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Future of STEM education: Multiple perspectives from researchers

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Future of STEM education: Multiple perspectives from researchers

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Editorial: Future of STEM education: Multiple perspectives from researchers

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KEYWORDS

STEM education, science, mathematics, engineering, technology

Editorial on the Research Topic
Future of STEM education: Multiple perspectives from researchers

In recent times, STEM has become a buzz word in the educational milieu. Standing for Science, Technology, Engineering and Mathematics, STEM has attracted attention from stakeholders in the educational ecosystem and even politicians. They recognize that with the rapid pace at which science and technology are developing and impacting on society, there is a need for students, who constitute the future workforce, to be proficient in STEM. While science and mathematics have traditionally been part of the subject offerings in schools, technology and engineering are not yet mainstream subjects in most schools. The importance of STEM has spawned research efforts to better understand the situation through evidence-based research.

In the context of the foregoing, this articles collection focused on getting multiple perspectives from STEM education researchers on the future of STEM education. The rationale was that by getting researchers to articulate views from the lens of their experiences, we can get the benefit of diverse perspectives that can inform the current debate on STEM education. A flexible interpretation of the theme was adopted.

The articles collection attracted 17 submissions but only seven were accepted after Editorial scrutiny, peer review, and revisions. Representing the efforts of 25 authors (including a Nobel Laureate in Physics) from 14 institutions in five countries, it truly presents multiple perspectives.

We present below a snapshot of the various papers featured in this articles collection.

Achieving multidimensional educational goals through standard-oriented teaching. An application to STEM education

In this study by Schiepe-Tiska et al., a view is advanced that while the emphasis on national educational standards has traditionally been on cognitive outcomes, there is also a need to focus on non-cognitive outcomes. In support of their stance, they propose a view that curricula that place emphasis on cognitive and non-cognitive standards have the potential to better tune teachers' perceptions to the multifarious challenges involved in promoting STEM education outcomes among students. To this extent, the authors suggest that changes need to be enacted at the levels of policy, teacher education, and classroom. These merit consideration from stakeholders.

The co-development of science, math, and language interest among Spanish and Finnish secondary school students

The study by Sainz et al. is cross national in nature. Such studies in STEM education are rather sparse in the educational literature, and there is a need for more of such work as it can present valuable country perspectives. The authors' insertion of language in the STEM education debate is noteworthy as this is not often explored; language is, after all, a key vehicle for learning. The findings, based on a 3-year longitudinal study involving secondary students, offer useful pointers on co-development of students' interest in the three disciplines of interest.

Development of interdisciplinary STEM impact measures of student attitudes and reasoning

STEM, by virtue of the four disciplines within it, is interdisciplinary in nature. While the impact measures of individual disciplines within the STEM continuum are available, that from an interdisciplinary viewpoint presents challenges. In this study, Mayes and Rittschof address the challenges of developing impact measures of students' attitudes and reasoning in STEM education. Psychometric indices are presented to show the efficacy of these measures. The findings would be useful to researchers who contemplate working on interventions related to interdisciplinary STEM education.

Inclusive instructional practices: Course design, implementation, and discourse

In this study by Salehi et al., useful perspectives on course design, implementation and discourse are presented as part of inclusive instructional practices that aim to promote good learning outcomes among students of different backgrounds. They draw upon findings from the fields of cognitive psychology, social psychology, and discipline-based education research to advance useful pointers that can help to promote equity in STEM education.

Potential factors to enhance students' STEM college learning and career orientation

An important aim behind promotion of STEM education is to interest the younger generation in STEM-oriented careers and innovations in STEM fields. Rivera and Li used a survey on high school students to explore potential factors that can enhance STEM college learning and careers. Six predictor variables were found to account for variations in STEM learning and career inclinations: (a) involvement of parents; (b) engagement in STEM activities; (c) academic experience; (d) pedagogy; (e) technology/facilities; and (f) self-esteem. The overall findings suggest possible directions for educational practice.

The future of embodied design for mathematics teaching and learning

The field of embodied cognition has triggered interest in exploring teaching and learning of STEM from design and analysis perspectives. In this study, Abrahamson et al. advance some insightful perspectives for improving teaching and learning of a STEM subject, mathematics, *via* innovative learning environments that leverage interactive technologies.

Developing pre-service teachers conceptualization of STEM and STEM pedagogical practices

From a pre-service teacher education perspective, much needs to be done to promote integrated STEM. Pursuant to this, Berisha and Vula worked with trainee teachers in mathematics and chemistry to explore collaborative practices in STEM through workshops. It was found that a conductive environment was fostered, in the process enhancing these teachers' conceptualization of STEM. Key attributes in this regard were the collaboration between university faculty to deliver the workshops, synergistic interactions between participants in the two disciplines, and meaningful professional development to better prepare these teachers before deployment in schools.

It is our hope that these articles collection would be useful not only for STEM education researchers but also for others in the educational fraternity. We also express optimism that the articles, which have been carefully curated for this Research Topic, would promote further research in STEM education as well as generate talking points among practitioners.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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Potential Factors to Enhance Students' STEM College Learning and Career Orientation

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In this study, we highlight the importance of high school students having a college-attending and career-ready mindset in STEM fields. With this purpose, we adopted a stepwise multiple regression analysis to determine which variables are significant predictors of students' STEM college learning and career orientation. The participants were 1,105 high school students from nine randomly selected high schools across greater Houston Texas. Forty-two percent of the variance on STEM college learning and career orientation as an outcome variable can be explained by six predictor variables: (a) parental involvement; (b) STEM related activities engagement; (c) academic experience; (d) teacher effective pedagogy; (e) technology/facilities; and (f) self-esteem. The results indicate that when students received support from teachers and parents, they could develop more positive attitudes toward future post-secondary education and career pathways in STEM fields.

Keywords: high school, STEM—science technology engineering mathematics, college readiness, career decision, parent involvement

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INTRODUCTION

In 1986, the idea of Science, Technology, Engineering, and Math (STEM) education was first brought up to the public in a report named "Neal Report: Undergraduate Education Statement" by the National Science Board (Prados, 1998). The National Science Foundation further suggested STEM education policy reform within K-12 education (Fortenberry, 2005). In 2009, former President Barack Obama re-emphasized the importance of STEM education and invested more money in STEM teachers' professional development (Johnson, 2012). In 2015, STEM education was incorporated into Every Student Succeeds Act (ESSA) signed by former President Obama (Every Student Succeeds Act, 2015). The ESSA is the latest reauthorization of the Elementary and Secondary Education Act (Every Student Succeeds Act, 2015). This reauthorization aims to enhance students' performance and interests in STEM education, to discover students' potential to be scientists, computer programmers, engineers, and mathematicians, as well as to enhance STEM teachers' teaching skills. For this reason, high school education emphasizes STEM curriculum and teacher professional development in STEM education, which will hopefully help enhance high school students' academic and career interests in STEM fields.

In this study, we highlighted the importance of high school students having a college-attending and career-ready mindset in STEM fields (Conley, 2010; Radcliffe and Bos, 2013). According to the Center on Education Policy (2011) and the College Board (2011), they suggested that developing the college-attending and career-ready mindset can enhance high school students' knowledge about their future-to-be (occupations) and their willingness to pursue a college degree. In addition, according to the Center on Education the Workforce (2013), between 2013 and 2020 there will be 55 million job openings; 76% of these jobs will require the applicants to have post-secondary education attainment and achievement (e.g., vocational certificate, associate's degree, or bachelor's degree).

To enhance high school students' STEM college learning and career orientation, we have to think from their perspective so as to better understand what they need. Then we can address what their schools can do for these students. With this purpose, we wanted to discover what factors influence high school students' STEM college learning and career orientation.

LITERATURE REVIEW

Career decision is the biggest challenge for high school students in the process of college and career readiness. This decision will force students to choose what they will study in college and what practical trainings they want to take. However, career decision is an ongoing process, and this decision is influenced by individuals' ecologies such as school and home according to Lent et al.'s social cognitive career theory (1994). Social cognitive career theory emphasizes that individuals' self-efficacy influences their formation of educational and vocational interests, decision making in education and career, persistence in academic and occupational endeavors, as well as performance attainment (Lent et al., 1994). Individuals' learning experiences influence their self-efficacy while individuals' learning experiences are influenced by person factors (e.g., gender and ethnicity) and background contextual factors (e.g., support system from school, home, or community). Social cognitive career theory was developed based on Bandura's social learning theory. Social learning theory emphasizes that an individual's beliefs, emotions, and thoughts are influencers of their behaviors (Bandura, 1977). These behaviors in turn help predict patterns of an individual's beliefs, emotions, and thoughts. Environment influences an individual's beliefs and behaviors, while those beliefs and behaviors help predict in what environment an individual may choose to stay.

For high school students, they need to make their first career decision regarding educational and career plans before they graduate. Therefore, helping high school students to understand what their academic and vocational interests are and enhancing their interests are important aspects. The research literature indicates that positive awareness and aspiration toward education and career among high school students can be fostered and developed through improvements in the multiple learning environments in which students reside (e.g., home and school), as well as through the development of protective factors within those environments (e.g., parents in the home environment and teachers or mentors in the school environment) (Wang and Staver, 2001; Gushue and Whitson, 2006; Kirdök, 2018).

The Role of Parents

Parents play a critical role in their children's educational and career paths and socialization (Ginevra et al., 2015; Heddy and Sinatra, 2017; Niles and Harris-Bowlsbey, 2017). According to Sharf (2006), children's relationship with their parents will influence what educational and career paths the children will take. When children make their educational and career decisions, they respect their parents' feedback as well as rely on emotional and financial support from their parents. Research indicates that parents' positive support such as encouragement and guidance would enhance children's self-determination on achieving educational goals (Urdan et al., 2007; Ramsdal et al., 2015; Zhang et al., 2019) and career goals (Urdan et al., 2007; Zhang et al., 2019). In addition, research indicates that if parents maintain positive attitudes about their children's educational and career endeavors, then children are more likely to actively continue their educational and career paths (Zhang et al., 2019).

Regarding increasing students' STEM learning interests and career orientation, parents' constant involvement in their children's learning has been shown to be an effective factor (Gottfried et al., 2016). According to Heddy and Sinatra (2017), students' learning interest in science can be better maintained when their parents get more involved in the learning process. Furthermore, research corroborated that parental involvement is associated with students' learning performance in math (Sheldon and Epstein, 2005).

The Role of Schools and Teachers

Students' academic and career paths can be affected or enhanced by schools and teachers. When high school students consider which academic or career path they would like to take, they rely on resources the school provides such as learning facilities (Xie and Reider, 2014), college and career guidance (Schwartz et al., 2016), as well as counseling service (Schwartz et al., 2016). In addition, students get to know their academic and/or vocational interests better when schools provide educational activities such as college and career day, and learning exposition (Zeng et al., 2018). Nugent et al. (2015) discovered that when students participate in STEM-related activities in informal learning environments, such as STEM summer camps, their STEM learning interests and career orientation are enhanced. These out-of-school STEM learning experiences could support and enhance students' STEM learning in classroom (Nugent et al., 2015).

Research indicates that students develop more positive awareness and aspiration toward education and career when they receive teachers' support in the classroom learning environment (Hurtado et al., 1996; Kao and Thompson, 2003; Lazarides and Watt, 2015) and parental involvement in their learning (Chavira et al., 2016; Holmes et al., 2018). Dalgety and Coll (2006) investigated first-year college students' learning attitudes and self-efficacy regarding chemistry learning; they found that these students' previous learning experience and achievement in high school may be critical to their self-efficacy in college-level chemistry learning. Lee et al. (2008) further argued that teachers play an important role in the process by which students make educational or career decisions, as students' positive learning attitudes and achievements are affected by teachers' instructional contents, tools, and skills.

With the aforementioned purpose of this study and review of literature focusing contextual factors on high school students' educational and career paths, one research question is addressed in this study: from high school students' perspectives, what factors (e.g., parental engagement, academic experience, and teachers' effective pedagogy) will influence their STEM college learning and career orientation.

METHODS

Our study adopted a mixed-method design. We collected quantitative data through a survey and qualitative data was collected through two focus group interviews. In this study, we primarily focused on the quantitative results; the qualitative results were used for supporting evidence through data triangulation.

Participants

The study was carried out in nine high schools across greater Houston, Texas. These nine schools were randomly selected to participate in the study (e.g., survey and focus group interviews) based on a list of high schools provided by one school district. The total of student participants was 1,540. Students who did not answer the survey completely were removed from the analysis. As a result, there were only 1,105 student participants in our study. Participants' distribution by grade level was 413 ninth grade, 324 tenth grade, 206 eleventh grade, and 162 twelfth grade students. There were 529 male students and 576 female students. The age range for participants was 14 years old to 17 years old (mean = 15.2). Regarding the focus group interviews, three students from each grade were randomly chosen for a total of 12 students (two focus group interviews).

Survey Instrument

A bilingual survey (Spanish/English) was developed for students. The survey was mainly designed to gather (a) basic background information, (b) systematic information on classroom/home teaching/learning environments, (c) systematic information on resources in the home learning environment, and (d) beliefs and attitudes toward STEM education and STEM careers and degrees. The survey contained nine constructs. These constructs were: (a) STEM related activity engagement; (b) STEM college learning and career orientation; (c) teacher support; (d) school support; (e) self-esteem; (f) parental involvement; (g) teachers' effective pedagogy; (h) safety and behavior at school; and (i) technology-assisted learning. There were 47 closed items with a six-point Likert scale. Each survey item offered one of two types of answer choices for the students. The first type of choice was the disagree-agree type (strongly disagree = 1; disagree = 2; slightly disagree = 3; slightly agree = 4; agree = 5; and strongly agree = 6). The second type of choice was the frequency type (never = 1; seldom = 2; sometimes = 3; frequently = 4; usually = 5; always = 6).

Examples of survey items and the Cronbach's Alpha values for each construct are provided below:

a. *STEM Related Activity Engagement* (Cronbach Alpha =0.7/5 items):
   In my STEM classes, I work with other students on projects during class and after school (disagree-agree choice).
b. *STEM College Learning and Career Orientation* (Cronbach Alpha =0.75/5 items):
   If I perform well in the STEM subjects, it will lead me to a great college or a great job in STEM fields (disagree-agree choice).
c. *Teacher Support* (Cronbach Alpha =0.86/5 items):
   My STEM teachers mentor me effectively in preparation for my STEM projects (frequency choice).
d. *School Support* (Cronbach Alpha =0.75/5 items):
   A guidance counselor at school has given me advice on how to get into a college or career in STEM fields after graduation (disagree-agree choice).
e. *Self-efficacy* (Cronbach Alpha =0.82/5 items):
   I am confident I can produce high quality work in my STEM classes (disagree-agree choice).
f. *Parental Involvement* (Cronbach Alpha =0.73/5 items):
   My parents support my attending STEM related activities at school (frequency choice).
g. *Teachers' Effective Pedagogy* (Cronbach Alpha =0.9/7 items):
   My STEM teacher uses open-ended or guided questions to help us deeply understand the idea behind the STEM curriculum (frequency choice).
h. *Safety and Behavior at School* (Cronbach Alpha =0.81/5 items):
   Discipline is fairly enforced at school (disagree-agree choice).
i. *Technology-Assisted Learning* (Cronbach Alpha =0.88/5 items):
   The computers and equipment available to students for STEM projects and labs are up to date (disagree-agree choice).

Survey Implementation

The procedure for survey implementation involved three steps including (1) survey development, (2) survey piloting, and (3) survey implementation.

