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Integrating Making with Authentic Science Classes: An Approach and Evidence

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Abstract

Although research has touted the value of making in educational settings, scant work has been done in formal school contexts utilizing quantitative methods. This could be attributed to the various challenges in integrating making in school settings. To fill in the gap, this study presents an approach to integrate making into science classes at the 3rd to 5th grade levels in a U.S. public school for four consecutive years (2015–2019). We examined the effect of the program on students' self-beliefs (self-efficacy, motivation, and self-concept) using a longitudinal quasi-experimental design. We also examined the effect of making on students' knowledge and skills using state testing data. Results suggest that when averaged across post school year surveys, students in maker classes (vs. control) reported higher self-efficacy beliefs in science and making as well as more interests in STEM-related careers. Moreover, over two school years, we observed that students in the control group experienced declines on some of our variables while our maker students did not. Data thereby speaks to the potential value and promise of integrating making into formal school settings. Practical implications are discussed.

Keywords Making · Digital fabrication · Teaching/learning strategies · Elementary education · Science education · Interactive learning environments · Applications in subject areas · Formal school contexts · STEM · STEM identities · Self-efficacy

Introduction

Since the hype days of making in the 2010s, a large amount of work has been done on integrating making in educational settings in the service of learning, particularly the learning of STEM. As much prior literature has noted (e.g., Lin et al., 2020; Timotheou & Ioannou, 2019), this work has mostly been situated in informal or semi-formal settings. Literature on making in formal contexts is scarcer because it is quite challenging for researchers to integrate technologies and pedagogies that are not part of traditional schooling practices into the classroom. The few projects that have attempted to integrate making in authentic classrooms have generally found positive value in integrating making into learning. However, each has adopted different ways of implementing making into the formal context of interest; no consensus has yet been reached on what works well and what does not. As noted by Tan (2019), there is still immense research value in understanding how different instructional designs of making integration affect the conceptual (i.e., learning and understanding) and dispositional (i.e., attitudes and mindsets) competencies of students.

Our research deployed a maker program for four years in a public elementary school in the U.S., where 3rd to 5th grade students (8 to 11 years old) engaged in maker activities for a week at a time in their regular science classes. We sought to address whether and how making affects students' self-beliefs (self-efficacy, motivation, and self-concept) in making, science, and STEM fields *overall* and *over time*. We focused on self-beliefs because they are considered key to students' future academic successes (e.g., Taylor et al., 2014) and career choices (e.g., Wang, 2013). In addition to self-beliefs, we also

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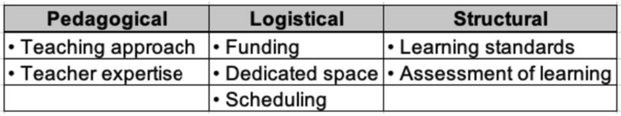
examined the effect of making on students' knowledge and skills. Together, our goal is to elucidate the value and promise of integrating making in formal classrooms.

Below, we begin by further elaborating on why making integration in formal settings merits research. We then provide a review of the different approaches that prior projects have used to integrate making into formal schooling. Next, we describe our model for making integration—our model presents a practical, rather than idealistic, approach that navigates the somewhat rigid constraints of the public school system in the United States, such that the goal of making integration in schools is actually achievable, instead of being a vision that only exclusive schools are able to attain. After that, we present the data we collected over the years of the program and conclude with a discussion that situates the contribution of our model and charts future research directions.

Background

Even though making has persistently been touted as a revolutionary way for teaching and learning (Bevan, 2017; Blikstein, 2013; Halverson & Sheridan, 2014; Kit Ng et al., 2022), it is enormously difficult to systematically and longitudinally implement making as an educational paradigm in authentic classrooms. In fact, a large proportion of studies that have integrated making into schools have been conducted in schools that have a different status from the mainstream public schools in one way or another. For example, studies have been conducted in private or charter schools (e.g., Litts et al., 2017), magnet schools with highly gifted or privileged children (e.g., Tan, 2019), public schools with unique and visionary administrative leadership that are willing to revamp their structure and curriculum (e.g., Henderson et al., 2017; Trahan et al., 2020), innovation schools that adopt different educational approaches (e.g., Flores, 2018), or schools in countries with much more open educational systems (e.g., Leinonen et al., 2020; Riikonen et al., 2020). These studies have their own merits (e.g., via demonstrating the utility of making), but their limited scope makes it difficult for researchers and policymakers to generalize their insights into mainstream public schools, where the bulk of the student population can be reached. This is exacerbated by the constraints that have to be addressed for making integration in formal settings. Below we classify and summarize the constraints as addressing the *pedagogical*, the *logistical*, and the *structural* aspects of schooling (see Fig. 1).

The pedagogical aspects involve primarily two problems: first, the need to change the approach to teaching in the classroom, and second, the lack of teacher expertise. According to Godhe et al.'s (2019) critical analysis of issues relevant to the integration of making in schools, changes in the pedagogical approach can include a repositioning of the teacher from a "sage on the stage" to a "guide on the side," allowing students to "mess around" or "tinker" without necessarily always being explicitly "on-task," a reconceptualization of what is considered "on-task" in the first place, and engaging students in projects that are "open-ended, collaborative and experimental" in nature. Since these pedagogical changes require very different skillsets from teachers, coupled with the interdisciplinary nature of making projects, a need for substantial professional development (PD) for teachers arises. For example, Trahan et al. (2020, p. 135) described how "substantial time and effort were given for a wide range of PD so that teachers could lead the 39 making related classes and utilize the 15 spaces (six at middle school and nine at high school) that came with the integration of making." This is problematic since few school districts are able to invest that significantly in training in-service teachers.



