning across multiple sources of data.

Of particular absence in the reviewed studies were investigations focused on educators. Not one study specifically focused attention on the professional development required for instructors to incorporate digital fabrication in the life sciences. We recognize that the training needs would differ based on university and K-12 settings. For instance, university STEM faculty may need targeted professional development about the value of student-centered approaches for learning, whereas K-12 teachers may need support connected to the technology itself and engineering or computer science content. Future studies should investigate the professional development support necessary for K-16+ educators to incorporate digital fabrication in the context of biological education.

New Directions: Students as Creators

We only found one study that investigated students acting as creators using 3D-printing technologies. Vones et al. (2020) described a 3D-printing workshop that allowed children to create objects using ocean plastic to learn about engineering and environmental sustainability principles. This was the only study that positioned students as creators. According to historical and theoretical perspectives on learning, students should be actively engaged in the design process, constructing a meaningful object to share with the world. We argue that this is a significant gap in the current literature.

Future research should investigate the learning that occurs when students create using technology, particularly in the life science domains. Studies investigating bioinspired design courses are promising contexts to conduct future research at the intersection of biology and engineering education and are becoming increasingly common in undergraduate education (Nagel et al. 2016). For example, the University of California, Berkeley currently offers a bioinspired design course that intentionally recruits students from different majors across campus. Students have access to a design studio with fabrication technology and work in diverse groups to engage in bioinspired design projects using knowledge of engineering, biology, medicine, art, architecture, and business. Past projects have included gecko-inspired adhesives, running robots, and medical prosthetics. Similarly, many K-12 schools have innovative programs and projects (e.g., Cook et al. 2015; Newley et al. 2019), but often lack the capacity to conduct rigorous research to investigate student learning outcomes in a systematic manner. Following recent calls from the National Academies of Sciences, Engineering, and Medicine (2020), we propose that university-based educators collaborate with K-12 schools to further investigate student learning outcomes in engineering and computer science. This collaboration can enhance continuity of learning experiences across a students' educational career, as advocated for by Dewey (1938).

During our literature search, we also considered other types of technology beyond 3D-printing that hold promise for integrating biology and engineering or computer science education. We identified several articles that used 3D-modeling and digital fabrication that were ultimately not 3D-printing (e.g., virtual reality, augmented reality). Similar to our review of papers focused on 3D-printing, we found that most of these studies did not investigate learning outcomes or position students as the creators. As technologies advance, more tools become available to enhance the way in which students learn and how educators engage students in content. We argue that any new technology implemented in the classroom should be implemented in a way that involves students in the creative process. Moreover, these technologies must be user friendly for both educators and student creators.

Conclusion

We evaluated 20 years of literature in our attempt to characterize the use of 3D-printing in biological education. While it is likely that we missed some studies in our pursuit, we were surprised by the lack of systematic investigations that examined the impact of 3D-printing on student learning in the life sciences. Past historical and theoretical works have shown the benefits of engaging students in the act of creation to solve interdisciplinary projects, but the use of this pedagogical approach in the life sciences is significantly lacking in the overall research literature. The historical and theoretical foundation provides a guide on how to be effective educators. As Skinner (1984) told us, those delivering the content must learn how to do so. Educators need to be more than just content experts. They need to realize that effective education must be a continual experience connecting all aspects of a student's life (Dewey 1938) and we need to do more than reproduce the status quo because we are responsible for democratizing science and making education equitable (Freire 1970). Students should not be viewed as empty vessels, but rather as participants in the creation and construction of knowledge (Papert and Harel 1991). We have known for more than a hundred years that the act of making holds tremendous promise in education and we are in an era that affords the opportunity to realize that promise.

We argue for additional studies to investigate the impact of student-driven creation at the intersection of biology and engineering or computer science education using mixed methods research designs that account for both the students' satisfaction and conceptual understanding of course content. We also strongly recommend that educational researchers and content experts in the biological and life sciences form partnerships, learn from one another, and work towards the goal of developing and properly assessing curriculum that engages students and educators as creators. Through more robust and systematic studies, we can develop the necessary evidence base to support broad changes in educator professional development practices and overall policy decisions about the value of students engaging in interdisciplinary projects that allow for active construction using cutting-edge technology.

Author's Contributions

A.K.H and D.D.L contributed to the conceptualization of the article. A.K.H., T.R.L., L.W.M., K.P., J.R., and D.D.L contributed to the data collection. A.K.H. analyzed and collated the final data set. A.K.H, T.R.L., L.W.M., K.P., J.R., and D.D.L contributed to the writing of the manuscript.

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Data Availability

The data underlying this article are available in the article and appendix.

References

Barrett, T, Pizzico, M, Levy BD, Nagel, RL, Linsey JS, Talley KG, Forest CR, Newstetter WC. 2015. *A review of university maker spaces.* Georgia Institute of Technology.