Step 1: For the development of the survey, we examined literature on: (a) home learning environment research (e.g., Peterson et al., 2005; Urdan et al., 2007; Sad and Gurbuzturk, 2013; Ramsdal et al., 2015); (b) parental involvement (e.g., Chavira et al., 2016; Holmes et al., 2018); (c) effective teaching practices in STEM programs (e.g., National Research Council., 2011; Bruce-Davis et al., 2014); and (d) STEM classroom learning environment research (e.g., Smith et al., 2009; Denson et al., 2015). Examining these studies helped us better understand areas of focus for the survey. In addition, we examined literature on College and Career Readiness Standards (e.g., American Institutes for Research, 2014; Neri et al., 2016), as well as literature on STEM Program Development (Lara-Alecio et al., 2012; Kim, 2016; Mupira and Ramnarain, 2018). By further examining these studies, we could develop items addressing educational experiences in home and classroom environments as viewed and experienced by the students during home and/or classroom activities.

Step 2: This step involved the piloting of the survey with two focus groups, one in Spanish and one in English, in an effort to do the final calibration of the instrument with high school students from ninth through twelfth grades. These focus groups assisted us by addressing any language ambiguity and/or revising poorly written items across all surveys.

Step 3: Upon obtaining all signed consent forms from the students and permission forms from their parents, the online survey was implemented. Students could choose an English or Spanish survey to answer. Students were led by teachers to a computer lab where they took the online survey. Regarding the implementation of the survey, a survey protocol designed by the researchers was given to the teachers. The average time for survey completion by participants ranged between 12 and 15 min.

Survey Analysis

A stepwise multiple regression analysis was used to determine which variables are significant predictors of an outcome variable. In our analysis, we used STEM college learning and career orientation as an outcome variable with the other eight constructs as predictor variables: (a) STEM related activity engagement; (b) teacher support; (c) school support; (d) self-esteem; (e) parental involvement; (f) teachers' effective pedagogy; (g) safety and behavior at school; and (h) technology-assisted learning. The variables that were selected in our multiple regression model were potent factors to predict the outcome variable (STEM college learning and career orientation). According to Larson-Hall (2016), significant factors included in the model have independent power to affect the outcome variable. In a stepwise multiple regression, "the choice of which factor is entered first is based on the strength of the correlation" (Larson-Hall, 2016, p. 240). In addition, a series of moderator analysis was conducted to determine if a relationship between two variables is moderated by a third variable. **Figures 1–4** show the moderator analyses that we conducted. For example, **Figure 1** illustrates if a relationship between students' "STEM related activity engagement" and "STEM college learning and career orientation" could be moderated by parental involvement.

Interview Questions for the Focus Group

With the preliminary results, six topics were developed to align to six significant predictors: (a) parental involvement; (b) STEM related activity engagement; (c) teacher support; (d) STEM teacher effective pedagogy; (e) technology-assisted learning; and (f) self-efficacy. There were one or two open-ended questions under each predictor, with a total of 10 questions. For example, under the topic of parental involvement, one of the questions was "In your view, what are the ways in which your school and teachers can get your parents involved in your STEM education and career readiness?" Under the topic of teacher support, one of the questions was "In your view, what are some of the key steps that STEM teachers need to take if they want students to become resilience (or persevere) in STEM? What do they need to do to get you college ready?"

Interview Implementation

Each of the interview sessions lasted 1.5 h. Each session included an explanatory introduction, interview questions, and a closing statement. During the session, all students were required to give their most considerate answer to all of the 10 interview questions. The 12 students in this focus group all agreed to audio recording of the sessions; they consented to allow that their quotes could be included in this study anonymously.

Several quotes by students were provided in the discussion section to support our survey findings. These quotes represented the overall thinking of the students in the focus group. To increase the reliability of findings from the interview, we invited one researcher to review the results and quotes. This researcher has worked in the field of education for over 5 years; her research expertise is mixed methods research and parental involvement. An additional researcher would "arrive at similar findings from the data" (Rafuls and Moon, 1996, p. 77).

RESULTS

SPSS Version 20 was used to examine the survey data. As stated in the method section, there were nine constructs on our survey, with a combined total of 47 items. These constructs were found to be highly reliable, with reliability coefficients ranging from 0.7 to 0.9 (mean = 0.8). As mentioned above, a stepwise multiple regression analysis was used to examine eight predictor variables with students' STEM college learning and career orientation specified as an outcome variable. These eight predictor variables considered in the equation were: (a) STEM related activity engagement; (b) teacher support; (c) school support; (d) self-efficacy; (e) parental involvement; (f) teachers' effective pedagogy; (g) safety and behavior at school; and (h) technology-assisted learning. Six significant predictor variables (factors) were identified in a stepwise multiple regression model: (a) parental involvement; (b) STEM related activities engagement; (c) academic experience; (d) teacher effective pedagogy; (e) technology-assisted learning; and (f) self-efficacy. A multiple R of 0.65 was obtained, accounting for 42% (adjusted) of the variance (See **Table 1**), suggesting that these six factors helped explained 42% of variance in students' STEM learning and career orientation. **Table 1** shows that these six identified predictors independently affect students' STEM college learning and career orientation; parental involvement has the strongest correlation with students' STEM college learning and career orientation.

DISCUSSION

The purpose of this study was to discover from students' perspectives what factors may influence their STEM college learning and career orientation. The results showed that 42% of the variance on STEM college learning and career orientation can be explained by six predictors that include: (a) parental involvement; (b) STEM related activity engagement; (c) teacher

TABLE 1 | Multiple regression analysis of STEM college learning and career orientation as an outcome variable.

Independent variable	Multiple *R*	R^2_{Change}	R^2_{Adt}	F_{Change}
1. Parental involvement	0.532	0.283	0.283	436.276***
2. STEM related activity engagement	0.620	0.101	0.383	179.831***
3. Teacher support	0.641	0.027	0.409	49.922***
4. STEM teacher effective pedagogy	0.644	0.003	0.412	6.458*
5. Technology-assisted learning	0.648	0.005	0.416	9.758**
6. Self-efficacy	0.650	0.004	0.420	6.907**
Total		0.423	0.420	

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

support; (d) STEM teacher effective pedagogy; (e) technology-assisted learning; and (f) self-efficacy. This overall finding indicates that students' physical and psychosocial learning environments should elevate their beliefs and behaviors in STEM learning, which would later help predict their future STEM college and career orientation. This indication is supported by Lent et al.'s social cognitive career theory (1994). The overall finding also indicates that students' physical and psychosocial learning environments should leverage their self-efficacy, which would help enhance their educational and career interests in STEM and persistence in academic and occupational endeavors. This indication is supported by Bandura's social learning theory (1977).

The results first revealed that ***parental involvement*** accounted for 28% of the variance in students' STEM college learning and career orientation, and that parental involvement had a significantly positive and moderate correlation with STEM college learning and career orientation. These findings indicate that if parents get more involved in their children's STEM learning, their children would be more determined and positive about their post-secondary education and career orientation in STEM fields. When parents get involved in their children's learning activities, they should be supportive and provide positive feedback to their children. When parents give encouragement, share expectation, and present positive attitudes, their children's academic and vocational interests can be enhanced (Urdan et al., 2007; Zhang et al., 2019). When communicating with their children about academic and career decisions, parents are suggested to maintain a reciprocal conversation with their children, to help the children understand their strengths, and to work with the children to help them analyze potential pros and cons of their decisions about their future. Meanwhile, in the conversation, parents should look at their children's behaviors, emotions, and cognitions (e.g., thinking process) from the view of the children instead of from the view of the parents alone. According to Lent et al. (2000), parents' disapproval can draw children away from their original career choice and may hinder their career progress. We further analyzed: (a) the relationship between parental involvement, students' STEM related activity engagement, and students' STEM college learning and career orientation (see **Figure 1**); and (b) the relationship between teacher support, parental involvement, and students' STEM related activity engagement (see **Figure 2**). With the results in **Figure 1**, we found that from students' perspectives, parental involvement could positively moderate the relationship between their STEM related activity engagement and STEM careers and degrees. With the results in **Figure 2**, we found that to enhance the relationship between parental involvement and students' STEM related activity engagement, teacher support plays a significantly critical role.

Second, the results revealed that by ***engaging in more STEM related activities***, students would feel more positive about their future post-secondary education and career orientation in STEM fields. To enhance students' STEM college learning and career orientation, STEM teachers are strongly suggested to provide their students with activities aligned to the students' academic interests and learning needs. Schools are suggested to develop and offer STEM-related activities or practicum to students for enhancing the students' educational and vocational interests in STEM. The practicum aims to give students opportunities to apply STEM theories and knowledge into real-life practice. Through participation in the practicum, students' STEM knowledge, skills and abilities can be enhanced in a sustained way. In the practicum, students will be able to communicate with teachers, peers, and professionals. Through educational communication and hands-on experience, students can integrate their theoretical knowledge and real-world practice, and their academic and vocational interests in STEM fields can be enhanced (Malin and Hackmann, 2017). With the results in **Figure 1**, to enhance students' STEM related activity engagement which could further enhance their STEM careers and degrees, we suggest that teachers help parents increase their level of involvement in their children's STEM learning. Additionally, teachers should work with schools to provide parents with capacity building activity so that parents can learn how to effectively engage in the education of their children. The goals of these activities are to enhance communication and collaboration between parents, students, and teachers, to optimize positive impacts on students' STEM college learning and career orientation.

Third, the results revealed that ***STEM teachers' support*** in students' STEM learning accounted for enhancing students' future STEM college learning and career orientation. We further analyzed the relationship between teachers' support, students' STEM related activity engagement, and STEM college learning and career orientation (see **Figure 3**). We found that from students' perspective, teachers' support could positively moderate the relationship between students' STEM related activity engagement and STEM college learning and career orientation. Teachers' support could also enhance students' STEM related activity engagement, which could further enhance their STEM college learning and career orientation. These findings are consistent with previous studies which found that when students received support from their teachers (Walker et al., 2004), the students could develop more positive attitudes, which later may influence their perspectives about future STEM activity engagement and post-secondary education pathways. To develop or enhance students' educational and vocational interests in STEM fields, teachers are encouraged to maintain a mentoring/apprenticeship program to give students guidance and assistance in STEM learning. More specifically, this program

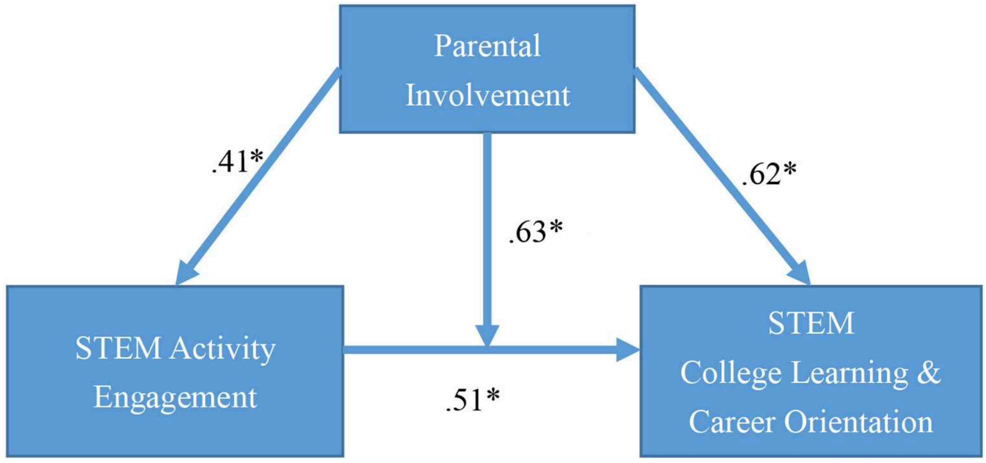

FIGURE 1 | The relationships between parental involvement, STEM activity engagement, and STEM college learning and career orientation by using a moderator analysis. *$p < 0.05$.

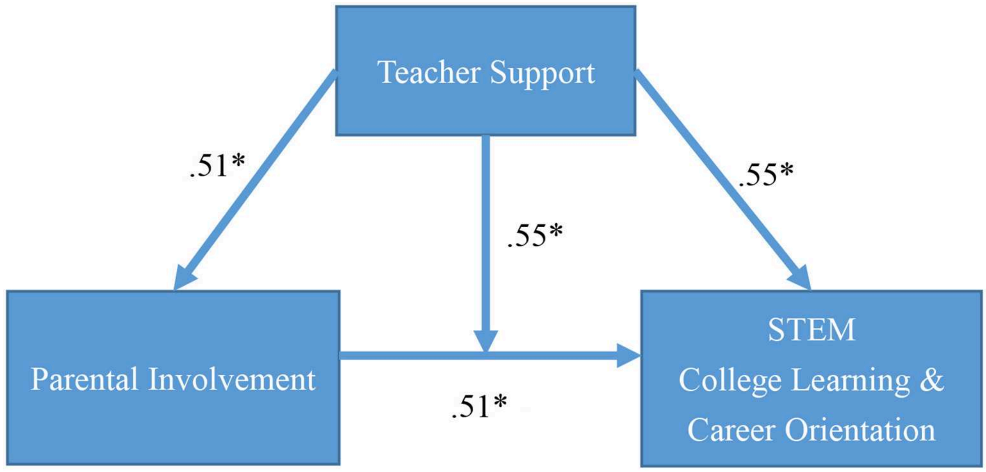

FIGURE 2 | The relationships between teacher support, parental involvement, and STEM college learning and career orientation by using a moderator analysis. *$p < 0.05$.

is to assist students with understanding real-world practices in STEM fields and effective ways to interact with professionals. Teachers should consider providing a 2-h window in their weekly schedule for their students to walk in for discussion and consultation; the aims of this discussion would be (a) to help the students solve their challenges in learning and life, (b) to enhance the students' learning interests, and (c) to assist the students with monitoring their learning growth and finishing their study in high school. Teachers are encouraged to help students develop future educational and career paths, and help the students get involved in community service. For example, teachers can to develop and participate in activities involving all their students (e.g., field trips and career talks by professionals).

Fourth, the results revealed that ***STEM teachers' teaching effective pedagogy*** could affect students' STEM college learning and career orientation. Regarding how teachers can enhance students' post-secondary education and career in STEM fields, teachers can modify their lesson plan by incorporating Trowbridge and Bybee's 5E model (Trowbridge and Bybee, 1996; Bybee et al., 2006): Engagement, Exploration, Explanation, Elaboration, and Evaluation. Ample evidence has shown the effect of 5E model on enhancing students' STEM academic performance (Lara-Alecio et al., 2012; Kim, 2016; Mupira and Ramnarain, 2018). To help strengthen students' STEM interests, Burke (2014) suggested to add "Enrichment" to the model. To pay attention to each individual's learning background and progress, teachers are encouraged to use differentiated instruction (LaForce et al., 2016). According to Tomlinson (2001), teachers can focus on adjusting lesson content, lesson process, and lesson product.

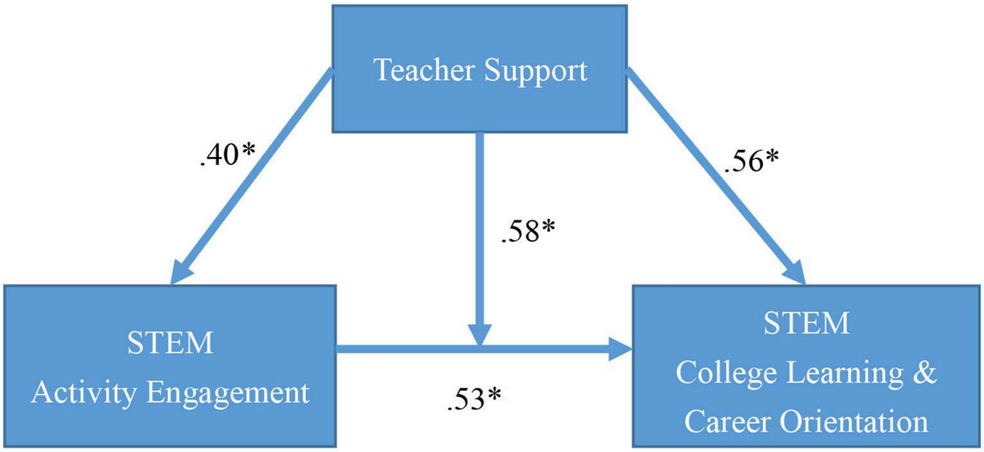

FIGURE 3 | The relationships between Teacher Support, STEM activity engagement, and STEM college learning, and career orientation by using a moderator analysis. *$p < 0.05$.