Pedagogical	Logistical	Structural
• Teaching approach	• Funding	• Learning standards
• Teacher expertise	• Dedicated space	• Assessment of learning
	• Scheduling	

Fig. 1 Issues in making integration into formal educational contexts

Logistical constraints consist of the limited resources that many public schools are typically subject to, and scheduling constraints that need to be taken into account. Unlike one-off technologies such as the purchase of laptops and tablets, making activities require both one-off equipment purchases (e.g., microcontroller boards and soldering stations) and the acquisition of consumables (e.g., wires, LEDs, and motors), which may be different from activity to activity. Based on their experience of integrating making in a 4th-grade science unit, Smith and Smith (2016, p. 33) acknowledged that "the first-year cost was substantial due to the purchase of nonconsumable materials, including the MaKey and Hummingbird Robotics Kits," and subsequently commented that "schools with limited budgets may want to consider applying for grants and contacting their parent-school organizations to help fund the materials." Resource limitations may also sometimes involve a lack of dedicated space to turn into a makerspace and for the storage of equipment and materials.

Another logistical constraint is that of scheduling, that is, the rigidity of class organization that public schools are usually required to adhere to. Classes are held according to a predefined timetable and designed to last a fixed amount of time per day. While not a problem in itself, this approach to class organization may clash with the voluntary nature of one's engagement in making activities (Dougherty, 2013), and the extended amount of time that making projects need to be completed.

Last but not least, structural constraints have been highlighted in much prior literature (e.g., Cohen et al., 2017; Godhe et al., 2019). Key characteristics that define the formality of formal educational contexts are first, the fact that they are structured around predetermined learning goals and standards and, second, the fact that students' performance with respect to these standards is sooner or later assessed in some way (Eshach, 2007). However, learning from making projects tends to be more emergent in nature (Godhe et al., 2019), since it is difficult to predict exactly all the subsets of knowledge and skills that a student would need to complete a making project from the onset. And moreover, how to assess learning in the context of a making project is as of yet unclear. Evaluation of learning outcomes in makerspaces is still a very active area of research (Lin et al., 2020).

Given the unique constraints present in traditional public schools, it is important to fill in the gap on how to integrate making in such settings. We present one such effort in a mainstream public school in the United States. We are particularly interested in ways of integration that are immediately applicable to the current context of such schools. Godhe et al., (2019, p. 324) concisely articulated the significance of our interests through the following: "arguments that maker technology is an inherently 'disruptive innovation' that extenuates the need to reinvent the current 'factory' model of mass schooling will contribute little to the improved introduction of maker technologies into schools in the near future. The 'status quo' is unlikely to radically alter over the next few years."

Before we present our own approach, in the next section, we first review similar attempts to integrate making into formal school contexts. We abstract out how they had addressed the issues that we described above based on information available in their associated publications.

Related Work

We reviewed the literature on making integration in formal school contexts and selected 14 papers that detailed making projects. The selection of the projects was guided by the following rationale: the paper described a making project that was deployed in a school setting; the project described engaged students who were enrolled at the school (vs., e.g., children brought to the school for the purpose of the project); the paper presented an evaluation component that described at least some results of the making project; and the paper provided enough details that we can analyze how the making project was implemented. Even though the focus of our own making program was on deployment in science classes, we included projects that took place in other broadly related subject matters. This is because our goal here is to understand the approach by which making is deployed instead of the details of the making activities themselves. Our analysis of the 14 making projects revealed the different ways by which they each approached the pedagogical, logistical, and structural aspects of making integration. We summarize main details of the approaches in terms of the integration context, teaching approach, and alignment to learning standards. We also summarize the effects of making that these projects have documented on students. A table summarizing our analysis of the 14 projects can be found in the Appendix.

In the projects reviewed, making was integrated predominantly in the context of a science class (e.g., Nugent et al., 2014; Smith & Smith, 2016; Tofel-Grehl et al., 2017), followed by in a technology class (e.g., Koh et al., 2019; Vuopala et al., 2020) or a craft class (e.g., Leinonen et al., 2020). In some cases, students worked on making projects at school but these were not tied to any particular class, for example, as part of a research program (e.g., Tan, 2019). Making activities in which students were engaged included general crafts, electronics, 3D printing, e-textiles, and robotics. In 6 projects, students' making activities were personalized to their interests, contexts, etc., and in 6 others, all students were made to do making activities that were essentially the same for all groups. In 2 projects, students were first engaged in generic making activities, before progressing to personalized activities.

In terms of the teaching approach adopted, we found 5 strategies that have been used in prior projects. *Direct instruction* of the skills and concepts needed by students to complete the making activities was common. In several projects, *mini-lessons* were provided in a "just-in-time" fashion as specific skills become needed by a project group. In other cases, the teacher adopted more of a facilitator role and *guided students' exploration* rather than providing instruction directly. The 2 last strategies that we saw used were *peer mentoring* and *external consultancy*. With peer mentoring, older students were present to mentor younger students in their making activities. With external consultancy, two projects enabled students to connect with external mentors for help and guidance.

In terms of learning standards, as per the typical requirements of formal educational settings, most of the making activities attempted to cover some kind of curriculum. The majority of the projects aimed to cover *cross-cutting or multidisciplinary concepts in science, computer science/information technology, or design*. For instance, the making program at Hillbrook Independent School in the 5th and 6th grade observed by Flores (2018) was aligned with the "Next Generation Science Standards" (NGSS), a set of expectations for science content used by many states in the U.S. Litts et al. (2017) describe a maker program focusing on codeable circuits that embedded computer science knowledge expected from typical high school computer science curricula such as the "K–12 Computer Science Framework." And Leinonen et al.'s (2020) making program in Finland focused on delivering multidisciplinary design skills such as creative brainstorming and prototyping. A few projects were aligned only with *specific* *content topics*. For example, the project reported by Tofel-Grehl et al. (2017) was tied to the science unit on electricity and the one by Becker and Jacobsen (2019) to the science unit on sky science. Last but not least, in 2 projects, the learning goals of the making activities were left to be *emergent*. That was in the case of a making project in preschool (Peppler et al., 2019), where learning standards are usually not as stringent and in a markedly unique school in Singapore (Tan, 2019).