Barron B, Martin CK. 2016. Making matters: A framework for assessing digital media citizenship. In K Peppler, E Halverson, YB. Kafai (Eds.), *Makeology: Makers as learners* (45-71). New York, NY: Routledge.

Blikstein, P. 2008. Travels in troy with Freire: Technology as an agent of emancipation. In P. Noguera & C. A. Torres (Eds.), *Social justice education for teachers: Paulo Freire and the possible dream* (205-244). Rotterdam, Netherlands: Sense.

Bevan B. 2017. The promise and the promises of making in science education. *Studies in Science Education, 53*(1), 75-103.

Blikstein P. 2013. Digital fabrication and 'making' in education: The democratization of invention. In J Walter-Herrmann, C Büching (Eds.), *FabLabs: Of machines, makers and inventors*. Bielefeld: Transcript Publishers.

Blikstein P, Worsley M. 2016. Children are not hackers: Building a culture of powerful ideas, deep learning, and equity in the maker movement. In K Peppler, E Halverson, YB Kafai (Eds.), *Makeology: Makerspaces as learning environments* (64-80). New York, NY: Routledge.

Brewer CA., Smith D. 2011. *Vision and Change in Undergraduate Education A Call to Action.* American Association for the Advancement of Science.

Burke M., Gordon L. "Newsom's proposed budget cuts to higher education force difficult choices ahead." *EdSource*, 15 May. 2020.

Cantrill C, Oh P. 2016. The composition of making. In K Peppler, E Halverson, YB Kafai (Eds.), *Makeology: Makerspaces as learning environments* (107-120). New York, NY: Routledge.

Chirikov I, Semenova T, Maloshonok N, Bettinger E, & Kizilcec R. F. 2020. Online education platforms scale college STEM instruction with equivalent learning outcomes at lower cost. *Science Advances*, *6*(15), eaay5324.

Committee on STEM Education. 2018. Charting a course for success: America's strategy for STEM education. *National Science and Technology Council*, 1-48.

Cook KL, Bush SB, Cox, R. 2015. Creating a prosthetic hand: 3D printers innovate and inspire a maker movement. *Science and Children, 53*(4), 80.

Cremin LA. 1964. *The transformation of the school: Progressivism in American education*, 1876–1957. New York, NY: Vintage Books.

Creswell J.W. 2009. *Research design: Qualitative and mixed methods approaches.* London and Thousand Oaks: Sage Publications.

DeBoer, GE. 1991. *A history of ideas in science education: Implications for practice*. New York, NY: Teachers College.

Delprato, DJ., Midgley, BD. 1992. Some fundamentals of BF Skinner's behaviorism. *American psychologist*, *47*(11), 1507.

Dewey, J. 1897. My pedagogic creed. *School journal, 54*(3), 77-80.

Dewey J. 1902. *The child and curriculum.* Chicago, IL: University of Chicago Press.

Dewey J. 1938. *Experience and education*. New York, NY: Kappa Delta Pi.

Freire P. 1970. *Pedagogy of the oppressed.* New York, NY: Bloomsbury Publishing.

Fosnot, CT, Perry, RS. 1996. Constructivism: A psychological theory of learning. In C.T. Fosnot (Ed.), *Constructivism: Theory, perspectives, and practice* (8-33). New York, NY: Teachers College Press.

Garas M, Vaccarezza M, Newland G, Mcvay-Doornbusch K, Hasani J. 2018. 3D-Printed specimens as a valuable tool in anatomy education: A pilot study. *Annals of Anatomy - Anatomischer Anzeiger*, *219*, 57–64. doi: 10.1016/j.aanat.2018.05.006

Garcia-Bonete MJ, Jensen M, Katona G. 2019. A practical guide to developing virtual and augmented reality exercises for teaching structural biology. *Biochemistry and Molecular Biology Education*, *47*(1), 16-24.

Garneli B, Giannakos MN, Chorianopoulos K, Jaccheri L. 2013 Learning by playing and learning by making. In M Ma, MF Oliveira, S Petersen, JB Hauge (Eds.), *Serious games development and applications* (pp. 76-85). Berlin, Heidelberg: Springer.

Gillet A, Sanner M, Stoffler D, Olson A. 2005. Tangible Interfaces for Structural Molecular Biology. *Structure*, *13*(3), 483–491.

Hasper E, Windhorst R, Hedgpeth T, Van Tuyl L, Gonzales A, Martinez B, Yu H, Farkas Z, Baluch, DP. 2015. Methods for Creating & Evaluating 3D tactile images to teach STEM courses to the visually impaired. *Journal of College Science Teaching*, 44(6), 92-99

Howell ME, Booth CS, Sikich SM, Helikar T, Roston RL, Couch BA, Dijk K. 2019. Student Understanding of DNA Structure–Function Relationships Improves from Using 3D Learning Modules with Dynamic 3D Printed Models. *Biochemistry and Molecular Biology Education*, *47*(3), 303–317.