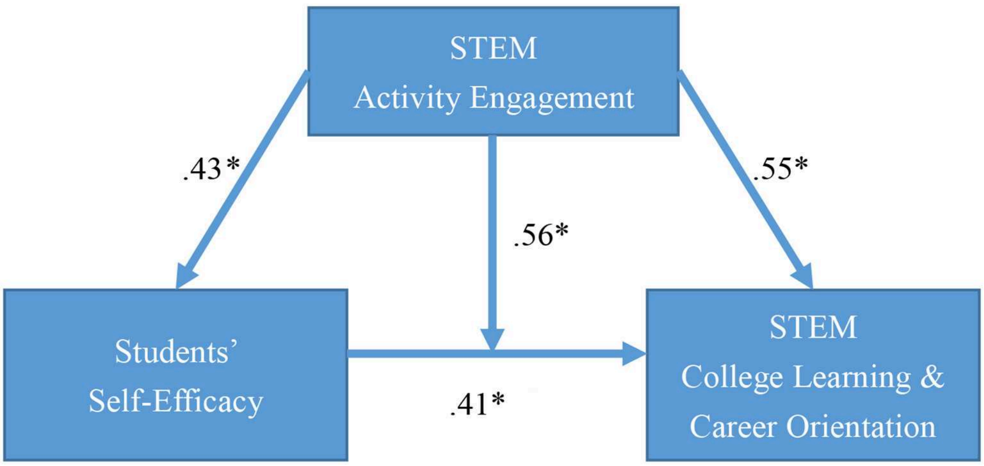

FIGURE 4 | The relationships between STEM activity engagement, students' self-efficacy, and STEM college learning and career orientation by using a moderator analysis. *$p < 0.05$.

Fifth, the results revealed that students' perceptions about ***classroom technology and facilities*** could influence their STEM college learning and career orientation. To enhance students' STEM college learning and career orientation, STEM teachers are advised to maintain a technology-assisted learning environment by working with school administrators (Hawkins et al., 2017). Students' learning is enhanced due to the multiple learning functions and interactive learning environments provided by using technology in the classroom. Some researchers (e.g., Hsu et al., 2015; Kaniawati et al., 2016) found computer-assisted or multimedia-assisted learning is more effective to facilitate students' STEM content knowledge learning when compared with traditional classroom learning. This is because the computer-assisted learning environment creates an opportunity for students to easily monitor their learning process and adjust their learning when they make mistakes (Hsu et al., 2015). In addition, a computer-assisted learning environment helps students gain some additional skills such as learning autonomy and computer literacy (Cerezo et al., 2014).

Sixth, the results showed that students' ***self-efficacy*** would help enhance their STEM college learning and career orientation. A student's self-efficacy is developed based on his/her previous learning experience, performance, and attitudes that can be directly influenced by teachers (Dalgety and Coll, 2006). To enhance high school students' self-efficacy, teachers are suggested to assist their students with goal-setting and goal achievement. Students with higher efficacy have higher goal commitment, and they are more likely to achieve their goals (Wilson and Narayan, 2016). According to Gist and Mitchell (1992) and Peterson (1993), self-efficacy manifests itself in successful completion of designated tasks. Our results further showed that students with higher self-efficacy believed more strongly that they could successfully finish STEM-related hands-on tasks and assignments ($r = 0.90$). We further analyzed the relationship between students' self-efficacy, STEM related activity engagement, and STEM college learning and career orientation (see **Figure 4**). We found that from students' perspectives, their STEM related activity engagement could positively moderate the relationship between their self-efficacy and STEM college learning and career orientation. These students' engagement in STEM related activities could enhance their self-efficacy, which could further enhance their STEM college learning and career orientation. With these findings, we suggest that to enhance students' self-efficacy, teachers should provide their students with more resources and opportunities to engage in STEM-related hands-on activities.

Finally, in order to continue building resilience in students, schools are strongly encouraged to continue increasing efforts that are clearly connected to teacher professional development and parental capacity building; these are key protective factors that can build and support students' resilience. From our qualitative results, we found that students valued how teachers can inspire them to try and attain a college degree or career in STEM fields.

> *"I feel like the STEM program gives us opportunities……and it's like one on one, the teacher and the student, and it really gives us more opportunities to put our learned knowledge into practice."*
> *"The STEM program allows us to explore different aspects of different fields……and to have us immersed into real-life situations."*

Students were cognizant of the fact that some teachers should not only bring real-life situations to STEM classrooms, but should also help identify how students can use different strategies to solve real-world problems. Additionally, teachers should invite a guest speaker to share with students how they can solve these problems in practical ways.

> *"I do think that teachers can help us focus more on real-world problems and guide us how we can solve these problems in different ways…..STEM teachers should have someone……someone who's really like an expert in the field……if we can seek this kind of person in the field, it can help us understand and solve the real-world problems in a more practical way."*
> *"Some of STEM teachers……like math and science……just teach us content knowledge……we need to know some practical skills to cope with real-world problems……we expect teachers to give us not only the knowledge but also practical skills……give us some examples of how these skills are, what these skills look like."*

Regarding parents, the students wanted their parents to get more involved in their learning and to work with teachers to help enhance their learning performance and interests.

> *"I feel like my parents do not pay attention to my learning process, but my grades instead……focusing on my grades is fine, but not the way they sit down with me and help my school work. I hope my parents could get more involved in school activities……it's important and they should be involved in the school, because they can get to know our teachers and understand how they can help us meet teachers' and school's expectations……teachers can also know how my parents think about my……STEM education."*
> *"I feel like parents should always encourage us on our learning performance, not criticize. They should not give us too much instructional criticism......but should help us be more focused on our learning process."*

CONCLUSION

To follow up on other studies emanating from the social cognitive career theory framework (e.g., Lent et al., 2008; Nugent et al., 2015; Gottfried et al., 2016; Zhang et al., 2019), we operationalized relevant variables focusing on high school students as our target population. The results of our study helped us to better understand that the interplay of socio-contextual, motivational, and instructional factors operating within learning environments can impact high school students' future STEM college learning and career orientation.

Our results revealed that to develop or enhance high school students' STEM college learning and career orientation, we should pay attention to their parental involvement, STEM related activity engagement, teacher support, STEM teacher effective pedagogy, technology-assisted learning, and self-efficacy. To develop and enhance high-school-aged children's STEM college learning and career orientation, parents are suggested get actively involved in their children's STEM learning. To sustain their STEM college learning and career orientation, parents should provide constant support and encouragement to their children in STEM learning. When developing and enhancing high school students' STEM college learning and career orientation, teachers should understand: (a) how each individual student may have different learning needs; (b) how to adapt instructional strategies and lesson materials to align to students' needs; (c) how to create interactive lessons using electronic learning materials; and (d) what learning resources to provide for enhancing their students' learning interests in STEM. Schools should provide students more educational and vocational STEM-related activities to further develop their STEM college learning and career orientation, as well as to put learned STEM knowledge into real-life practice. We encourage that parents, teachers, and schools work together to hopefully have a more positive impact on high school students' educational and career decisions in STEM fields.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ozgur Ozer (Harmony Public Schools). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

HR contributions are school connection, data collection, and manuscript revising. J-TL contributions are data collection, data analysis, manuscript drafting, and manuscript revising.

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The Future of Embodied Design for Mathematics Teaching and Learning

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A rising epistemological paradigm in the cognitive sciences—embodied cognition—has been stimulating innovative approaches, among educational researchers, to the design and analysis of STEM teaching and learning. The paradigm promotes theorizations of cognitive activity as grounded, or even constituted, in goal-oriented multimodal sensorimotor phenomenology. Conceptual learning, per these theories, could emanate from, or be triggered by, experiences of enacting or witnessing particular movement forms, even before these movements are explicitly signified as illustrating target content. Putting these theories to practice, new types of learning environments are being explored that utilize interactive technologies to initially foster student enactment of conceptually oriented movement forms and only then formalize these gestures and actions in disciplinary formats and language. In turn, new research instruments, such as multimodal learning analytics, now enable researchers to aggregate, integrate, model, and represent students' physical movements, eye-gaze paths, and verbal–gestural utterance so as to track and evaluate emerging conceptual capacity. We—a cohort of cognitive scientists and design-based researchers of embodied mathematics—survey a set of empirically validated frameworks and principles for enhancing mathematics teaching and learning as dialogic multimodal activity, and we synthetize a set of principles for educational practice.

Keywords: cognition, design, embodiment, gesture, mathematics, multimodality, teaching, technology

INTRODUCTION

Philosophy of cognitive science is undergoing considerable change. This change, dubbed the *embodiment turn* in the history of philosophy (Nagataki and Hirose, 2007, pp. 223–224; see also Zlatev, 2007), challenges the classical Cartesian mind–body divide (Merleau-Ponty, 1945/2005), which dominated 20th century perspectives on the fundamental infrastructure and mechanism of the human mind. Scholars of embodiment seek to evaluate the intriguing hypothesis that thought—even thinking about would-be abstract ideas—is inherently modal activity that shares much neural, sensorimotor, phenomenological, and cognitive wherewithal with actual dynamical corporeal being in the world. By this token, higher-order reasoning, such as solving an algebra equation, analyzing a chemical compound, editing a journal manuscript, or engineering a spacecraft, transpires not in some disembodied cerebral space and not as computational procedures processing symbolic propositions but, rather, by operating on, with, and through actual or imagined objects. Sprouting in the late 20th century as the confluence of intellectual efforts from philosophy, cognitive psychology, robotics, movement scholarship, and linguistics, the embodiment turn has now come of age, priding its own societies, conferences, and handbooks (Shapiro, 2014; Newen et al., 2018).

The embodiment turn in philosophy entertains a spectrum of perspectives on the mind, which range from relatively conservative views of cognition as amodal cerebral activity grounded on traces of multimodal sensorimotor activity (Barsalou, 2008) to radical views of cognition as, by and large, content-less integrated simulations of multimodal sensorimotor activity (Hutto and Myin, 2013, 2017). The mind, per some of the more pioneering suggestions, is more than the brain organ—it extends from the brain, through the sensing-cum-actuating body, and into natural and cultural ecology, where it entangles reciprocally with fellow humans, artifacts, media, and symbolic systems (Hutchins, 1995; Clark and Chalmers, 1998; Melser, 2004).

Empirical evidence has been accruing in support of embodiment theories of cognition. When, in conversation, we refer to our relationship with another person in terms of journeying together (e.g., "We had a rough start, but we've come a long way"), we coopt schematic images of mundane experience (a journey) to express the states of intangible ontologies (a relationship; Lakoff and Johnson, 1980). When we read, we form meanings from words via tacitly activating their motor implication (Hauk et al., 2004) and via imaginarily configuring spatial relationships (Glenberg and Kaschak, 2002). When we write with keyboards, we implicitly form negative vs. positive valence toward affect-neutral words, such as "drawer" or "linkup," depending on how many of their characters are keyed with the left or right hand, respectively (Jasmin and Casasanto, 2012). And interfering with the gestures of abacus experts, as they solve a problem *without* an abacus, compromises their performance (Brooks et al., 2018). It appears, thus, that many of our cognitive faculties are constituted as situated activities. Cognition develops in context—Varela et al. (1991) contend that cognitive structures emerge from recurrent patterns in perceptually guided action (see also Piaget, 1968).

The embodiment turn has impacted the field of educational research (Abrahamson and Lindgren, 2014; Pouw et al., 2014; Lee, 2015; Shapiro and Stolz, 2019). In particular, the emergence of theoretical and empirical support for central tenets of the embodiment turn has resonated strongly with educational researchers already committed to foregrounding the role of physical activity, such as manipulation, in cognitive development (Allen and Bickhard, 2015). Thus, the embodiment turn helped educational researchers braid together a robust intellectual strain with roots in genetic epistemology (Piaget, 1968), enactivism (Varela et al., 1991), phenomenology (Merleau-Ponty, 1945/2005), pragmatism (Dewey, 1944), pedagogy literature (Montessori, 1967; Skemp, 1976; Rousseau, 1979; Freudenthal, 1983; Froebel, 2005), and their various historical elaborations and embroideries (e.g., Papert, 1980; von Glasersfeld, 1987; Wilensky, 1991; Pirie and Kieren, 1992; Steffe and Kieren, 1994; de Freitas and Sinclair, 2014).

Invigorated by this paradigmatically converging body of literature, scholars of teaching and learning have sought to interpret implications of the embodiment turn for theorizing, designing, and practicing education in a range of disciplines. These have included literacy (Glenberg et al., 2004), chemistry (Scherr et al., 2013; Flood et al., 2015a), astronomy (Gallagher and Lindgren, 2015; Rollinde, 2019), kinematics (Zohar et al., 2018); mathematics (Núñez et al., 1999; Roth, 2009; Nemirovsky et al., 2013; Nathan et al., 2014; Smith et al., 2014; Hutto et al., 2015), and moral development (Antle et al., 2013). Our article focuses on mathematics, where there has been significant interest in embodiment among educational researchers (Radford et al., 2009; Hall and Nemirovsky, 2012; Schoenfeld, 2016).

Educational research inspired by the embodiment turn often looks to understand new forms of teaching and learning enabled by educational design that caters to multimodal situated activity. These have included interactive technologies responding to kinetic qualities of students' motor actions, such as moving virtual objects, whether by on-screen manipulation (Leung et al., 2013; Sinclair and Heyd–Metzuyanim, 2014) or remote-sensed gesture (Abrahamson and Trninic, 2011), as well as ambulatory motion (Nemirovsky et al., 1998; Ma, 2017; Marin et al., 2020). Research studies evaluating these embodied designs typically gather and analyze participants' multimodal behaviors, using technology for tracking eye gaze (Duijzer et al., 2017), gesture (Nathan et al., 2014), whole-body movement via GPS (Hall et al., 2015) or motion sensors (Nemirovsky et al., 1998), computer interaction logs via telemetry (Pardos et al., 2018), brain activity (Lyons and Beilock, 2012), and multi-variate speech patterns (Levine and Scollon, 2004), often triangulated with qualitative analyses or audio–video data. These multimodal data may then be mined using machine-learning algorithms (Ochoa and Worsley, 2016; Worsley et al., 2016).

Research efforts to create and evaluate learning environments that implement embodiment theory to practice have, in turn, resulted in a set of empirically validated practicable methodologies for building and facilitating instructional activities. The rationale of creating and offering practicable sets of principled educational methodologies is hardly new. Recently, these "manuals" have variably been called design principles (Kali et al., 2009), design heuristics (Nielsen, 1994; Pratt and Noss, 2010), design guidelines (Antle et al., 2011), design issues or points (Dillenbourg and Evans, 2012), design and evaluation themes (Klemmer et al., 2006), design frameworks (Abrahamson, 2014), theory–practice intermediate frameworks and design tools (Ruthven et al., 2009), conjectures (Nemirovsky, 2003), hypothesized affordances (Sarama and Clements, 2009), and precepts (Lindgren and Johnson–Glenberg, 2013). *The objective of this article is to introduce a set of heuristic design frameworks and related principles, emphases, and issues for consideration in building mathematics learning activities where enacting physical movement is taken as constitutive of conceptual reasoning.* Whereas these frameworks and related issues all cohere around the broad intellectual sway of embodied cognition, they should be regarded as complementary, reflecting the range and nuances of embodied-cognition literature (Abrahamson, 2018; Johnson–Glenberg, 2018; Nathan et al., 2019). Furthermore, whereas the intellectual grounds and practicable products of our collective work represent broad territories of current educational research on mathematics teaching and learning motivated by the embodiment turn, we make no claims for exhaustive coverage of this dynamic field of scholarship and practice. Rather, we characterize and demonstrate several notable dimensions of current work in this field so as to chart directions for its future development.