In terms of how making affects students, we found that most of the projects indicated positive gains in *knowledge and skills* of the targeted content (e.g., Litts et al., 2017; Nugent et al., 2014; Vuopala et al., 2020). Other effects of making included positive changes in students' *attitudes and mindsets* (e.g., self-efficacy, Flores, 2018) and *knowledge and skills at a meta level* (e.g., a better understanding of the inquiry learning process, Becker & Jacobsen, 2019), critical and design thinking (Forbes et al., 2021), and teamwork (Peppler et al., 2019). A few projects also indicated effects on students' *emotional states* (e.g., excitement and satisfaction, Koh et al., 2019; Leinonen et al., 2020) and *self-understanding* (e.g., understanding of themselves as learners, Becker & Jacobsen, 2019; Yu-mei et al., 2017).

Overall, multiple attempts have been made to integrate making into formal education settings and have yielded promising results. However, these efforts differ from one another (in some cases substantially) in how to implement making. While this could be attributed to the differences in specific contexts where the approaches were developed, the varieties in making implementations do create a problem as it is unclear what is *essential* to such implementations (e.g., a practitioner may wonder whether he/she should or should not make making activities generic given the constraints of the school; see Papavlasopoulou et al., 2016). Relatedly, the implications of making integration are somewhat unclear, owing to both differences in implementing making and the variety of variables assessed in previous studies. Admittedly, more data is in need to fully address these issues, but the challenges inherent in formal settings present a major roadblock to extensive data collection. Below, we present our approach to integrate making in science classrooms that is meant to be a synthesis of past attempts and a meaningful starting point for future research efforts.

Our Approach to Making Integration in Public Schools

Our project integrated making into science classes at the 3rd to 5th grade levels in a public school in the United States for four consecutive years (2015–2019). Making was done during the regular time slots (that ranged from 30 min to 1.5 h depending on the grade level) assigned to the science class every day. Interventions lasted for one week of every science unit in the school curriculum. The elementary school academic calendar in the school district was such that each six-week period addressed one science unit. For a 36-week academic year, this totaled up to 6 six-week periods or 6 science units being addressed. In other words, we deployed one maker week per science unit.

Making activities were designed by the research team in consultation with the teachers, and each science lesson of the maker week consisted of five main parts: (i) initial instruction by the teacher; (ii) making instruction by a member of the design/research team; (iii) students' engagement in making; (iv) conducting a science exercise with the artifacts made; and (v) post-exercise notetaking and discussion led by either the teacher or the researcher. More specifically, instruction for the making activities in the classroom was delivered by a postdoctoral researcher with a doctorate degree in education. She was assisted in the classroom by a computer science doctoral student, who was also the lead in the design of the making activities, as well as by one to two psychology undergraduate students. The postdoctoral researcher was involved in the design process of all the making activities and was consequently familiar with all the materials. In the classroom, she followed a lesson plan designed for each making activity. The lesson plans were designed by a doctoral student in science education, in collaboration with the postdoctoral researcher herself. Oversight was provided for all the making activities, materials, and lessons by a faculty member trained in computer science and electrical engineering.

We developed our approach to integrate making activities into formal classes so that the activities may work within the different constraints imposed in public schools. On the dimensions reviewed above, our approach can be characterized as follows:

- Integration context: the making activities were deployed in science classes and were the same for all students;
- Teaching approach: the teaching strategies involved direct instructions and 'just-in-time' mini-lessons;
- Alignment to learning standards: the making activities were aligned to specific science content topics as per the learning standards dictated by the state.

We found that it is not manageable to personalize making projects in a class of the size that is typical in mainstream public schools, even though helpers were brought to the classroom to assist the students. Direct instructions were still needed on the science concepts being addressed by the making activities. Some direct instructions on making concepts and skills were also provided but were limited. For making concepts and skills, instructions were provided mostly in a "just-in-time" fashion either as a class or to individual student groups as needed. This was because first, science was required to be the focus of the class, and not making, and second, the various student groups had very different pacing in terms of how fast they could complete the making tasks and faced different types of difficulties. And finally, it was critical that we aligned the making activities with the science learning goals that the teacher already meant to cover in the class at that point of time.

Regarding the specific making activities, we developed and deployed three general types: *making enables science learning*, *making to demonstrate science learning*, and *learning of the making tools themselves*. Below in the "Making-Based Classroom Activities: Two Examples" section, we briefly describe two examples of how we integrated making into science classes. Details of other examples can be found elsewhere (Schlegel et al., 2019). For the first type, *making enables science learning*, students would build tools that lead them to learn a science concept. The first example in the "Making-Based Classroom Activities: Two Examples" section of students building mother and child cup robots to learn inherited and learned traits falls into this category. The second type entails engaging in *making to demonstrate science learning*. The second example in the "Making-Based Classroom Activities: Two Examples" section of students building a lighted quiz board to classify animal environments falls into this category. And the third type is about *learning of the making tools themselves*. An example of this type is a making activity where students built circuits in order to learn about circuits themselves. We did not prescribe the type of making activity for an intervention before the design of the activity itself. The type of activity was decided based simply on what the best fit was for the science learning standard and the making progression at the time of the intervention. However, we typically ended up with at least one or two making activities of each of the three types in one school year.

Making-Based Classroom Activities: Two Examples

The first example of our making integration is a making activity for the fifth-grade science unit on "Inherited and Learned Traits." (Fig. 2). The learning objective is for students to understand that inherited traits transfer from a "parent" to a "child," whereas learned traits are acquired through a learning process. In the making activity, students built a Styrofoam mother cup robot and a child cup robot. They used the modeling software TinkerCad to design feet for the cup robots and 3D print them. While they could design different feet for the mother and child, the feet for the two needed to share similar traits. The teacher or mentors went around to check the students' designs for inherited traits and discussed with them before the feet were printed. Students could also use markers and colored paper to decorate their cup robots with facial traits, which should also have similarities. Afterwards, students created electronic circuits with vibrating motors that they attached to the cup robots to enable them to move around. By switching the circuit on and off, the students were able to create different "dance patterns." They could create completely different dance patterns for the mother and the child, indicating that dance moves are learned.