Kilpatrick WH. 1918. The project method. *Teachers College Record, 19*(4), 319-335.

Kitchenham, B. 2004. Procedures for performing systematic reviews. *Keele, UK, Keele University*, *33*(2004), 1-26.

Leduc-Mills M, Eisenberg M. 2011. The UCube: A child-friendly device for introductory three-dimensional design. Proceedings from IDC '11: *The Tenth International Conference on Interaction Design and Children*. New York, NY: ACM.

Li F, Liu C, Song X, Huan Y, Gao S, Jiang Z. 2017. Production of accurate skeletal models of domestic animals using three-dimensional scanning and printing technology. *Anatomical Sciences Education*, *11*(1), 73–80.

Lohning AE, Hall S, Dukie S. 2019. Enhancing Understanding in Biochemistry Using 3D Printing and Cheminformatics Technologies: A Student Perspective. *Journal of Chemical Education*, *96*(11), 2497–2502.

Lozano MTU, Damato R, Ruggiero A, Manzoor S, Haro FB, Méndez JAJ. 2018. A study evaluating the level of satisfaction of the students of health sciences about the use of 3D printed bone models. *Proceedings of the Sixth International Conference on Technological Ecosystems for Enhancing Multiculturality - TEEM18*.

Martin L, Dixon C. 2013. Youth conceptions of making and the Maker Movement. Proceedings from IDC '13: *The Twelfth International Conference on Interaction Design and Children*. New York, NY: ACM.

Martin L. 2015. The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research, 5*(1), Article 4. https://doi.org/10.7771/2157-9288.1099

Martin L, Dixon C. 2016. Making as a pathway to engineering and design. In K Peppler, E Halverson, YB. Kafai (Eds.), *Makeology: Makers as learners* (183-195). New York, NY: Routledge.

Martinez SL, Stager G. 2013. *Invent to learn: Making, tinkering, and engineering in the classroom.* Torrance, CA: Constructing Modern Knowledge Press.

Mcdonald S, Comrie N, Buehler E, Carter N, Dubin B, Gordes K, … Hurst A. 2016. Uncovering Challenges and Opportunities for 3D Printing Assistive Technology with Physical Therapists. *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS 16*.

Montessori M. 2012. *The montessori method.* New York, NY: Transaction publishers.

Nagel JK, Pittman P, Pidaparti R, Rose C, Beverly C. 2016. Teaching bioinspired design using C–K theory. *Bioinspired, Biomimetic and Nanobiomaterials*, *6*(2), 77-86.

National Academies of Sciences, Engineering, and Medicine. 2020. *Building Capacity for Teaching Engineering in K-12 Education*. Washington, DC: The National Academies Press.

National Research Council. 2010. *Synthetic Biology: Building on Nature's Inspiration.* Washington, DC: The National Academies Press.

National Research Council. 2012. *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

National Research Council. 2014. *STEM integration in K-12 education: Status, prospects, and an agenda for research.* Washington, DC: National Academies Press.

National Science Board, National Science Foundation. 2020. *Science and Engineering Indicators 2020: The State of U.S. Science and Engineering*. NSB-2020-1. Alexandria, VA.

Newley A., Kaya E, Yesilyurt E, & Deniz, H. 2019. Animatronic Lions, and Tigers, and Bears, Oh My! *Science and Children, 56*(8), 64-71.

O'reilly MK, Reese S, Herlihy T, Geoghegan T, Cantwell CP, Feeney RN, Jones JF. 2015. Fabrication and assessment of 3D printed anatomical models of the lower limb for anatomical teaching and femoral vessel access training in medicine. *Anatomical Sciences Education*, *9*(1), 71–79.

Papert S. 1980. *Mindstorms: Children, computers and powerful ideas*. New York, NY: Basic Books.

Papert S, Harel I. 1991. Situating constructionism. *Constructionism, 36,* 1-11.

Papert, S. 1999. Papert on Piaget. *Time magazine's special issue on "The Century's Greatest Minds,"* 105.

Peppler K. 2013. STEAM-powered computing: Using e-textiles to integrate the arts and STEM. *Computers and Education, 46*, 38-43.

Piaget J. 1980. The psychogenesis of knowledge and its epistemological significance. In M Piattelli-Palmarini (Ed.), *Language and learning: The debate between Jean Piaget and Noam Chomsky*. Cambridge, MA: Harvard University Press.

Resnick M, Rosenblum E. 2013. Designing for tinkerability. In M Honey, D Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 163-181). New York, NY: Routledge.