Our set of design principles are organized in the next section around six research programs on embodiment and mathematics learning. The programs differ in nuanced ways with respect to the researchers' assumptions concerning mathematical epistemology, ontology of mathematical objects, and the role of social interaction in enacting and understanding mathematical concepts. We view these differences as important both for honing our collective research efforts and for charting these efforts toward shaping a shared field of study. Our design-based research programs are as follows:

1. **Embodied design**. How should embodiment inform the design of STEM educational experiences? *Embodied design*, a pedagogical framework, draws on principles of genetic epistemology, Enactivism, ecological dynamics, and cultural–historical psychology to engage students' naturalistic sensorimotor capacity and stage opportunities for guided negotiation between grounded ways of knowing and mathematical forms and practices.
2. **Action–cognition transduction**. How do actions change one's mind? *Action–cognition transduction* explains how body movement can induce mental states that mediate sense making, inference, and proof.
3. **Gesture and multimodality studies**. How do gestures influence STEM teaching and learning? Do people studying mathematics gesture together and, if so, how does doing this support learning? *Gesture and multimodality studies* reveal how mathematics teaching and learning is embodied and used to ground formalisms and abstractions to the physical environment, support simulated action of mathematical ideas, and invoke conceptual blends and metaphors.
4. **Graspable math**. How does abstract thinking arise from concrete experiences? *Graspable math* engages the perceptual–motor system to reify the hierarchical structure of algebraic formalisms.
5. **Playful learning**. Why might STEM education need opportunities for playful learning? *Playful learning* constitutes a set of principles for motivating content learning through engaging in technology-based joyful challenging tasks.
6. **Embodiment perspectives on teacher education**. How should embodiment inform the design of teacher education and professional development? *Embodiment perspectives on teacher education* looks to involve multiple stakeholders, including university professors, who should all be informed by the promise of embodiment pedagogy.

The paper ends with a synthetic summary of these frameworks, where we chart exponents of these frameworks with respect to the ontology of manipulated objects and the role of sociality in mathematics learning.

THEORETICALLY INFORMED AND EMPIRICALLY VALIDATED FRAMEWORKS FOR THE DESIGN OF FUTURE MATHEMATICS EDUCATION

This paper proposes the framework of *embodied design* (Abrahamson, 2009a, 2014) as means of implementing the embodiment turn in the form of mathematics learning activities. The framework of *embodied design* applies to "tools whose operatory function is engineered specifically so as to . . . cultivate . . . the development of particular sensorimotor schemes as a condition for masterful control of the environment in accord with task demands," sensorimotor schemes that thereby "come to ground the mathematical concepts we want these students to learn" (Abrahamson and Bakker, 2016, p. 5). Below, we elaborate on the framework and then discuss affiliated research programs.

Embodied Design: A Research-Based Framework for Building Mathematics-Education Resources

Embodied design is a theory-to-practice approach to mathematics education that draws on the embodiment turn in the philosophy of cognitive sciences as well as on cognitive-developmental and sociocultural theory to articulate integrated guidelines for building and facilitating pedagogical materials and activities. The framework has been evolving through decades of numerous empirical-research projects all investigating mathematical cognition, teaching, and learning. Embodied-design studies have utilized diverse media—mechanical, electronic, and hybrid—to tackle enduring didactical challenges respecting a range of curricular subject-matter content, such as probability, proportionality, and algebra. Operating in the design-based orientation to educational research (Collins, 1990; Edelson, 2002; Easterday et al., 2016; Bakker, 2018), embodied-design investigations seek both to evaluate the purchase of embodiment theory in educational research and, reciprocally, to utilize the iterative, cyclic method of design practice—ideate, build, implement, evaluate, re-theorize, and over again—as an empirical context for conducting studies poised to elaborate on embodiment theory. Through these studies, a set of heuristic design guidelines were articulated, generalized, and refined.

The phrase "embodied design" was, perhaps, first coined by van Rompay and Hekkert (2001), Dutch industrial designers who used the cognitive-semantics theory of conceptual metaphor (Lakoff and Johnson, 1980) to predict emotional affects humans would attribute to architectural structures, such as bus stops (see also Kim and Maher, 2020). Thecla Schiphorst also used the phrase "embodied design," first circa 2007 in an unarchived online site and, later, in a co-authored ethnographic study of "strategies for embodied design," which surveyed HCI expert techniques for accessing and modeling users' movement experiences with interactive products (Alaoui et al., 2015). Abrahamson, who founded the Embodied Design Research Laboratory at UC Berkeley in 2005, recycled the phrase "embodied design" into the learning sciences literature with his paper, Embodied Design: Constructing Means for Constructing Meaning (Abrahamson, 2009a). As such, a particular conceptualization of embodied design for STEM education was branded, pioneered, and formulated by the Berkeley cohort. This paper, however, presents the work of scholars who may use the phrase more loosely, bringing to bear a spectrum of philosophical and theoretical commitments from cognitive-science scholarship related to multimodal interaction.

At its broadest, the embodied-design framework outlines an approach for creating STEM learning environments that stage mediated negotiations between intuitive and disciplinary orientations toward phenomena relevant to targeted conceptual learning. For example, students who judge correctly, if qualitatively, that some diagonal line is "steeper" than another line should come to accept the rise-over-run geometrical comparison analysis of these same two lines, which yields a compatible quantitative inference. Through participating in embodied-design activities, teachers and students therefore experience opportunities to surface their tacit sensorimotor orientation to situations in juxtaposition with proposed cultural forms, such as mathematical models, that reframe these situations (Abrahamson, 2004, 2007a,b, 2013, 2015a,b, 2019; Abrahamson and Wilensky, 2007). Importantly, embodied designs set students up for correct intuitive responses or performances before presenting them with analytic procedures that validate yet enhance these intuitions. Embodied-design research studies focus on tutor–student collaborative pedagogical negotiations at the conceptual epicenter of struggling to perceive a proposed disciplinary display, such as a diagram, as signifying or facilitating the enactment of intuitive know-how respecting a source phenomenon in question. This struggle requires perceptual re-orientation toward the source phenomenon. We ask how teachers and learners reconcile these socio-cognitive tensions and what epistemic resources they bring to bear in so doing.

Whereas Abrahamson's earlier investigations of embodied design sought to build activities that draw on students' innate or early *perceptual* capacity—specifically their mathematically correct intuitive qualitative judgments in comparing two *a/b* intensive quantities, such as ratio (Abrahamson, 2002), probability (Abrahamson, 2009b, 2012a,b), or slope (Thacker, 2010, Thacker, 2019; Lee et al., 2013)—later studies focused on students' capacity to achieve new *motor* coordination for enacting solutions to manual-control problems (Abrahamson and Trninic, 2011, 2015; Howison et al., 2011). As such, Abrahamson refers, respectively, to two genres within embodied design—a perception-based genre, and an action-based genre (Abrahamson, 2014). Below, we offer brief design examples of each genre and discuss general principles for its implementation. These designs were each evaluated empirically with several dozen middle-school students, who participated individually or in pairs in task-based semi-structured clinical interviews.

Perception-Based Embodied Design

Perception-based embodied designs target *a/b* concepts, such as likelihood (favorable events/possible events), slope (rise/run), density (total object area/total area), and proportional equivalence in geometrical similitude ($a{:}b = c{:}d$). Further common to these designs is a general lesson plan by which students are invited first to articulate their naïve view with respect to a situation and only then to engage in modeling, reflecting, and discussing, by which to negotiate and reconcile the formal view as complementary to, and empowering of their naïve view (Abrahamson, 2009b). This collaborative achievement of teacher and student depends on students coming to see the proposed model as expressing, validating, and explaining their own intuitive judgment of the target properties in the situation. Abrahamson (2014) has named this perceptual accomplishment *inferential parity*. **Figure 1** demonstrates the case of probability.

As a rule, all participants anticipated that the plurality of scoops would bear 2 green and 2 blue marbles, with 4 green or 4 blue scoops being rarest, and so on. However, in building the sample space with cards and crayons, they generally argued that there are only five things you can get (the combinations) and did not initially appreciate why the different arrangements (variations on each combination) might be relevant. Yet once the full sample space was completed and then arranged as an iconic bar chart (Abrahamson, 2006), all study participants were eventually able to perceive the distribution of variations on each combination (1–4–6–4–1 in the five columns) as resonant with their own intuitive judgment respecting the relative likelihood of actual experimental outcomes. That is, they achieved a sense of inferential parity between their perceptions of a situation

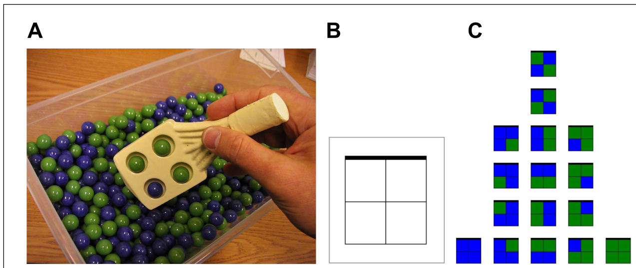

FIGURE 1 | Selected materials from a design for the binomial: **(A)** an open urn full of green and blue marbles with a scooper for drawing out four marbles; **(B)** a card for indicating possible outcomes using green and blue crayons (the thick line indicates "this side up" so as to distinguish rotations); and **(C)** the sample space of all possible experimental outcomes, made up of 16 such cards.

and its proposed mathematical model (cf. "More-A, More-B," Tirosh and Stavy, 1999).[1]

Action-Based Embodied Design

Similar to perception-based embodied design, action-based embodied design, too, seeks to ground mathematics concepts in students' innate/early capacity. Here, the capacity in question recruited by the pedagogical design is humans' ecologically adaptive sensorimotor facility of coordinating the enactment of goal-oriented physical interaction. Participants in action-based embodied designs tackle motor-control problems: They are assigned the task of performing a technologically mediated manipulation of material or virtual objects, in an attempt to achieve a specified goal state. Action-based embodied designs are predicated on the research-based general hypothesis that, in the course of attempting to perform complex movements, such as simultaneous orthogonal bimanual manipulations, people spontaneously discern new sensorimotor perceptual structures that facilitate and regulate effective motor control; with appropriate intervention, these new structures, in turn, can become signified as mathematical objects. Empirical implementations of these designs serve as contexts for evaluating and elaborating this general hypothesis.

Intellectually, the action-based genre of embodied design draws on genetic epistemology, and in particular the notion of reflective abstracting (Piaget, 1968; Abrahamson et al., 2016c), as well as on various dynamic-systems ecological theories of sensorimotor and cognitive development (Kelso, 1984; Thelen and Smith, 1994, Smith, 2006; Mechsner et al., 2001; Chow et al., 2007; Kostrubiec et al., 2012; Wilson and Golonka, 2013). Within educational theory, action-based embodied design's implication of mathematical notions as grounded in kinesthesia affiliates the framework with various dynamical models of cognition, such as in the literatures on concept image (Tall and Vinner, 1981) or enactivist theories of conceptual growth (Pirie and Kieren, 1994). We will illustrate the genre in broad strokes with a paradigmatic case of the Mathematics Imagery Trainer (Abrahamson and Trninic, 2015).

Students working with the Mathematics Imagery Trainer for Proportion (see **Figure 2**) are asked to move two cursors up and down so as to find locations that make the screen green. Once they succeed, they are asked to move both hands, keeping the screen green. The system is set so that the screen becomes green only when the right and left hands' respective heights above the base relate by a particular ratio. Here the system is set at a 1:2 ratio, so that green feedback is activated only when the right hand is twice as high along the monitor as the left hand (see Abrahamson et al., 2014, for the case of other ratios).

Figure 2 sketches out our Grade 4–6 study participants' common four-step interaction sequence toward discovering an effective operatory scheme: (**Figure 2A**) while exploring, the student first positions the hands incorrectly (red feedback); (**Figure 2B**) stumbles upon a correct position (green); (**Figure 2C**) raises the hands, maintaining a fixed interval between them (red); and (**Figure 2D**) corrects the position (green). Note in **Figures 2B,D** the different spatial intervals between the cursors or hands.

Whereas the instructor never draws students' attention to the interval, they construct this interval spontaneously as a new operable ontology, a perceptual means of solving the motor-control problem (Abrahamson et al., 2011). Engaging this affordance facilitates and regulates the bimanual enactment of a movement pattern that satisfies the task specifications. Specifically, students discover that the higher they raise their hands, the larger the interval should be, and vice versa.

Once students have both determined an effective means of enacting the target movement and articulated their strategy (see **Figure 3A**), we overlay symbolic artifacts onto the screen—first a grid (see **Figure 3B**) and then numerals (see **Figure 3C**). In response, the students utilize these artifacts as frames of reference to enhance the enactment, explanation, or evaluation of their manipulation strategies (Abrahamson et al., 2011). In so doing, the students shift from qualitative to quantitative language. These shifts in perceptual and semiotic orientation toward the sensory display are often accompanied by changes in bimanual action schemes, for example, students switch from raising both hands simultaneously to scaling the hands sequentially, 1 grid unit on the left, 2 on the right. Abrahamson (2014) has named this strategic cognitive accomplishment of reconfiguring interaction forms *functional parity*.

Eye-tracking studies of students' interactions both in this activity and other action-based embodied designs that use Mathematics Imagery Trainers for a variety of concepts have validated the general hypothesis: (a) students construct new perceptual structures—*attentional anchors*—as their means of performing the assigned motor-control tasks (Hutto and

[1]For further details on this project, including a cluster of computer-based simulated experiments used in the studies, the reader is referred to https://edrl.berkeley.edu/projects/seeing-chance/.

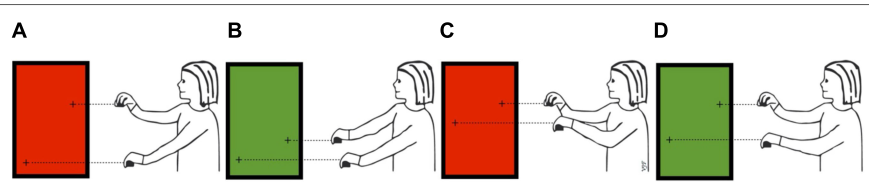

FIGURE 2 | The Mathematics Imagery Trainer for Proportion: schematic activity sequence (Art credit: Virginia J. Flood). **(A)** while exploring, the student first positions the hands incorrectly (red feedback); **(B)** stumbles upon a correct position (green); **(C)** raises the hands, maintaining a fixed interval between them (red); and **(D)** corrects the position (green). Note in B and D the different spatial intervals between the cursors or hands.

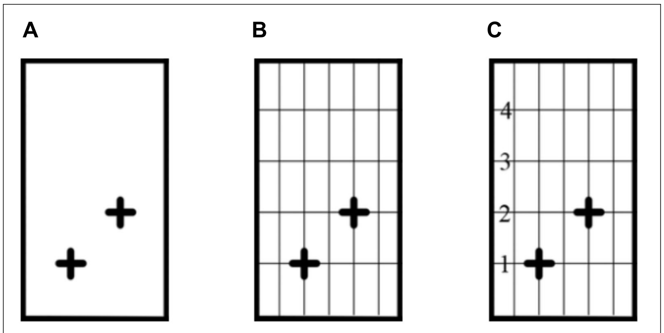

FIGURE 3 | Symbolic artifacts overlaid onto the Mathematics Imagery Trainer activity space: **(A)** the two cursors; **(B)** a grid; **(C)** numerals.