The second example concerns the third-grade science curriculum unit, "Organisms and Environment". Students built a parallel circuit attached to a quiz board (Fig. 3 left). They then pasted printed pictures of environments (jungle, tundra, savanna, and desert) (Fig. 3 right) onto the quiz board. Questions were then shown to the students on a large screen display, and each student pair had to light up the LED associated with the correct environment. Examples of questions posed are "This environment has an extremely cold climate" and "This type of environment is known for having a rainy climate and lush green vegetation Fig. 3."

Research Methods

Research Design and Participants

We conducted a longitudinal quasi-experimental study to evaluate the effectiveness of our program. Specifically, we collected data by administering pre and post surveys at the beginning and the end of each school year to students in our

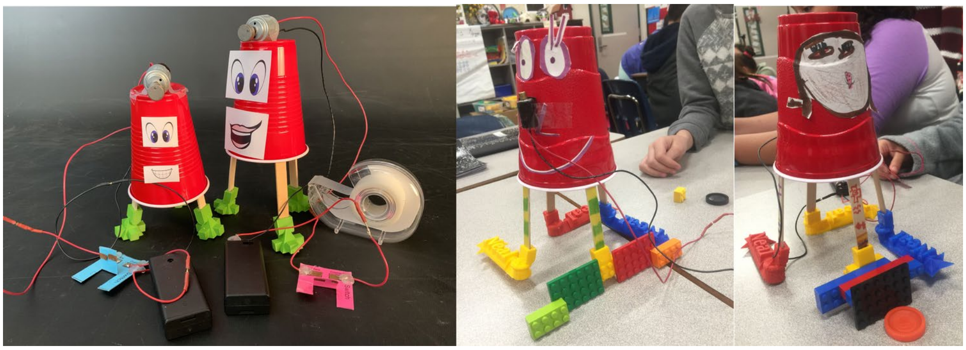


Fig. 2 Making activity for fifth-grade science unit, "Inherited and Learned Traits"

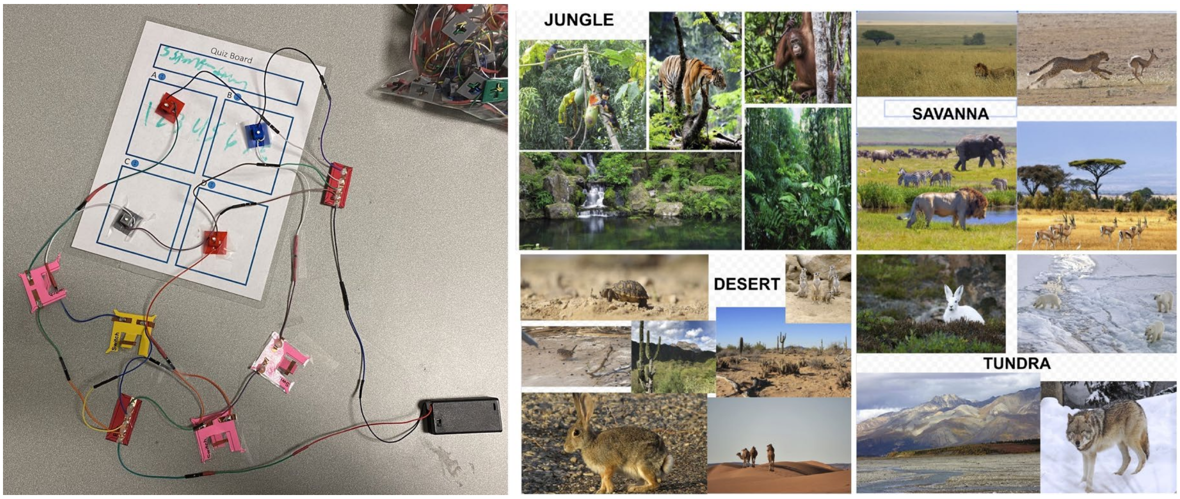


Fig. 3 Maker activity for third-grade science unit, “Organisms and Environment”

making program as well as to students in multiple control classes within the same school. This design allowed us to assess the potential causal effects of making and track how differences between maker and control classes vary over time (Kim & Steiner, 2016). In addition to survey data, we also obtained state standardized testing data and compared the maker group to the control group on this variable.

We recruited a sample of 358 students in the maker program (250 Hispanic, 83 African American, 15 Caucasian, 1 Multiracial, 9 Unknown) in 3rd to 5th grade classrooms (students aged 8 to 11 years) and a sample of 1046 students from unselected classes as the control group (737 Hispanic, 173 African American, 113 Caucasian, 13 Multiracial, 10 Other, or Unknown). Classes to participate in the maker program were chosen by the school principal based on different factors of her own discretion. We then used the unselected classes at the same grade level as our control classes. For example, during most years there were four teachers at each grade level, among which two were selected to be in the program by the principal and the classes of the remaining two would serve as our control classes. Most of the students in our target school were from underrepresented groups in STEM (72% Latino, 26% African American, 96% on reduced lunch programs, > 50% Low-English Proficiency). Due to the instability of the student population of our focal school (i.e., students move in and out of the specific campus and school district on a frequent basis),[1] the majority of our sample in the maker group (79.1%) were in the program for one entire school year. About 29.3% of the students were in the program for two consecutive school years. Just as students in the maker group, most students (66.5%) were in the control group for one school year; a minority of students (4%) were in the control group for two consecutive school years.

Research Questions

We were primarily interested in the following research questions:

1. What are the overall effects of our making program on children’s self-beliefs, more specifically, on self-efficacy (i.e., individuals’ evaluations that they have the ability to perform well, Bandura, 1982), motivation (Ryan & Deci, 2000) and self-concept (Markus & Nurius, 1986) in making, science and more general STEM contexts?
2. How do these differences between maker and control classes vary over time?

As suggested by our brief review of the literature (see the “Related Work” section above), making could result in positive changes in students’ *attitudes and mindsets* and *self-understanding* (e.g., Becker & Jacobsen, 2019; Flores, 2018; Yu-mei et al., 2017). Self-beliefs capture aspects of *attitudes and mindsets* and *self-understanding* that are deemed key to academic success and career selection (e.g., Taylor et al., 2014; Wang, 2013). Thus, our hypothesis was that students in our maker program (vs. the control group) should report more positive self-beliefs in making, science and more general STEM fields *overall*, i.e., across post surveys.