Reymus M, Fotiadou C, Kessler A, Heck K, Hickel R, Diegritz C. 2018. 3D printed replicas for endodontic education. *International Endodontic Journal*, *52*(1), 123–130.
Rousseau JJ. 1762. *Émile, ou De l'éducation*. Cityone de Geneve.

Sheridan KM, Konopasky A. 2016. Designing for resourcefulness in a community-based makerspace. In K Peppler, E Halverson, YB Kafai (Eds.), *Makeology: Makerspaces as learning environments* (30-46). New York, NY: Routledge.

Skinner, BF. 1974. *About behaviorism.* New York: Knopf.

Skinner, BF. 1984. The shame of American education. *American Psychologist*, *39*(9), 947.

Tanner JA, Jethwa B, Jackson J, Bartanuszova M, King TS, Bhattacharya A, Sharma R. 2020. A Three-Dimensional Print Model of the Pterygopalatine Fossa Significantly Enhances the Learning Experience. *Anatomical Sciences Education*.

Teeter SD, Husseini NS, Cole JH. 2020. Assessing changes in attitudes toward engineering and biomechanics resulting from a high school outreach event. *Journal of Biomechanics*, 109683.

Vones K, Allan D, Lambert I, Vettese S. 2018. 3D-printing ‘Ocean plastic’–Fostering children’s engagement with sustainability. *Materials Today Communications*, *16*, 56–59.

Table 1. *Total studies reviewed versus included*

Database	**Total**	**Included in Review**
ACM	152	2
Wiley	7	4
EBSCO	8	2
Springer	53	0
ScienceDirect	216	4
NSTA	18	1
Total	454	13

Appendix A. Studies included in review

No.	**Authors, Years**	**Journal / Conference**	**Area of Study**	**Participants**	**Sample Size**	**Methodology**	**Instruments**	**Printed models**
1	Gillet et al. 2005	*Tangible Interfaces for Structural Molecular Biology*	Molecular Biology	High School & College Students	N/A	Qualitative	Observations	Augmented Reality (AR) & 3D-printed models for complex molecules
2	O'Reilly et al. 2015	*Anatomical Sciences Education*	Anatomy	Medical Students	22	Mixed	Likert-scale student satisfaction survey with open-response questions	3D printed anatomical models of the lower limb
3	Hasper et al. 2015	*Journal of College Science Teaching*	STEM	College students who are blind or visually impaired (BVI)	14	Mixed	Student satisfaction survey & Focus groups	3D printed tactile images of visual laboratory materials (pictures)
4	McDonald et al. 2016	*ASSETS '16 Proceedings of the 18th International Conference on Computers & Accessibility*	Physical Therapy	Physical Therapy Faculty & Physical Therapy (PT) students	4 PT faculty; 65 PT students	Mixed	Pre/post student satisfaction surveys; Student design projects Faculty survey to understand liability issues	3D printed Assistive Technologies for Physical Therapy
5	Li et al. 2016	*Anatomical Sciences Education*	Veterinary Medicine	Pre-veterinary students	203	Quantitative	Likert-scale student satisfaction survey	3D printed skeletal models of domestic animals

6	Vones et al. 2018	*Materials Today Communications*	Environmental Science	K-12 students	6	Qualitative	Student design projects; Observations	3D printing objects from ocean plastic
7	Reymus et al. 2019	*International Endodontic Journal*	Dentistry	Dental students	105	Quantitative	Student satisfaction survey	3D printed models of teeth
8	Lozano et al. 2018	*TEEM'18: Proceedings of the Sixth International Conference on Technological Ecosystems for Enhancing Multiculturality*	Anatomy	College students	280	Quantitative	Likert-scale student satisfaction survey	3D printed models of bones
9	Garas et al. 2018	*Annals of Anatomy-Anatomischer Anzeiger*	Anatomy	College students	23	Quantitative	Likert-scale student satisfaction survey; Pre/post conceptual assessment	3D printed models of heart, shoulder, and thigh
10	Lohning et al. 2019	*Journal of Chemical Education*	Biochemistry	College students	201	Mixed	Student satisfaction survey with open-response; course grades	3D models of proteins
11	Howell et al. 2019	*Biochemistry and Molecular Biology Education*	Biochemistry	College students	130	Mixed	Student satisfaction survey; Pre/post conceptual assessment; Focus groups	3D printed models and interactive learning modules

12	Tanner et al. 2020	*Anatomical Sciences Education*	Anatomy	College students	118	Quantitative	Likert-scale satisfaction survey; Pre/post conceptual assessment	Pterygopalatine fossa
13	Teeter et al. 2020	*Journal of Biomechanics*	Biomechanics	High School students	200	Quantitative	Pre/post Likert-scale survey about identity and attitudes	3D printing outreach activity for high school students