Sánchez-García, 2015; Abrahamson and Sánchez-García, 2016b; Abrahamson et al., 2016c; Shvarts and Abrahamson, 2019); and (b) these attentional anchors emerge as mathematical ontologies that students can describe, measure, reconstruct, and symbolize in other media, such as paper and pencil.[2]

In an AI-embedded version of the Mathematics Imagery Trainer, a virtual pedagogical tutor with naturalistic speech-and-gesture capabilities, "Maria," responds to students' manipulations with individualized prompts that summarize students' actions, draw their attention to particular screen regions, encourage them, and offer new challenges (Flood et al., 2015b,c; Abdullah et al., 2017). The utility of the AI-tutor's responses depends on the capability of machine-learning algorithms to emulate human-tutors' real-time intuitive inference from the student's actions to the student's thoughts (Pardos et al., 2018). Given the increasing access of young students to interactive technologies ("apps"), developing Maria and her like could be one major frontier of embodied design-based research efforts.

The embodied-design framework has been expanded by Abrahamson, his students, and international collaborators to formulate the framework's theoretical and practicable approach to multiple aspects of sensation, perception, cognition, and social interaction. **Appendix A** lists further readings pertaining to these research efforts.

Summary of Design Rationale and Principles

Mathematics imagery trainer

Moving in a new way. Working individually or in pairs, students tackle an interactive motor-control problem. The solution emerges as a particular attentional orientation, by which students coordinate the motor enactment of a movement form that instantiates the activity's targeted mathematical concept.

Signifying the movement. Students adopt elements of mathematical instruments newly interpolated into the work space. Initially, they adopt the elements as means of enhancing the enactment, evaluation, or explanation of their solution strategy; yet in so doing, they shift into perceiving their own actions through a mathematical frame of reference.

Reconciling. Finally, students reflect on logical–quantitative relations between their conceptually complementary informal and formal perceptions-for-action.

Action–Cognition Transduction: How Performing Motor Actions Impacts Mathematical Reasoning

In this section, the focus is on whether and how actions that are initiated by the motor system lead to changes in cognitive processes—in essence, *how actions change our minds*—and how this would influence our reasoning about *mathematics knowledge and mathematics education*.

Action-Cognition Transduction: Reciprocity Between Doing and Thinking

That our mental faculties influence our motor behaviors is well established, since the thoughts I have can direct me to act: I can reach for a glass of water to satisfy my goal of obtaining something to drink (e.g., Wolpert et al., 2003). By acknowledging that the cognitive and motoric systems are coupled, we can ask whether and how the effects run the other direction. Indeed, the reciprocity of input and outputs in both directions is a common property of many physical devices and biological systems. Speakers (sound out/electrical signal in) and microphones (sound in/electrical signal out) are the same devices; as are LEDs (light out/electrical signal in) and optical sensors (light in/electrical signal out); and motors (rotation out/electrical signal in) and generators (rotation in/electrical signal out). In biological transduction, movement can induce cognitive states. For example, directing people's eyes to trace a specific pattern can help solve Dunker's classic tumor–radiation problem (Thomas and Lleras, 2007). The hypothesized theoretical basis for *action–cognition transduction* (ACT) is the proposed notion that actions can themselves induce cognitive processes and effectively change how we think. Through ACT, the eye gaze action pattern of convergence induces the convergence idea that will destroy the tumor. Coming at this another way, interfering with motor responses can impair cognitive functions selectively. Botox injections, which paralyze the currogator supercilli muscles between the eyebrows—the muscles we wrinkle when experiencing anger and frustration—selectively interferes with reading comprehension of emotionally angry sentences, but not of happy or neutral sentences (Havas et al., 2010).

Is There Evidence That Learners' Actions Influence Their Cognitive Processes?

There are several means by which our actions influence our cognitive processes. How children categorize and compare unfamiliar objects can be influenced by how they hold and move them (Smith, 2005), but not how they observe the object being held or moved. People's thoughts about familiar objects include the motor information for how they have handled those objects in the past and plan to use them in the future (Yee et al., 2013). For example, it was harder for people to think about

[2]For further details on this project, the reader is referred to https://edrl.berkeley.edu/projects/kinemathics/

familiar objects (but not unfamiliar objects) when performing secondary movements designed to be incompatible with typical object use. Indeed, many models of memory retrieval posit the re-enactment of object-related actions that were performed during initial learning (Damasio, 1989; McClelland et al., 1995). Together, these results suggest two ideas central to ACT: (1) that our memories for objects, both real and imagined, are constituted, in no small part, by motor schemas for past and future handling of the objects; and (2) that performing actions may induce (or interfere with) memories of these objects, as hypothesized by ACT, even when the objects are not present, and, as with mathematical objects, even when they are imaginary (Nemirovsky and Ferrara, 2009).

What Does a Theory of ACT Offer for Learning Environment Design? the ACT of Mathematics Education

For mathematics education, we may extend ACT to formal, mathematical objects such as shapes, graphs, and symbols. This is because, psychologically, we treat mathematical objects as physical objects through mechanisms such as analogical mapping and conceptual metaphor (Lakoff and Núñez, 2000; Nathan and Alibali, in press). People perceive and manipulate algebraic symbols as though they were objects that can be picked up and moved (Alibali and Nathan, 2007; Landy and Goldstone, 2007; Ottmar and Landy, 2017). Students' self-imposed restrictions on their gestures can also limit their performance on generalization and prediction tasks. Middle school algebra students (n = 38) who confined their gestures to the frames of graphs of linear functions struggled to generalize to distal values that exceeded the frame (Bieda and Nathan, 2009). Once those same gestures revealed larger values, through transformations such as rescaling the axes, students were able to generalize to greater X-Y values, $X^2(1) = 12.6$, $p < 0.001$. In geometry, people's (n = 90) depictive gestures while reasoning geometrically predicted mathematical insight ($d = 0.44$, $p < 0.05$) and intuition ($d = 0.65$, $p < 0.05$) over and above contributions of spoken language, suggesting that gestures may facilitate reasoning and that its contribution may partly be non-verbal (Nathan et al., in press). However, the production of *dynamic* depictive gestures—gestures that both represented the objects and simulated transformations (e.g., dilating triangles, skewing quadrilaterals) and explored their generalized properties—most strongly predicted mathematically valid proof production ($d = 1.40$, $p < 0.001$), even when controlling for participants' spatial ability and math expertise.

ACT can inform design of embodied interventions. Directed body movements of high school students produced greater learning gains than mathematically comparable non-body-based activities in tests of understanding mathematical similarity [$F(1,162)56.4$, $p < 0.05$, $\eta^2 = 0.04$; Smith, 2018). Elsewhere, directed actions also led to superior geometry proof performance ($n = 120$; $d = 0.62$, $p < 0.05$), prompting the investigators to conclude that "actions can induce cognitive states ... Furthermore, the experimental design we used allows us to conclude that it is *specific* actions—those we deemed *grounding actions*—that cause these benefits, rather than performing actions more generally" (Nathan et al., 2014, p. 192, original italics). The ACT approach has been extended to the design of an embodied video game, *The Hidden Village* (Nathan and Walkington, 2017; Walkington et al., 2019a), which tracks players' movements in real time as it prompts players to make mathematically relevant actions that foster superior intuitions, insights, and proof performance (see **Figure 4**). Dynamic gestures of object transformations led to more successful geometric reasoning, especially when the gestures were made collaboratively and distributed across the hands and arms of multiple participants (Walkington et al., 2019a).

How Do Learners' Actions Influence Their Cognitive Processes? an Emerging Theory

There are two general ways within ACT that movement can influence cognition and benefit mathematics thinking and learning: cognitive offloading and simulation. These theoretical accounts are not mutually exclusive and employ cognitive rather than behaviorist mechanisms. With *cognitive offloading*, actions extend working memory and attention limits of an otherwise highly constrained cognitive system. Findings that collaborative gestures are extended over multiple people's bodies offer one of the best illustrations of this (Walkington et al., 2019a). These extended collaborative gestures help people manage the complexity of a cognitively demanding task, thus freeing up resources used for mathematical reasoning and learning.

Simulation provides another locus of cognitive support. Dynamic gestures directly support students' investigation of generalizable properties of space and shape through body movements by enacting various transformations on simulated mathematical objects. Movement, such as dynamic gesture production, depends on the generation of goal-directed motor programs, which activate predictors (feedforward mechanisms) for many or all plausible outcomes of the proposed actions so that during movement execution the system can make rapid course corrections or quickly determine goal achievement (Wolpert et al., 2003). These predictors perform like mental models that "run through" the steps toward plausible outcomes, and in so doing, support model-based reasoning and inference making (Nathan and Martinez, 2015), which can enhance scientific and mathematical learning.

Theory-Driven Design for Embodied Mathematics Education

Mathematically relevant actions can be a useful ideomotor resource for improving mathematics reasoning. Interventions that promote task-related movements, including implicit directed movements from video game play, explicit instructions, and collaborative contexts, all potentially contribute to improved mathematics performance through ACT by offloading or through simulation of object-related actions (Nathan, 2017). Mathematically relevant depictive gestures foster intuition and insight about basic properties. Dynamic depictive gestures appear to be critical for producing mathematically valid proofs regarding generalized spatial properties by enacting simulated transformations of the objects. Observing these same actions is less effective, suggesting that motoric image schemas may have primacy for making certain general conjectures. The research also

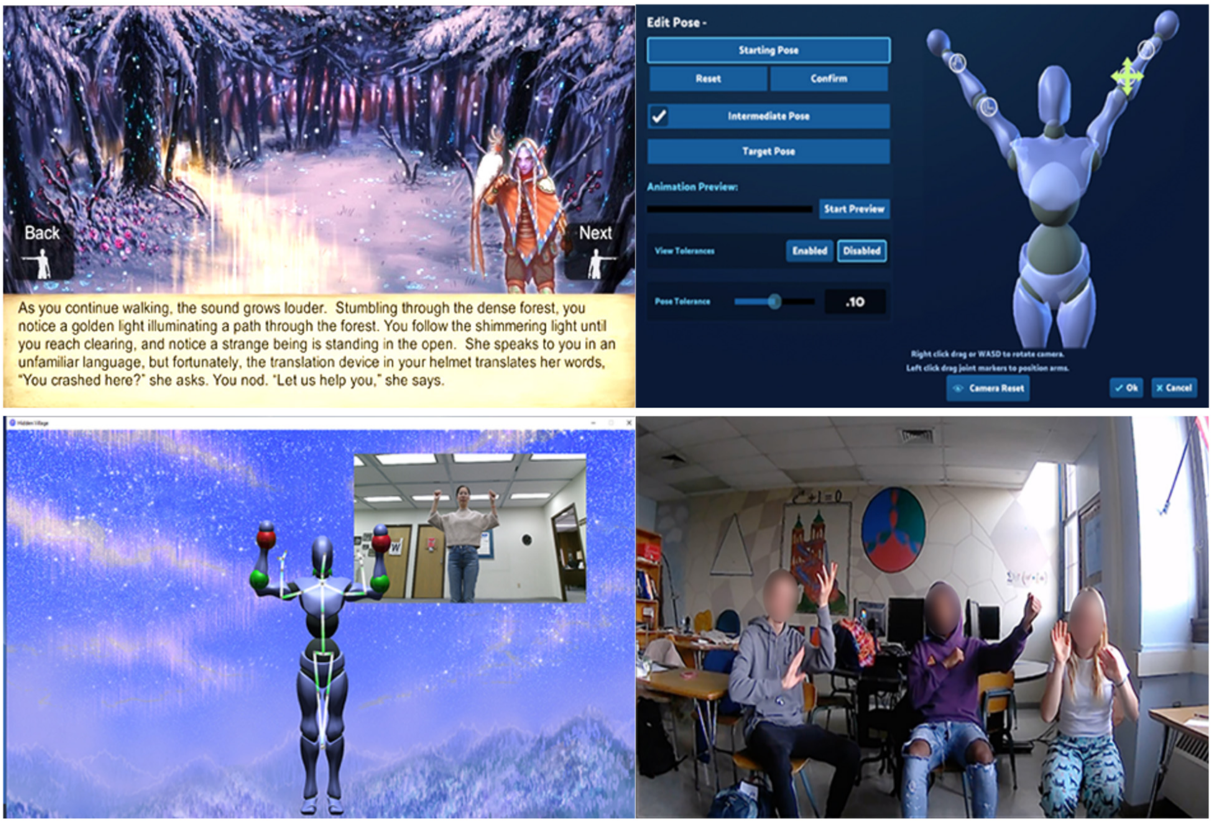

FIGURE 4 | The Hidden Village is a video game that elicits and tracks players' mathematically relevant actions in support of their subsequent mathematical reasoning. **(Top-left)** Players engage with the game narrative, and **(Top-right)** can create their own math content with poses **(Bottom-left)** that are tracked in real time (with an optional skeleton overlay, as shown). **(Bottom-right)** Students engage in collaborative gestures during game play and while reasoning mathematically.

clarifies that it is not simply that all actions facilitate thinking and learning. Actions that are not conceptually relevant exhibit few if any benefits for mathematical thinking and learning, while those that enact the relevant conceptual relations show improvements in cognitive performance, including mathematical intuition, insight, proof production, problem solving and learning (Lindgren and Johnson–Glenberg, 2013; Nathan et al., 2014; Walkington et al., 2020a). Action–Cognition Transduction offers a promising new framework for understanding how actions shape thought and for designing interventions that elicit directed actions as a viable channel for the future of embodied mathematics education.

Summary of Design Rationale and Principles

Action–cognition transduction

Action-cognition transduction. Action and cognition enjoy reciprocity: Just as cognitive processes can induce motor behaviors for performing goal-directed actions, performing actions can induce cognitive states that perform reasoning, problem solving and learning.

Fostering abstr-action. Actions that are either self-generated or externally directed can facilitate mathematical intuition and proof. The most effective actions are those that are relevant to the mathematical principles of interest.

Extended embodiment. People explore mathematical ideas deeply when they are encouraged to collaboratively co-construct body movements.

The Roles of Gesture, Collaborative Gesture, and Multimodality in Mathematics Teaching and Learning

In this section, we first give a general overview of research on gesture, and then we discuss a specific design-based research program, in which learners engage in collaborative gestures within a mathematics learning game.

Background: Research on Gesture, Teaching, and Learning

Gestures are movements of the hands, arms, and body that are produced in the effort of thinking and/or communicating. From a semiotic perspective, gestures are signs that people use to make meaning in the three ways that Charles Sanders Peirce (1894; see also Atkin, 2013) described: as indices, icons, or symbols. *Indices* make meaning by being connected to things, for example, pointing to an element in an equation. *Icons* make meaning by resembling things, for example, tracing a triangle in the air to refer to that triangle. *Symbols* make meaning by being associated with particular meanings, for example, making a "thumbs up" gesture to mean *good*. Thus, people use gesture to *indicate* objects and locations, to *represent* objects, events and ideas, and to *symbolize* ideas in agreed-upon ways (Clark, 1996). Mathematics teaching and learning commonly occur in rich environments that include a wide range of physical objects, tools, 3-dimensional models, diagrams, sketches, and symbolic inscriptions. Communication that occurs in such rich settings is usually multi-modal and grounded in the environment, and gesture is an integral part of such communication (e.g., Nathan et al., 2017c). Gesture is also intimately tied to action (Hostetter and Alibali, 2008), and, as such, gestures are ubiquitous in learning settings that involve actions, including working with physical manipulatives and constructing models. In mathematics education settings, both teachers and students regularly use gestures in all of these ways, as previous studies have richly documented (e.g., Flevares and Perry, 2001; Arzarello et al., 2008; Arzarello and Robutti, 2008; Nemirovsky and Ferrara, 2009; Alibali and Nathan, 2012).