For the role of time, due to the instability in our sample, we decided to look at the temporal change from the beginning of the program to the end of the second school year, as

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[1] In cases of students transferring from the maker class to the control class (or vice versa), we retained their survey data until the point of transfer (e.g., students who transferred from maker to control would only have maker entries in our dataset); for state testing data, we dropped their data entries entirely.

this strikes a balance between the available sample and our research interests. Given research suggesting that students generally experience a decrease in self-efficacy and self-concepts in STEM-related areas during elementary and high school (Eccles et al., 1997; Fredricks & Eccles, 2002; Gottfried et al., 2001; Jacobs et al., 2002; Lofgran et al., 2015; Watt, 2004), we hypothesized that students in the control group should experience similar negative self-changes. However, this should not be the case, or at least less so, for students in the maker group. Initial results based on the data of the early years of this project did suggest that making had promising influences on students' self-beliefs (Schlegel et al., 2019).

In addition to self-beliefs, we also wondered if making could lead to positive gains in students' *knowledge and skills*, as suggested by previous research (e.g., Litts et al., 2017). To address this question, we compared the maker group to the control group on state standardized testing data we obtained.

Data Collection

We measured nine variables that tap into three general types of self-beliefs—self-efficacy, motivation, and self-concept—in making, science and more general STEM fields: (1) maker self-efficacy, (2) science self-efficacy, (3) making interests, (4) science interests, (5) STEM career interests, (6) science-related job interests, (7) maker identity, (8) science identity, and (9) STEM possible selves. Most of our survey measures (with the exception of science-related job interests discussed below) took the format adapted from The Self Perception Profile for Children' (SPPC; Harter, 1985) that was originally designed to measure children's self-esteem (Muris et al., 2003): In a "structured alternative format," the students were given a pair of statement about themselves: one affirmative and one negative. For example, "Being good at writing is an important part of who I am" versus "This is not a very important part of who I am"). Students were asked to first choose one statement out of the two and then rate the extent to which that statement was true of them ("sort of true" OR "really true"). We ensured students understood the survey format by giving them a practice item at the beginning of each survey. The survey items were then recoded onto a 4-point Likert scale where higher numbers indicate more positive self-beliefs.

Maker and Science Self-Efficacy

We measured the self-efficacy of students in two domains: maker ($M = 2.98$, $SD = 1.00$) and science ($M = 3.13$, $SD = 0.94$). Each domain was measured by having participants pick between two face-valid items adapted from Bandura (2006): "I am good at building or making things" VS. "I'm not very good at building or making things" for maker self-efficacy, and "I feel I am very good at science" VS. "I worry whether I can do the assigned science work" for science self-efficacy.

Making and Science Interests

We measured students' interests in both making ($M = 3.20$, $SD = 0.93$) and science ($M = 3.44$, $SD = 0.84$), each with one face-valid item. Making interests were assessed by having students choose between "I like to build or make things" and "I don't really like to build or make things". Science interests were measured by having students choose between "I like science" and "I do not like Science."

STEM Career and Science-Related Job Interests

We assessed students' interests in STEM careers by adapting the measure used by Robnett and Leaper (2013). Students were given seven STEM-related careers: scientist, engineer, science teacher, math teacher, computer programmer, astronaut, doctor. For each career, they rated whether they would want to have them in the future (e.g., "I want to become an astronaut when I grow up" VS. "I want to be something different"). Students' responses to the seven items were internally consistent ($\alpha = 0.75$) and were averaged ($M = 2.13$, $SD = 0.72$). For students' interests in science-related jobs, we developed a more idiographic measure. Students were first asked to list a job that "someone who is good at science might have." Then they rated how much they would like to have that job on a 5-point Likert scale (1 = *not at all*; 3 = *somewhat*; 5 = *a lot*, $M = 3.51$, $SD = 1.36$).

Maker and Science Identity

We adapted the Maker Mindset Assessment (The Maker Effect Foundation, 2015) into a 12-item scale to measure students' maker identity (i.e., the extent to which students see making as an important part of who they are). Students were asked to choose between statements like "I like making things with my hands" and "I don't like making things with my hands"; their responses were internally consistent and averaged ($M = 3.20$, $SD = 0.53$, $\alpha = 0.81$). Meanwhile, we assessed science identity (i.e., the extent to which students see science as an important part of who they are) with another single-item measure that read: "Being good at science is an important part of who I am" VS. "This is not a very important part of who I am" ($M = 3.12$, $SD = 0.97$).

STEM Possible Selves

We measured STEM possible selves (i.e., the beliefs about having a job someday involving STEM-related activities) with

Table 1 Post academic year effects of maker intervention on survey variables

	Condition						
	Maker	Control					
Variables	*M* (*SD*)	*M* (*SD*)	*t*	*df*	*p*	*d*	95% CI
Maker self-efficacy	3.11 (0.91)	2.86 (0.98)	3.77	929	<0.001	0.26	[0.12, 0.38]
Science self-efficacy	3.20 (0.92)	3.04 (0.94)	2.48	942	0.01	0.17	[0.03, 0.29]
Making interests	3.15 (0.88)	3.12 (0.97)	0.49	933	0.63	0.03	[− 0.10, 0.16]
Science interests	3.35 (0.89)	3.35 (0.85)	−0.10	941	0.99	0.001	[− 0.12, 0.12]
STEM career interests	2.30 (0.73)	1.98 (0.67)	6.77	958	<0.001	0.47	[0.23, 0.42]
Science-related job interests	3.52 (1.41)	3.21 (1.33)	3.38	1010	0.001	0.23	[0.13, 0.49]
Maker identity	3.18 (0.62)	3.17 (0.50)	0.30	514.77	0.76	0.02	[− 0.07, 0.09]
Science identity	3.13 (0.94)	3.02 (0.97)	1.61	940	0.11	0.11	[− 0.02, 0.24]
STEM possible selves	2.93 (0.71)	2.88 (0.66)	1.04	962	0.30	0.07	[− 0.04, 0.14]

a seven-item scale adapted from Anderman and colleagues' work (1999). The seven items contained pairs of statements that begun with "I might have a job where I…." VS. "I probably won't have a job where I…" and ended with "help build things," "discover new things," "make and invent new things," "use technology every day," "uses math," "uses science," and "uses writing." Students were asked to choose and rate the statements that they believed were true of them. Responses to the seven items were internally consistent ($\alpha = 0.77$) and were collapsed into one composite ($M = 2.89$, $SD = 0.70$).

State Testing Data

Fifth-grade students receive the local state's assessments of academic readiness for science near the end of the school year. The test involves every science unit covered during the year. Third-grade and fourth-grade students do not receive science examination from the state. As such, we only examined the state testing data of fifth-grade students.

Results

We first examined whether our maker intervention (vs. control) had an *overall* effect on self-beliefs. We aggregated participants' scores on each of the nine self-variables across post surveys. We then performed independent-sample *t*-tests via the software SPSS comparing the maker and the control group on the aggregated scores. The results are presented in Table 1. The analyses revealed significant differences in *maker self-efficacy*, *science self-efficacy*, *STEM career interests*, and *science-related job interests*. When aggregated across post-surveys, students in the maker (vs. control) group generally reported more self-efficacy in making and science as well as more interests in STEM careers and science-related jobs. Meanwhile, students' STEM possible selves along with their identity and interests in making and science did not differ between the intervention group and the control group. These patterns in part confirmed our expectation, suggesting that making has benefits on at least some aspects of self and identity.

We proceeded by taking into account the factor of time and examining how differences between maker and control group varied throughout two school years. We conducted a 2 (intervention: maker vs control) × 2 (time: pre-survey at year 1 vs post-survey at year 2) multivariate analyses of variance (MANOVA) on each self-belief variables. Multivariate analyses revealed a significant main effect of time, F (9, 95) $= 4.24$, $p < 0.001$, Wilk's $\Lambda = 0.71$, and partial $\eta^2 = 0.29$. The main effect of intervention was not significant, F (9, 95) $= 1.18$, $p = 0.32$, Wilk's $\Lambda = 0.90$, and partial $\eta^2 = 0.10$. The two-way interaction approached significance but did not cross the 0.05 level of significance, F (9, 95) $= 1.85$, $p = 0.07$, Wilk's $\Lambda = 0.85$, and partial $\eta^2 = 0.15$. Turning to univariate analyses, estimates of main effects are presented in Tables 2 and 3; estimates of the two-way interaction are presented in Table 4. Given the large amount of comparisons involved, here we focused on the findings of primary interest (i.e., the interaction between intervention and time).

As can be seen in Table 4, the analyses revealed significant two-way interactions predicting *science self-efficacy*, *maker self-efficacy*, *science interests*, *making interests*, and *STEM career interests*. The two-way interaction approached, though did not reach, the 0.05 level of significance for *STEM possible selves*. We conducted simple effect analyses for each of these interactions (see Table 5). The general pattern of results is consistent with our hypothesis: over time, students in the control group tended to report decreased self-efficacy beliefs and less interests in making and science. They also reported decreased interests in STEM careers (and to a lesser extent in possible selves). The negative self-change seemed not to be the case—or at least less so—for students in the maker group. The latter seemed to be able

Table 2 Univariate analyses on the main effect of maker intervention on survey variables

Variables	F	p	η_p^2	Intervention	M (SE)
Maker self-efficacy	1.06	0.31	0.01	Maker	3.18 (0.08)
				Control	3.03 (0.12)
Science self-efficacy	1.18	0.28	0.01	Maker	3.24 (0.07)
				Control	3.40 (0.12)
Making interests	0.01	0.91	0.00	Maker	3.36 (0.07)
				Control	3.35 (0.11)
Science interests	0.36	0.55	0.004	Maker	3.49 (0.08)
				Control	3.59 (0.13)
STEM career interests	1.89	0.17	0.02	Maker	2.38 (0.07)
				Control	2.20 (0.11)
Science-related job interests	0.02	0.90	0.00	Maker	3.77 (0.12)
				Control	3.74 (0.19)
Maker identity	0.01	0.92	0.00	Maker	3.36 (0.04)
				Control	3.35 (0.07)
Science identity	0.001	0.98	0.00	Maker	3.29 (0.08)
				Control	3.29 (0.12)
STEM possible selves	0.18	0.67	0.002	Maker	3.00 (0.07)
				Control	3.06 (0.11)

$df = (1, 103)$

to retain their previous levels of self-beliefs over time, and even reported an increase on one of the key variables (i.e., science self-efficacy).

Last, to test if making led to positive gains in *knowledge and skills*, we examined the difference between the maker and the control group in fifth-grade students' state science examination percent scores. An independent-samples t-test failed to reveal a significant difference between the maker group ($M = 0.67$, $SD = 0.17$) and the control group ($M = 0.67$, $SD = 0.19$), $t(1356) = 0.02$, $p = 0.99$, $d = 0.00$, and 95% CI [−0.04, 0.04]). The null finding could be attributed to the fact that the questions in the exams involved topics not covered by our intervention (as we only intervened for 1 week out of every 6 weeks in a school year). We will return to this issue in the next section.