This sub-section reviews research about (1) teachers' gestures in mathematics instruction and their roles in student learning, and (2) students' gestures in mathematics education settings and the ways in which they inform teachers' instructional practices.

Teachers' gestures and their role in students' learning

Teachers use gestures in many different ways during instruction. They point to physical objects and to inscriptions on the board or in students' work; they represent actions and objects that are not physically present; and they invoke ideas with movements that refer to ideas and concepts in agreed-upon ways. Different sorts of gestures contribute in distinct and important ways to students' learning (Alibali et al., 2011).

Teachers regularly use pointing gestures to guide students' attention to elements of the instructional context, and to support students' focus on relevant information. Indeed, some research suggests that pointing gestures are the most frequent type of gesture that teaches use during mathematics instruction (Alibali et al., 2011).

Classrooms and other settings in which mathematics learning takes place are perceptually rich, and many of the objects and inscriptions that are used in these settings are visually complex. Teachers use gestures to guide students' attention to elements in the instructional context that are relevant in the moment. Experimental evidence demonstrates that pointing gestures influence speech comprehension, especially when the verbal message is degraded (Thompson and Massaro, 1986, 1994), and that pointing gestures can influence the information that people encode from visuospatial representations, such as graphs of linear equations (Yeo et al., 2017).

Representational gestures express information via resemblance—that is, such gestures resemble, in some respect, their intended meanings. Representational gestures can represent via handshapes (e.g., using the hands to form a triangle) or via motion trajectories (e.g., tracing a triangle in the air with a finger). Some scholars have argued that such gestures arise from mental simulations of actions or perceptual states (Hostetter and Alibali, 2008, 2019). As such, representational gestures reflect—and may evoke in others—representations of visual, spatial, and motoric information. For example, a teacher might simulate taking objects off the two sides of a pan balance with her gestures (Alibali and Nathan, 2007), or a teacher might depict different sorts of angles using the position of her hands (Alibali et al., 2014). Such gestures may serve to highlight or *schematize* particular elements of a complex perceptual–motor event or situation, both for the gesture producer and for the recipient of the gesture (Kita et al., 2017).

Some gestures have forms and meanings that are "agreed upon" by members of a community. Some examples include the thumbs-up gesture and the "OK" gesture. Conventional gestures can also emerge in smaller communities, such as classrooms. For example, Rasmussen et al. (2004) describe the emergence and use of a gesture for the concept of slope invariance in a differential equations course. They describe how the gesture, which they term *slope-shifting gesture*, comes to be used to invoke a particular meaning within the classroom community—a form of local conventionalization. Another example is the gesture used in classroom activities termed "slope aerobics" or "algebra aerobics" (Carter, 2014; Lamb, 2014). In these activities the teacher calls out a category of slopes or functions (e.g., "positive slope!" or "y = x!") and students produce a gesture with their arms that depicts that slope or the graph of the function. The gestures are agreed-upon and practiced by the students, so that the teacher's commands elicit particular sorts of body movements.

All of these types of gestures may be used by teachers as part of their efforts to establish and maintain shared understanding, or *common ground,* with their students. *Common ground* refers to the knowledge, beliefs, and assumptions that are shared by participants in an interaction (Clark and Schaefer, 1989). Of course, the goal of instruction is often to help students build *new* knowledge, but this is generally accomplished by connecting to prior, shared knowledge.

Teachers establish and maintain common ground to support students in building new knowledge in several key ways: (1) by managing attention to shared referents, which may be accomplished with pointing gestures); (2) by connecting to already-shared prior knowledge, which may be expressed in representational gestures or conventional gestures; and (3) by implementing classroom practices that provide students with common experiences, and then re-invoking these shared experiences, which can be accomplished by pointing to aspects of the environment that may reactivate those ideas, or by simulating actions that reinvoke prior actions. As should be clear, teachers' gestures can play key roles in each of these ways of fostering common ground (Nathan et al., 2017a; Alibali et al., 2019).

Students' gestures and their role in teachers' instruction

Students also commonly use gestures in mathematics learning settings, so any consideration of gesture in mathematics teaching and learning must also take students' gestures into account. Students often produce gestures as part of their effort to communicate, whether they are asking questions, explaining their reasoning, or interacting with peers. In most cases, students' gestures express information that is redundant with their speech, but, at times, students' gestures express information that they do not express in speech. These gestures can reveal important information about students' thinking.

Non-redundant or "mismatching" gestures are common when people talk about knowledge that is based in perception or action (Hostetter and Alibali, 2019). People may express their perceptual or action-based knowledge in their gestures, while at the same time expressing some aspects of that knowledge in verbal form. If learners are unable to fully articulate their perceptual or action-based knowledge in words, some of that knowledge may be expressed uniquely in gesture. Non-redundant gestures have been documented in students' explanations in a wide range of mathematics domains, including early number (Gunderson et al., 2015), quantity (Church and Goldin–Meadow, 1986), equations (Perry et al., 1988), mathematical proof (Nathan et al., 2014), control of variables tasks (Stone et al., 1991), balance tasks (Pine et al., 2004), seasonal change explanations (Crowder and Newman, 1993; Crowder, 1996), and plate tectonics explanations (Singer et al., 2008).

When students express some aspects of their knowledge uniquely in gestures, then teachers who wish to obtain a complete picture of those students' knowledge must attend to those gestures. In this respect, attention to students' gestures is critical for accurate assessment of student knowledge. However, most standard assessment practices do not incorporate opportunities for expressing knowledge in gestures, and many assessment approaches actively inhibit gesture, for example, by requiring students to write or type.

Learners may express knowledge uniquely in gestures at an early point in the learning process, and, at a later point, they may express those same ideas in verbal form (e.g., Singer et al., 2008). In this sense, the knowledge that learners express uniquely in gestures may reflect new ideas that learners are "working on"—ideas that they are considering, evaluating, or consolidating. When learners express aspects of their knowledge in gesture but not in speech, they are often highly responsive to instruction or feedback (Church and Goldin–Meadow, 1986; Perry et al., 1988). In this sense, learners' gestures reveal that their knowledge is in transition (Alibali and Goldin-Meadow, 1993).

Given that gestures reflect learners' emerging knowledge, learners' gestures may reveal aspects of knowledge that are not fully developed and that may require support from teachers or more advanced peers. Thus, teachers may draw on or interpret students' gestures as indicators of areas in which they need scaffolding or direct instruction (Goldin–Meadow et al., 1993). Indeed, teachers do adjust their instruction based on the nature of students' gestures, for example, by offering a wider variety of problem-solving strategies to learners who produce mismatching gestures (Goldin–Meadow and Singer, 2003).

Learners may use gestures to highlight certain aspects of complex perceptual or spatial tasks when they think or communicate about those tasks. These gestures may reveal the aspects of those tasks that learners are focusing on. In this way, students' gestures may reflect their *schematization* of complex tasks—that is, their tendency to focus on some elements of the task and to neglect others (Kita et al., 2017). Thus, teachers may be able to infer students' focus of attention by attending to their gestures. In this way, students' gestures provide teachers valuable information about how best to engage or intervene with them.

The previous sub-section provided a general introduction to gestures, how they arise, and how they are used by students and teachers. In this section we use these ideas, as well as research on embodied learning, to motivate design-based research on a collaborative embodied game that leverages student action and gesture. Our design processes interleaved the development of a theory of how learners gesture in collaborative settings with the iterative development of digital mathematics game experiences to facilitate collaborative uses of gesture.

Gesture and collaborative embodiment

Current theories of embodiment and gesture (e.g., Hostetter and Alibali, 2008; Abrahamson and Sánchez-García, 2016b; Nathan and Walkington, 2017) have not yet fully addressed the collaborative nature of embodiment that occurs in classrooms as students are learning in physical proximity. This is in part because much of the experimental work on embodiment and gesture in mathematics has been conducted through laboratory studies with individual participants (e.g., Cook et al., 2008; Edwards, 2009; Nathan and Walkington, 2017; Pier et al., 2019). Research on gesture in multi-party interactions (e.g., Goldin–Meadow, 1999; Walkington et al., 2019a) presents evidence and synthesizes prior studies showing that the presence of multiple learners *fundamentally* changes the nature of how mathematical ideas can be embodied, in a way that is not describable as the sum of each individual's actions. A theory of *collaborative embodiment* in mathematical domains is vital to understand mathematical cognition as it unfolds in classrooms and with increasingly prevalent technological innovations for collaborative learning.

Gesture studies offer an important link between individualized and social forms of embodiment. This is because, while gesture production has well-established cognitive benefits for the individual actor (e.g., Goldin–Meadow, 2005), gesture production is facilitated when speakers operate in a social context (e.g., Vygotsky, 1978; Goodwin, 2000; Moll and Tomasello, 2007), even when the speakers cannot see one another (Alibali et al., 2001). One hypothesis is that humans are motivated toward social interactions through a process of *shared intentionality*, a fundamental disposition toward having shared experiences with interlocutors (Tomasello and Carpenter, 2007). Because of shared intentionality, we can elevate mutual gaze to joint attention, turn mere social coexistence to cooperative communication, and transform group activity from parallel actions into collaboration (Shvarts and Abrahamson, 2019). Shared intentionality allows us to build on our capacities for biological adaptation to form cultural practices, and co-construct and preserve knowledge that can be shared socially and passed across generations (Tomasello, 2009). Gesture scholars have shown how shared intentionality contributes to fostering common ground during classroom discourse by drawing attention to shared referents that may be physically present or invoked through metaphoric gesture (Nathan and Alibali, 2011; Alibali et al., 2013a). In one study, desire for intersubjectivity led students in a middle school classroom to refine their idiosyncratic representations of 3D objects so others could apprehend and use them during group problem solving (Nathan et al., 2007).

Research on collaborative gesturing

When students work together to solve mathematics problems, they build and manage collaboration through multiple modalities. Gestures operate synchronously with speech, acting as a key mechanism to create cohesion and bind conversational elements during collaborative work (Koschmann and LeBaron, 2002; Enyedy et al., 2015). Singer et al.'s (2008) study of 6th graders engaging in an earth science project found that gestures were used collaboratively to foreshadow ideas not yet reflected in speech, and that they helped students both to communicate their new ideas and to engage with each other's understandings. Group members engaged in *multimodal co-construction*, such that the external nature of gestures allowed students to copy, extend, correct, and revise each other's conceptions through gesture. Flood (2018), through an analysis of a middle school student's interactions with tutors around concepts of speed and ratio, demonstrates how *multimodal revoicing*—using gesture in conjunction with speech to reproduce, elaborate, or selectively modify an idea presented by a learner—can be used by tutors to move students toward conventional or culturally appropriate forms of reasoning. Another line of work (Hall et al., 2015; Ma, 2017; Ma and Hall, 2018) has explored *ensemble routines*, in which high school students learn to position and orient their bodies and coordinate their perspectives to accomplish a collective goal (e.g., formulating marching band patterns or large-scale geometric constructions), sometimes with the assistance of GPS technologies. This is similar to the work of Kelton and Ma (2018), which calls for considering "whole bodies" (rather than just hands) as instruments for embodied mathematical interaction and the development of mutual interdependence and shared sense-making among collaborators (see also Marin et al., 2020).

Two prior studies of teachers (Walkington et al., 2019a) and high school students (Walkington et al., 2020b) presented a taxonomy for learners' use of *collaborative gestures*—jointly enacted physical movements demonstrating mathematical relationships. By jointly enacted, we mean that when gesturing collaboratively, a learner makes a gesture whose meaning is explicitly related to and inextricably tied to the gestures of a different learner. These studies found that when proving geometric conjectures, learners repeat one another's gestures through *echoing gestures* (one gesture occurs after another) or *mirroring gestures* (gesturing at the same time). Learners respond to one another's gestures through *alternation gestures*, in which they use gesture to build on or refute an idea communicated by an interactional partner through gesture. And learners can physically co-represent a single object using *joint gestures*, in which they operate in and build representations in a shared gesture space. **Figure 5** shows groups of pre-service and in-service teachers working together to create a dynamic mathematical diagram for a geometry conjecture about an angle inscribed in a circle, as they formulate a joint gesture. These teachers are playing a computer-supported learning

FIGURE 5 | Collaborative gestures used to create a dynamic diagram for a math conjecture.

game, in which they are presented with geometric conjectures to prove without using pencil or paper. Although they were not specifically told to gesture, many gestures emerged, as they jointly constructed mathematical explanations.

Walkington et al. (2019a) found that although collaborative gestures were used in the majority of teachers' proof attempts, less experienced teachers tended to make fewer collaborative gestures and were more likely to struggle with formulating a proof. They also found that some learners were quite central to collaborative gesture activity—they both initiated collaboration via gestures (e.g., echoed someone else's gesture) and received gestural collaboration from others (e.g., someone echoed a gesture they had made)—while others were less balanced in terms of giving and receiving, and still others remained on the fringes of gestural activity. Follow-up analyses (Schenck et al., in press) suggested that the teachers were more likely to make collaborative gestures if their interactional partners did, if they were in smaller groups, or if they believed gestures had a positive impact on instruction. The average number of collaborative gestures made by group members significantly positively predicted correct proof.

Another study with high-school students playing the learning game in the same circumstances (Walkington et al., 2020b) found similar results, although high-school students had a lower tendency to produce collaborative gestures (approximately one quarter of geometry proofs). Students used such gestures in the establishment of common ground or intersubjectivity (Nathan and Alibali, 2011). Some categories of what were termed "collaborative talk moves" (e.g., learners agreeing, making an assertion, or rephrasing a contribution) were related to learners' tendency to produce collaborative gestures and to their success at solving problems together.

Across both studies, gesturing collaboratively was generally associated with more valid geometric reasoning than making non-collaborative gestures or no gestures. **Figure 6** shows the accuracy of groups in the teacher study (left) and the high school study (right), when no gestures were made proving conjectures, when gestures were made that were not collaborative, and when collaborative gestures were used. Learners' accuracy is shown for three outcomes: intuition, or whether they were correct in their judgment of whether the conjecture was true or false; insight, or an understanding of the "gist" of the conjecture and the key mathematical ideas (Zhang et al., 2016); and whether they formulated a valid transformational proof (Harel and Sowder, 1998) of

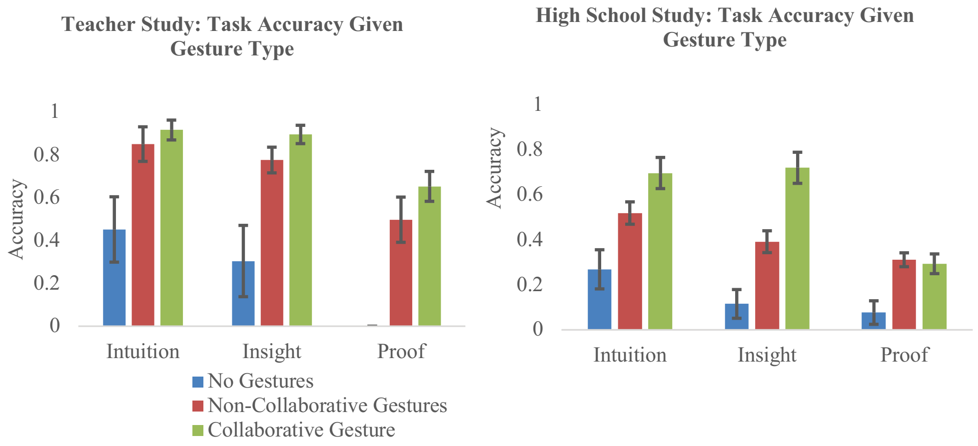

FIGURE 6 | Bar graphs depicting differences in performance when proving geometric conjectures depending on whether and how learners in a group gestured.

why the conjecture was always true or false. The trends in the graphs show that not gesturing during a proof attempt is associated with low levels of performance, while making any kind of gesture is often associated with substantially higher performance. In some cases, making collaborative gestures seems to be associated with even higher performance than non-collaborative gestures. These trends support other research suggesting that gestural mimicry improves learning (Vest et al., under review). Although here the relationship between collaborative gesture and valid mathematical reasoning is correlational, a growing body of research suggests that gesturing can itself change learners' reasoning and support learning (Novack and Goldin-Meadow, 2015). However, findings for the causal role of gesture in directly supporting reasoning are mixed (e.g., Walkington et al., 2019b), and the facilitative effect of interventions intended to allow learners to leverage body movements may occur only under certain circumstances (Walkington et al., 2019b).