Table 3 Univariate analyses on the main effect of time on survey variables

Variables	F	p	η_p^2	Time	M (SE)
Maker self-efficacy	1.43	0.24	0.01	Pre-survey at year 1	3.19 (0.09)
				Post-survey at year 2	3.03 (0.10)
Science self-efficacy	0.58	0.45	0.01	Pre-survey at year 1	3.27 (0.11)
				Post-survey at year 2	3.37 (0.09)
Making interests	7.92	0.006	0.07	Pre-survey at year 1	3.50 (0.07)
				Post-survey at year 2	3.21 (0.10)
Science interests	3.54	0.06	0.03	Pre-survey at year 1	3.64 (0.08)
				Post-survey at year 2	3.44 (0.10)
STEM career interests	3.44	0.07	0.03	Pre-survey at year 1	2.38 (0.08)
				Post-survey at year 2	2.20 (0.08)
Science-related job interests	13.36	< 0.001	0.12	Pre-survey at year 1	4.13 (0.14)
				Post-survey at year 2	3.38 (0.16)
Maker identity	0.06	0.81	0.001	Pre-survey at year 1	3.36 (0.05)
				Post-survey at year 2	3.35 (0.05)
Science identity	0.88	0.35	0.01	Pre-survey at year 1	3.36 (0.10)
				Post-survey at year 2	3.23 (0.10)
STEM possible selves	0.11	0.74	0.001	Pre-survey at year 1	3.04 (0.07)
				Post-survey at year 2	3.02 (0.08)

$df = (1, 103)$

Table 4 Univariate analyses on the interaction between intervention and time on survey variables

Variables	F	p	η_p^2
Maker self-efficacy	4.04	0.05	0.04
Science self-efficacy	9.57	0.003	0.09
Making interests	6.97	0.01	0.06
Science interests	4.02	0.05	0.04
STEM career interests	6.17	0.02	0.06
Science-related job interests	0.80	0.37	0.01
Maker identity	1.11	0.30	0.01
Science identity	1.74	0.19	0.02
STEM possible selves	3.84	0.053	0.04

df = (1, 103)

Discussion

Despite the growing interests in integrating maker activities into education programs, relatively little work has been done in formal settings (e.g., Lin et al., 2020; Papavlasopoulou et al., 2016,Timotheou & Ioannou, 2019). We presented one approach to incorporate making into science classes within a traditional public-school setting (in the United States context). We additionally utilized a longitudinal quasi-experimental study design to evaluate the impact of our program, an approach that is well-suited to discern causality (Kim & Steiner, 2016). The data partially confirmed our expectation, suggesting the benefits of making for at least some aspects of student self and identity. Specifically, we found when aggregated across post surveys, students in the maker (vs. control) group evidenced higher self-efficacy beliefs in both making and science. This is in line with prior research (e.g., Becker & Jacobsen, 2019; Forbes et al., 2021). Students in the maker group also reported more interests in STEM careers and science-related jobs, suggesting making may have implications over students' career development.

When we included both pre- and posttests in our analyses to consider the role of time, we observed a more nuanced picture: From the beginning to the end of their second year, students in the control group reported decreased self-efficacy beliefs in science and making, and decreased in interests in science, making and STEM careers. Students in the maker group, in contrast, were rather stable in their interests and even experienced an increase in science self-efficacy over the same period. Interestingly, much prior literature has indicated a sharp decline in children's STEM-related self-concepts in elementary and high schools (Eccles et al., 1997; Fredricks & Eccles, 2002; Gottfried et al., 2001; Jacobs et al., 2002; Lofgran et al., 2015; Watt, 2004)—a pattern we similarly observed among students in control classes, but not among students in maker classes. In other words, the students in our maker classes did not seem to suffer from the negative self-changes typically observed during this developmental period.

The question that remains is why these patterns occur. Eccles and colleagues (1997) contend that a major factor behind the deterioration of students' STEM-related self-concepts is a mismatch between formal classroom settings and students' developmental needs (e.g., relatedness, autonomy). For example, formal classes are often stressful, as they encourage students to compete with one another and the teachers often have to act in controlling ways in order to manage their classes. Our maker science class sessions, on the other hand, operated within many of the same constraints of typical public-school classrooms while attempting

Table 5 Simple effect analyses on the effect of time among the maker and the control group

		Time				
		Pre-survey at year 1	Post-survey at year 2			
Variables	Intervention	*M* (*SE*)	*M* (*SE*)	p	d	95% CI
Maker self-efficacy	Maker	3.13 (0.10)	3.24 (0.11)	0.44	0.06	[−0.37, 0.16]
	Control	3.24 (0.16)	2.83 (0.17)	0.06	0.39	[−0.02, 0.85]
Science self-efficacy	Maker	3.00 (0.11)	3.50 (0.09)	< 0.001	0.39	[−0.79, −0.24]
	Control	3.55 (0.18)	3.24 (0.15)	0.17	0.35	[−0.14, 0.76]
Making interests	Maker	3.37 (0.07)	3.35 (0.10)	0.87	0.05	[−0.19, 0.23]
	Control	3.62 (0.12)	3.07 (0.16)	0.002	0.51	[0.21, 0.89]
Science interests	Maker	3.49 (0.09)	3.50 (0.11)	0.91	0.04	[−0.24, 0.21]
	Control	3.79 (0.14)	3.38 (0.18)	0.02	0.39	[0.06, 0.77]
STEM career interests	Maker	2.35 (0.08)	2.41 (0.09)	0.55	0.06	[−0.27, 0.14]
	Control	2.42 (0.14)	1.99 (0.14)	0.01	0.46	[0.10, 0.77]
STEM possible selves	Maker	2.94 (0.08)	3.07 (0.08)	0.12	0.18	[−0.32, 0.04]
	Control	3.15 (0.13)	2.96 (0.13)	0.18	0.18	[−0.09, 0.48]

to make these classes more hands-on than traditional science classes: Students worked with their peers to build and assemble tools for science experiments and science-related activities. Mini-lessons or "just-in-time" lessons were provided, instead of the usual extended lectures delivered by instructors in a top-down fashion. These features could enable students to see themselves initiators—and their peers as collaborators (rather than competitors)—of making and learning. They might also be more inclined to see their instructors as facilitators as opposed to controlling figures. Such shifts in students' perceptions of themselves, their peers and their instructors likely contributed to students' satisfaction of key development needs, such as relatedness and autonomy (Ryan & Deci, 2000). We suspect that the nurturing of these needs is what made the typical negative self-changes observed in this developmental period less likely. Obviously, the design of our study does not allow us to test what specific components of our approach led to the effects we saw. Thus, it is important for future research to examine the underlying mechanisms of making-based classes.

Still, our approach to integrate making in the classroom struck a compromise between the "spirit" of making and the traditional ways of teaching. We saw what we consider impressive impact given the somewhat limited nature of our intervention in terms of the overall time in the school year (i.e., 1 week of every 6) and the context (i.e., exclusively science classes). This is highly encouraging for a long-term goal of integrating making in all schooling. Given self and identity play a key role in students' academic successes (e.g., Taylor et al., 2014) and future decision-making more generally (Markus & Wurf, 1987; Schlegel et al., 2013; Wang, 2013), it is of great value to be able to intervene on children' self-beliefs at such an early developmental stage (i.e., 8 to 11 years old). Some of our findings even provided direct evidence that making could help initiate (or at least maintain) positive development in career choices. For example, we found our intervention helped the students maintain interests in STEM careers. This is despite the fact that our intervention occurred only in science classes. The implication is that the benefits of making could be both long-term and far-reaching—being able to "spill" over from one context (science) to others that are related (other STEM areas).

It is also worth noting that we integrated making in the classrooms of a public school in a low socio-economic status region where the majority of students were from underrepresented groups in STEM fields. As such, another implication of our work is that making integration in formal settings bears the potential to create positive changes at a societal level (i.e., towards more egalitarian education). While this vision is shared among many (Bevan, 2017; Blikstein, 2013; Halverson & Sheridan, 2014; Kit Ng, et al., 2022), past research has utilized varying implementations of making, leaving it difficult for administrators and policymakers to leverage making-based education. Though more data collection can surely shed light on this issue, such efforts are hindered by the challenges to integrate making in traditional school settings. In the introduction, we enumerated major challenges in pedagogical (e.g., teaching approach), logistical (e.g., scheduling), and structural (e.g., learning standards) aspects of school settings. We also discussed how our approach, as a synthesis of past work, circumvented some of these issues (i.e., in integration context, teaching approach and alignment to learning standard). Although different types of schools differ in their constraints (e.g., public vs. private school, different testing and curriculum requirements in different states) and our approach may not as easily apply to classes on a different subject (e.g., math), our work demonstrated that the integration of making within formal education is feasible, in addition to being fruitful. The model presented in our research marks a solid starting point for future research to integrate making and technology-fused learning into other aspects of formal school settings.

This research is of course not without limitations: First, the findings are based exclusively on self-report measures. Future research could complement our understanding with a broader variety of measures such as peer reports. Second, many of our variables are measured with a single item, due to the number of variables assessed, the constraint of survey length at this developmental period and the limited time available. Follow-up studies should ideally use longer scales. Relatedly, most of our variables are measured on a 4-point Likert scale. This might have constrained the variability of some of the variables, leaving it difficult to detect trajectories (e.g., a child rated himself/herself as 3 on a 4-point scale at the beginning of the program would have little space for further growth). As a case in point, we did not observe differences in maker and science identity. Future research should examine the implications of making using more fine-grained scales.

Finally, future research should continue examining the implications of making on students' knowledge and skills. We had examined fifth-grade students' standardized test scores but failed to find an effect of making on this variable. This might be because the test covered a broader variety of topics beyond the knowledge that we were trying to deliver in making activities. Future research should focus on the knowledge that is more closely aligned with the learning objective of making. For example, if the goal of making is to learn about inherited (vs. learned) traits, one could examine students' performance on a test that specifically addresses this topic, as opposed to a generic test that we used in our study.

Conclusion

In sum, the current research described an approach to integrate making into the science classes of a U.S. public school, a setting that can be particularly challenging for making-based education. Using a longitudinal quasi-experimental study design, we found evidence that our making intervention helps students maintain positive self-beliefs in making, science and STEM fields: Over the course of two academic years, students in the control group experienced negative self-changes (in science and making self-efficacy, science and making interests, and STEM career interests); in contrast, students in the maker group did not experience such deterioration. The findings speak to the promise and feasibility of integrating making into formal class settings.

Appendix

					TEACHING APPROACH					LEARNING STANDARDS			EFFECTS				
Authors	Target Grades	Country	Integration Context	Making Activities	Direct instruction	Mini-lessons	Guiding exploration	Peer mentoring	External consultancy	Cross-cutting concepts	Specific content topics	Emergent	Knowledge and skills	Attitudes and mindsets	Meta-knowledge and skills	Emotional states	Self-understanding
Smith and Smith	4th	USA	Science	Personalized	X	X				X	X		X				
Litts et al.	11th	USA	Science	Generic	ND					X			X				
Tofel-Grehl et al.	8th	USA	Science	Generic	X						X		X				
Yu Mei et al.	5th	China	Technology	Generic	X						X		X				X
Flores	5-6th	USA	Science	Personalized	X		X		X	X				X			
Becker and Jacobsen	6th	Canada	Science	Personalized			X				X				X		X
Koh et al.	9th-12th	USA	Technology	Personalized	ND					ND					X	X	
Nugent et al.	2-9th	USA	Science	Generic; Personalized	ND					X			X	X			
Peppler et al.	K	USA	Pervasive	Generic			X					X	X		X		
Tan	7-12th	Singapore	Pervasive	Personalized		X		X	X			X			X		
Forbes et al.	K-2	Australia	Pervasive	Generic	ND						X		X	X	X		
Leinonen et al.	4th-6th	Finland	Craft	Generic; Personalized	X					X			X			X	
Rikonen et al.	7th	Finland	Technology	Personalized				X		X			X				
Vuopala et al.	3rd, 5th	Finland	Technology	Generic			X			X			X			X	
Our approach	3rd-5th	USA	Science	Generic	X	X					X		X	X			X

The row shaded in blue indicates our approach.

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Data Availability Data of this study are available from the corresponding author upon request.

Declarations

Ethics Approval This research was approved by Institutional Review Board at Texas A&M University (#IRB 2014-0449D) and was performed in line with the principles of the Declaration of Helsinki.

Consent to Participate Written informed consent was obtained from the parents of our student samples.

Competing Interests The authors declare no competing interests.

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