The research reviewed here can provide the basis for a theory of collaborative embodiment, which recognizes that joint mathematical activity is a complex endeavor, in which interactional partners use shared multimodal resources, including speech, body position, gesture, writing, diagrams, and manipulatives (Arzarello et al., 2009). During collaboration, learners align their gesture spaces (i.e., the physical space in which they gesture and the socially constructed mathematical meaning of the space) and, in some cases, their body position and orientation (e.g., Kelton and Ma, 2018), in order to facilitate shared interpretation of mathematical ideas (Nathan et al., 2007; Yoon et al., 2014). Collaborative gesture specifically, and collaborative embodiment more generally, can become an interactional resource for meaning-making that can operate without technical language (Flood et al., 2015a). Collaborative gesture can be potentially powerful for establishing common ground and jointly advancing a group's geometric understanding through embodied exploration together. Understanding ways to leverage this tendency to jointly embody, particularly in the context of motion-based, GPS, and holographic technology tools, may create novel opportunities for learners to come to understand mathematical ideas together in meaningful, embodied ways.

Summary of Design Rationale and Principles

Gesture, collaborative gesture, and multimodality in mathematics

Teacher gestures. Teachers use pointing, representational, and conventional gestures to establish and maintain common ground.

Student gestures. Learners' gestures can reveal knowledge not in speech, emerging or transitional knowledge, and how learners schematize information.

Collaborative embodiment. The presence of multiple learners fundamentally changes the nature of gestures, as learners leverage shared multimodal resources.

Gestures during collaboration. Learners can jointly embody ideas using gestures that build off one another, and these gestures may facilitate mathematical learning, particularly in the context of action-based technology tools for learning.

Graspable Math: Concretizing Algebraic Solution Procedure

Over the past several decades, there have been significant advances in our understanding of how grounded and embodied cognition can help facilitate abstract learning. Theorists have argued that grounding abstraction in perceptual–motor-based actions offers an alternative to representing symbols as purely amodal, abstract, and arbitrary symbol systems, where the focus is on interpretation and rote manipulation of symbols (cf. Barsalou, 2008). Principles of grounded and embodied cognition suggest that successful perceptual practice and manipulation of algebraic structures uses cognitive systems that correctly embody mathematical rules and turn action into meaning (Dourish, 2004). Grounding one's mathematical knowledge and reasoning has also been shown to support the transfer of knowledge to new situations (Landy and Goldstone, 2007; Goldstone et al., 2010).

At first look, it might seem that symbolic notation is intangible and not naturally given to embodiment. However, prior work in cognitive science has established that algebraic reasoning is rooted in at least three basic perceptual processes (Landy et al., 2014a; Goldstone et al., 2017). First, abstract symbols are treated as physical objects distributed in space (Dörfler, 2003; Nogueira de Lima and Tall, 2008; Landy and Goldstone, 2009; Landy, 2010). Second, seeing symbols involves perceptual processes such as grouping and attention (Kirshner, 1989; Landy and Goldstone, 2007, Landy and Goldstone, 2010; Murayama et al., 2013; Landy et al., 2014b). Third, learning to operate on algebraic notations involves learning attentional tendencies (Landy et al., 2008; Goldstone et al., 2010; Marghetis et al., 2016). For example, Landy and Goldstone (2007) demonstrated how perceptual grouping based on Gestalt principles affects how people interpret algebraic symbols in ways that may either adhere to or conflict with order-of-operations rules. Together, this suggests that students rely on the visual patterns available in notation clusters to learn reasonable patterns of mathematical behaviors taken upon symbolic objects. These findings have implications for research and practice, where turning algebraic notations into tangible objects that enforce their own rules through physical movements may help improve mathematics learning. In turn, this research on learning within dynamic systems could help transform many of the traditional distinctions between abstract and concrete knowledge. Perhaps, if students could actually—not only imaginatively—manipulate mathematical symbols, as though these were worldly objects, this could help tap into students' perceptual learning systems and provide unique opportunities for students to explore the inherent structure of algebra physically and visually.

Graspable Math: The Interactive Math Notation

Building on this theoretical conjecture, Ottmar et al. (2015a) have explored how virtual tools can be designed to reify theory of embodied cognition in the form of dynamic algebra interfaces, where symbols can be picked up and rearranged. Over the past several years, they have developed *Graspable Math* (*GM*), an innovative dynamic learning technology that utilizes gesture-initiated actions to explore algebraic structure (Ottmar et al., 2015a). In GM, symbols are tactile virtual objects that can be flexibly picked up, manipulated, and rearranged through specified gesture–actions. In this approach, mathematical structure can be appreciated through exploration and manipulation. GM makes the implicit structure of mathematical objects overtly visual by grounding algebraic expressions and transformations in space and action. Through these physical manipulations of virtual objects, GM transforms algebra from a set of arbitrary rules for transforming symbolic statements to intuitive notions of manipulating concrete objects in quasi-natural ways.

In GM, the actions are called "gesture–actions" to distinguish them from gestures as they are often used in the psychological sense (Alibali and Nathan, 2012; Alibali et al., 2013b; Novack et al., 2014). These gesture–action routines were designed as dynamical virtual embodiments of imaginary symbolic manipulations people typically experience in performing algebraic transformation. For example, to simulate the imaginary perception of "moving the +3 over to the other side of the equal sign, making it −3," GM lets students literally swing a digital "+3" over the equal sign, where it becomes "−3" (Ottmar et al., 2015a). Through gesture–actions, users can combine terms, apply operations to both sides of an equation, and rearrange terms through commutative, associative, and distributive properties (see **Figure 7**).

It is hypothesized that as users engage with the GM system, the actions enable students to develop new sensorimotor schemes that can help facilitate mathematical reasoning by fostering grounded understandings of the mathematical properties and operations that the actions embody. In turn, these can facilitate learning new mathematical concepts. The actions taken are bound to a virtual visualization that reflects one way of imagining the corresponding mathematical transformation. For example, touching a term and moving it leftward will apply the commutative property, with the result that the term will literally move leftward. Gesture–actions are designed to emulate engaging in an appropriate physical action, and for each action there is a corresponding visualization. Ultimately, GM's dynamic transformations and gesture–actions facilitate the exploration of algebraic structure in a low-risk learning environment and can provide opportunities to experience fluid, distinctive visualizations and fast feedback (Ottmar and Landy, 2017).

Empirical Support for Dynamic Notation Systems

Graspable Math has shown potential as a tool that provides opportunities for students to play with the structure of algebra in ways that are unavailable through traditional classroom tools. Below we highlight some of our empirical findings that demonstrate the usefulness of this approach for learning and engagement.

Perceptual-motor training in GM can have impacts on student outcomes

In several studies, GM has been shown to increase student performance and engagement compared to static methods of

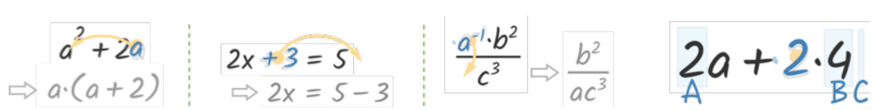

FIGURE 7 | The Graspable Math dynamic algebra notation interface: examples of gesture–actions for factoring, rewriting equations, and inverting powers with negative exponents. Results of gesture–actions are depicted in gray.

instruction (Landy and Goldstone, 2007, Landy and Goldstone, 2010; Ottmar et al., 2015b; Weitnauer et al., 2016; Manzo et al., 2017; Ottmar and Landy, 2017; Sawrey et al., 2019). One study using a puzzle-based version of GM (*From Here to There*) found that a 2.5-h intervention in intact classrooms with no instruction led to gains on a comprehensive test of procedural fluency covering all basic algebra identities and transformations (effect size of 0.82 improvement *over regular classroom instruction*; Ottmar et al., 2015b). A second RCT with 500 6–7th grade students found improvements on measures of conceptual understanding over traditional problem sets with hints and immediate feedback (effect size = 0.18; Sawrey et al., 2019).

Perceptual–motor training in GM before instruction can better prepare students for future learning

In a classroom study, using GM to explore concepts before instruction led to greater learning gains over the reverse order (Ottmar and Landy, 2017). These findings are in line with other work that shows that using concrete analogies or examples first and then fading these supports over time leads to stronger learning outcomes (Fyfe et al., 2014).

Dynamic algebra tools like GM can vastly increase efficiency and success in problem-solving by decreasing cognitive load

After a brief training, students were able to solve difficult equations using dynamic support available in GM more efficiently than on paper (Weitnauer et al., 2016). Students' increased outcomes were partially attributable to the speed and fluency with which they moved through the content itself (Ottmar et al. (2015b); Hulse et al., 2019). These results suggest that GM's dynamics may play a valuable role, comparable in ways to calculators, not as a replacement for paper-and-pencil solving but as a supportive scaffold that allows students to cope with more challenging situations by carrying less cognitive load (Sweller, 1994).

Distributed dynamic algebras may increase engagement and ameliorate the negative effects of math anxiety

Graspable Math was designed with the goal of making students more familiar with algebraic notations while providing scaffolding and feedback, thus increasing their confidence and comfort in dealing with equations. GM does not allow for simple transcription errors of the kind many students find particularly frustrating, and thus it decreases math anxiety. While higher math anxiety typically relates to lower math achievement, these relations have not been found when students use GM (Ottmar et al., 2020).

We also have evidence that dynamic touch-screen systems help increase students' engagement and interest in learning algebra: students overwhelmingly reported that they enjoyed solving problems and learned more through the app than traditional instruction (Ottmar et al., 2012, 2015a).

Dynamic technologies like GM can provide insight into students' mathematical problem solving and thinking

Graspable Math logs all user interactions and behaviors, when students are solving problems, providing rich information about student problem-solving process, mathematical strategy, behaviors, and errors. These in-app measures, such as resetting and exploration, have been found to predict learning gains (Hulse et al., 2019). Further, recent work has demonstrated that pause time before solving predicts the efficiency and flexibility of the mathematical strategy that students use (Chan et al., 2019). More research is underway to examine the mechanisms by which GM facilitates learning, engagement, and mathematical problem-solving strategies.

Conclusion

Graspable Math is an innovative, research-based software platform intended to supplement regular mathematics instruction. GM: (1) integrates formal syntax and grounded semantics; (2) is suitable for use by teachers in classrooms and by a large proportion of struggling students; and (3) can be used as a framework for exploring fundamental issues in mathematics learning. GM is a promising educational tool that addresses a relatively untapped area of practice-focused, cognitively motivated, perceptually guided instructional technology. GM focuses on the perceptual strategies successful students use to read and transform equations and develops an intervention to connect these experiences to meaningful structures in a precise and fluid interface. GM allows the procedural advantages of physically moving symbols to seamlessly integrate into conceptually challenging lessons. It is anticipated that this increase in familiarity and strong grounding in perceptual learning that underlies procedural fluency will better prepare students for future instruction and improve learning in advanced areas that assume the ability to read and manipulate equations. GM represents a first step at moving beyond static abstract symbols toward a dynamic concrete interface that provides an integrated, embodied notation experience capable of supporting a variety of mathematics curricular needs.

Summary of Design Rationale and Principles

Graspable math

Grounding of abstraction in perceptual-motor actions. Algebraic reasoning is rooted in basic perceptual processes.

Embedding action and perception into new technology tools. Dynamic notation systems that integrate embodied, perceptual-motor training in notation can support mathematics teaching and learning.

Insight into students problem solving and thinking. Data logged in technologies can be used to unpack mechanisms by which embodiment and action relate to student thinking, problem solving processes, and learning.

Playful Mathematics: Why Games Count

Previous sections have argued for a theorization of mathematics teaching-and-learning as a collaborative, multimodal, perceptual–motor phenomenon; and, accordingly, for educational designs that create opportunities for students to ground mathematical notions in embodied enactment of conceptually oriented movement forms. This section focuses, specifically, upon how the design of digital game-based environments can provoke embodied mathematics learning through play and gesture (for more general reviews of game-based mathematics learning, the reader is referred to the numerous works cited below).

Motivating Games for Mathematics Learning

The fundamental rationale for gamifying education is that games increase players' motivation, engagement, and learning (e.g., Gee, 2005; Steinkuehler and Duncan, 2008; Martin, 2011). In mathematics in particular, well-designed games can provoke players to voluntarily mathematize the digital context in a process called *theorycrafting* (e.g., Steinkuehler and Williams, 2009; Devlin, 2011). Consequently, numerous educational designers—academic (e.g., Barab et al., 2010; Gresalfi and Barnes, 2016; Zandieh et al., 2018; Kang et al., 2020) as well as commercial (e.g., Ritzhaupt et al., 2009)—have therefore developed learning games. However, the quality of these games is inconsistent: too many learning games mix the "entertainment value of a bad lecture with the educational value of a bad game" (Squire and Jenkins, 2003, p. 8). Designers of mathematics learning games, in particular, often struggle to integrate curricular content into game mechanics and experiences, instead merely intjecting comic relief into calculation tedium. Consequently, students' playful physical/digital actions are not semiotic enactments, that is, they do not constitute, bear, or otherwise suggest enactment of the targeted mathematical notions. An embodied perspective, whereby motor actions enact prospective concepts, offers new horizons for game-based learning, as discussed earlier (e.g., From Here to There, The Hidden Village).

We focus here on an exemplar of embodied playful mathematics design, a videogame titled *Rolly's Adventure* (RA; Williams, 2015; Williams–Pierce, 2017), that requires players to engage in co-speech gesture when describing their experience and learning. Such descriptive co-speech gesture occurs during communication with others, whether a researcher or fellow players (Stevens et al., 2008; Williams–Pierce, 2017). Playing on one's own is considerably less likely to elicit gesture. As discussed in earlier sections, gestures can express information related to mathematical reasoning that are not contained within the accompanying speech. Accordingly, the goal of this section is to describe how mathematics teaching in multimodal game-based environments requires attending to such gestures. Digital environments that use novel interactive representations of mathematical notions may provoke non-redundant gestures at a particularly high rate, such that teachers and researchers must attend to gesture to gain a comprehensive view of the playful mathematical learning.

Playful Mathematics Learning With Rolly's Adventure

Rolly's Adventure (see **Figure 8**) was designed to require manual actions both when playing the game (physical manipulation that results in digital action) and when discussing it (co-speech gestures). The design employed novel, non-standard mathematical representations and interactions to mitigate students' mathematics anxiety (Papert, 1980; Williams-Pierce, 2016).

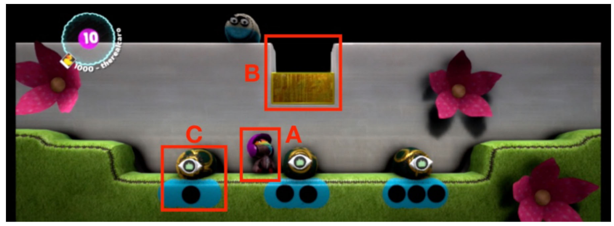

FIGURE 8 | The first puzzle in RA, with red annotations. **(A)** The player's avatar; **(B)** the fraction (the golden block) that must be operated upon in order to fill the unit (the hole that the golden block is within); **(C)** the primary interaction method (a round button) and its attendant label (the single black dot). The player must determine which round button will perfectly fill the unit: activating **(C)** enacts "1 × 1/2," which replicates **(B)**; whereas activating the middle button enacts "2 × 1/2," perfectly filling the (w)hole unit.

Players enter RA without being told the underlying mathematical structures, interactions, or desired learning content, similar to both the Mathematics Imagery Trainer and *The Hidden Village*, but contrasting with Graspable Math, where the mathematics is overt. Only through iterative action–reflection cycles, experiencing failure and feedback, do they discover that the game is designed to enact fraction multiplication (Williams–Pierce, 2019). In making sense of the game, students must draw on their mathematical knowledge to model the situation in ways that are advantageous to solving the embedded and emerging problems. **Figure 9** shows Christian's verbal–gestural utterance, as he describes the game objects mathematically, including quantitative relationships between those objects and operations that transform one object into the other in RA (Williams-Pierce, 2016). Christian began by giving a specific example of a game puzzle, where the block is an improper fraction, 1 1/2, nested within the unit hole. He then treated that block as a unit, with his gestures indicating that he is smoothly re-unitizing (Hackenberg, 2007; Steffe and Olive, 2010): from the block as an improper fraction in relation to the unit hole, to the block as the unit whole that can then be acted upon (Williams–Pierce, 2017). Christian's verbal–gestural utterance reveals the mental model he has developed of the game and the underlying mathematical structures, and it illustrates a form of transfer through reflection generalizations (Ellis, 2007; Williams-Pierce and Thevenow-Harrison, under review).

Designers seeking to integrate mathematical content into game mechanics should consider creating realistic situations that afford both proximal actions (manipulation) and distal actions (the digital outcome) that enact normative dynamics of mathematical transformations (Abrahamson and Bakker, 2016; Dittman et al., 2017). Students' gestures demonstrate their productive struggle to coordinate between features of the situation and elements of mathematical forms (Abrahamson, 2004; Nemirovsky et al., 2020). As such, teachers who incorporate games into their curriculum are encouraged to facilitate classroom discussions that legitimate gestural utterance, so that they can support students' mathematical modeling.

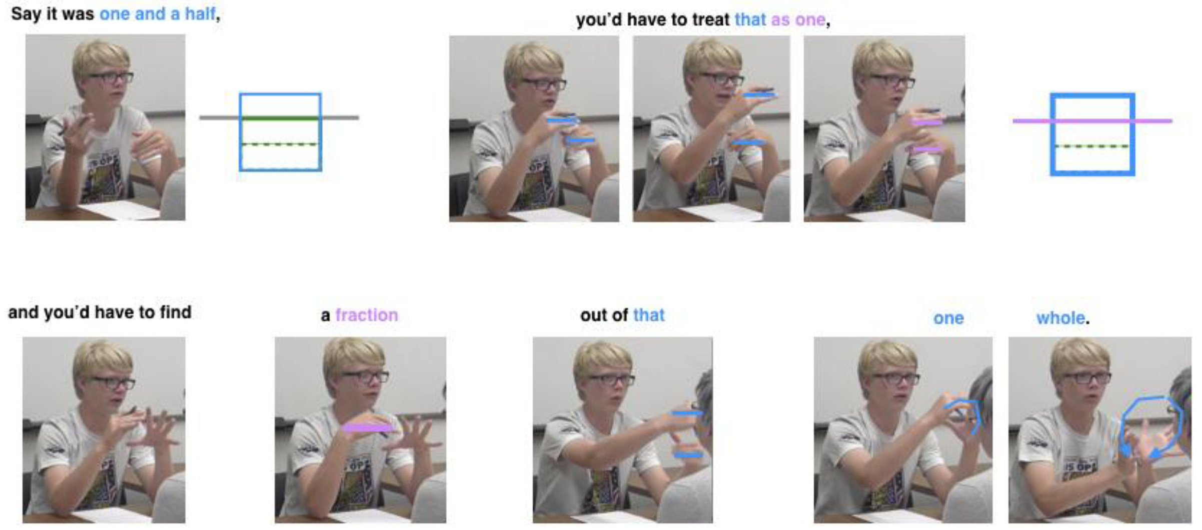

FIGURE 9 | Christian (pseudonym) using a mathematical model to explain his game tactics. Gestures have been enhanced in blue (the improper fraction quantity that represents a gold block) and purple (the unit whole that represents the hole containing the block) to connect Christian's gestures more clearly with his spoken language; independent images of his referents have been supplemented.

Summary of Design Rationale and Principles

Designing for voluntary mathematization

Novel non-standard mathematical representations and interactions can provoke voluntary mathematization by the player–learner.

Designing for semiotic enactments

Semiotic enactments can be supported by designing a game that requires players–learners to use co-speech gestures to communicate about the underlying mathematical patterns.

Learning as a multimodal synthesis

Understanding the processes of learning within a mathematical game requires synthesizing the player–learner's digital actions, spoken language, and physical gesture.

Embodiment Perspectives on Teacher Education

A current movement in K–16 mathematics education is for instructors to teach using student-centered techniques that help make content accessible to students, especially students from historically underrepresented (HU) groups. Although an agreed-upon definition of student-centered learning does not exist, a unifying theme entails students developing their own knowledge, where "learning is personalized to the students' unique needs, interests, and aspirations, and designed with their ideas and voices at the table" (Kaput, 2018, p. 10). Neumann (2013) encapsulates these various characteristics by describing student-centeredness as a process of focusing *on* students, *in* students, and *with* students. Instructors create lessons based *on* students' educational needs and course goals, where students organically react to the lesson's activities, engage *in* their own sense-making, and where instructors work in partnership *with* students. Although instructors generally have good intentions of implementing student-centered learning that emphasizes conceptual understanding, inservice K-12 teachers (Yurekli et al., 2020), prospective K–12 teachers (Loughran and Hamilton, 2016), and collegiate faculty (Estrada et al., 2018) do not always enact their intended teaching methods.

In this section, we describe barriers that prevent K–16 instructors from integrating student-centered teaching, summarize effective professional development (PD) strategies, and offer examples of how embodiment can support student-centered learning, be integrated as part of teacher education or professional development, and foster equitable instruction.

Toward Student-Centered Pedagogy Informed by Embodiment Perspectives

Whereas prospective K–12 teachers study student-centered instructional methodologies in their university preparation courses, they are generally challenged in implementing these methodologies in the school classroom. Given that some education faculty, mathematics faculty, university supervisors, and K-12 in-service supervisors have differing views on concept-based and student-centered teaching and learning, K-12 teachers struggle to transform their teaching (Simon, 2013, 2018). Researchers have implicated a theory–practice divide (Loughran and Hamilton, 2016), whereby university courses provide intellectual theory, while field-based practices provide authentic experiences (Horn and Campbell, 2015)—prospective teachers are not equipped to bridge this divide without guidance from university faculty and cooperating teachers. Worse, prospective teachers receive inconsistent views from university faculty and K–12 teachers about mathematics content, teaching, and learning. Zeichner et al. (2015) claim that, "too often these [elements] are not in dialogue and leave the novice teacher as the sole mediator of multiple knowledge sources" (p. 124).

In-service teachers likewise struggle to integrate research-to-practice, even after they partake in PD. Richards and Skolits (2009) cite teachers' "unfamiliarity with instructional strategies promoting student engagement, inadequate training regarding these strategies, and insufficient support in the classroom" (p. 41) as reasons for the persistence of teacher-centered classroom practices. Moreover, teachers may perceive their school environment as unsafe for change, believe that administrators are unsupportive of such teaching, and fear violating state or national mandates (Greenberg and Baron, 2000; Fullan, 2001; Goleman et al., 2002).

Collegiate faculty, too, are slow to adopt student-centered teaching, despite the call for faculty to make STEM courses more inspiring, to assist students facing mathematical challenges, and to create an atmosphere of a community of STEM learners (PCAST, 2012). Handelsman et al. (2004) attribute this predicament to faculty being unaware of evidenced-based teaching methods. Yet even faculty who *are* aware of the research may distrust its findings, and in particular those who themselves learned via lecture. Furthermore, some faculty fear losing their identity and credibility as a researcher, if they focus on their teaching (Brownell and Tanner, 2012). Finally, transforming one's teaching is effortful and cumbersome, requiring time, support from faculty and administrators, and resources.

In their synthesis of the literature, Richards and Skolits (2009) delineate that PD designed to integrate new teaching strategies must "incorporate hands-on, experiential learning opportunities, that are embedded in authentic contexts in which teachers can thoroughly connect with the new strategies" (p. 42). Experiences such as these allow teachers to better understand and connect the content and strategies by taking time to apply, analyze, and synthesize the strategies in ways that will be meaningful in the teachers' classrooms. In their own research, Richards and Skolits found that teachers were more likely to integrate a new teaching strategy if they understood the educational theory behind the strategy, observed the strategy modeled, related the new strategy to existing teaching practices, and received on-site support as they integrated the new strategy for the first time. Some researchers (Speer et al., 2005, 2010; Deshler et al., 2015) have investigated effectiveness of PD for collegiate instructors, but the research remains minimal in this domain and much of the work is with graduate students. Given the wide range of research demonstrating that embodiment facilitates mathematics learning (Abrahamson, 2009a; Radford et al., 2009; Hall and Nemirovsky, 2012; Schoenfeld, 2016; Oehrtman et al., 2019; Soto–Johnson and Hancock, 2019) and the call for student-centered learning in K–16 mathematics education (Conference Board of the Mathematical Sciences [CBMS], 2016), the time is ripe to educate prospective teachers, in-service teachers, and collegiate instructors regarding embodiment.

Embodiment can inform teacher education and PD in the same way that it informs mathematics educational experiences, as long as these experiences are designed *for* students, *in* students, and *with* students in mind. Content courses designed for prospective teachers or as part of PD can be designed with activities that require play or action in either the physical or virtual world. Embodied, authentic, hands-on, body-on, activities intentionally designed based on the learning goals, the students' needs, and the students' background knowledge Abrahamson et al. (2012a) satisfy PD recommendations. Furthermore, as part of lessons instructors might intentionally gesture for students and convey how the gesturing exemplifies some aspect of the content. Given learning dwells in the student, instructors must learn to become attuned to students' gesturing, motor-actions, and accompanied verbiage and be prepared to help them become conscious of their unconscious actions. Such observing and reporting students' actions back to them may help students to begin to build intuition and to transform their physical or virtual experiences to abstract concepts. This is the juncture where instructors collaborate with students and help them bridge the experience, the play, the motor-actions, the verbiage, and the abstract concepts. Such facilitation requires modeling in prospective teachers' collegiate mathematics content courses and PD designed to introduce embodiment to in-service mathematics teachers.

Embodiment in Professional Practice: A Design for Teacher Education

Figure 10 illustrates how embodiment has been used with prospective K–12 mathematics teachers as they learn properties of Euclidean transformations. In this activity, learners embody points on the Cartesian plane. They hold onto rope, which represents the segments of a polygon, and collaboratively engage in translating along the plane, rotating 45°, 60°, and 90° about a given point, and determining the image of their polygon when it is reflected about parallel lines and intersecting lines. Besides learning properties of these transformations, the students come to realize that Euclidean transformations are rigid motions on the plane. Realizing this via paper-and-pencil media is difficult, because one transforms a single point at

FIGURE 10 | Enacting Euclidean transformations: Guided by a university instructor, three mathematics teachers study a tarped Cartesian coordinate system in preparation for rotating a rope triangle over the plane. They current occupy (–1, –1), (1, 4), and (2, –2).

a time (Yanik, 2014). The action of moving simultaneously, the gestures that materialize via student–student conversations, and the teacher–student dialogues that emerge during such an activity epitomize student-centeredness through embodiment. This activity has also been used as part of PD for K-12 teachers and collegiate instructors (Soto–Johnson, 2016; Nathan et al., 2017b; Soto, 2019).

Prospective teachers are generally trained to inform their students about the choices that are made in the classroom, as such, integrating embodiment into teacher education and professional development should begin with regular brief introductions to embodied cognition. This can be as simple as stating that body movement can be a first sign that learning is occurring and that learners can demonstrate their understanding via *multimodal utterances*, which include eye motion, facial expressions, gesture, gaze, body poise, body motion, tone of voice, etc. (Nemirovsky and Ferrara, 2009). This is a good first step for audiences to understand the educational theory behind an activity, as suggested by Richards and Skolits (2009).

These utterances can also display what Estrada et al. (2018) refer to as *micro/macro affirmations*, which are particularly relevant for HU students. The authors promote micro/macro affirmations such as space left between people when interacting (e.g., physical closeness), eye contact, subtle teasing, voice tone, and actions that convey vulnerability and constitute utterances. Embodied activities that deliberately attend to these characteristics can serve as steppingstones toward such affirmations and support equity. Another benefit of embodiment is that it can provide a non-linguistic on-ramp to mathematics concepts, which can facilitate learning for students who may have a language barrier. Embodiment provides such learners access to concepts through body-based interventions and ways to express their reasoning in non-verbal ways. Given gestures can suggest learner readiness (Goldin–Meadow et al., 1993), practitioners' abilities to attend to learners' gestures may serve as micro-affirmations and give students confidence and make them feel more included. Through embodied activities that support micro/macro affirmations, HU learners or learners who consider themselves "unteachable" may experience new points of access to content presented through movement, concrete experiences, and body-based forms of engagement, which are all forms of student-centered learning.

Summary of Design Rationale and Principles

Embodiment perspectives on teacher education

K-16 student-centered teaching and learning. K-16 teachers should teach using student-centered techniques, where students can create and share their own knowledge.

Teacher education on embodiment. Embodiment can be integrated via content courses and K–16 PD, where learners engage in physical or virtual play. Learning to be attuned to students' gesturing, motor-actions, and accompanied verbiage and helping students become conscious of their unconscious actions may help students build intuition and transform their actions to abstract concepts. Important for instructors to become cognizant of their own gestures and intentionally convey their gesturing to students.

Students develop a multimodal voice. Embodiment provides learners access to concepts through body-based interventions and can frame teachers' formative assessments of students' reasoning that is expressed in non-verbal ways.

GENERAL SUMMARY AND IMPLICATIONS FOR MATHEMATICS EDUCATION DESIGN AND RESEARCH

These are exciting times for cognitive scientists investigating the futures of mathematics education. An interdisciplinary research intersection has formed, where three frontiers—paradigm-changing theory of human learning (embodied cognition), new human–computer interaction platforms (e.g., with gesture or gaze sensors), and powerful methods for measuring, coding, modeling, and monitoring individual and collective student activity in real time (multimodal data analytics, artificial intelligence, machine learning, and visualization)—converge to innovate learning environments offering naturalistic experiences that foster conceptual knowledge grounded in sensorimotor cognitive and affective processes. We, a cohort of collaborating learning scientists and mathematics educators and teacher educators who practice embodied design-based research, have surveyed some of the perspectives, evidence, and principles we bring to bear in working with the multiple stakeholders of mathematics educational enterprises—primarily students, teachers, and technology experts—to explore the futures of mathematics education. Whereas technology is rapidly evolving, we hope that some of the heuristic design principles we have demonstrated and delineated will endure and prove useful to our colleagues and fellow scholars.

As a cohort, we continue to investigate these tenets of embodied design:

- The meaning of mathematical concepts is grounded in individuals' cognition in the form of modal processes, which are non-verbal and non-symbolic. This enactive know-how (System 1; Kahneman, 2011) may complement, be redundant with, or be totally distinct from our linguistic and inscriptional formalisms.
- Participants in embodied-design activities discover and develop concept-grounding enactive processes, even when they are not aware *that* or *what* they are learning (Abrahamson et al., 2016c; Nathan and Walkington, 2017; Mathayas et al., 2019).
- Mathematics knowledge can cross the epistemic divide from enactive to linguistic–symbolic through mediational processes that include discourse, reflection, expression, and argumentation, using a variety of modalities and media (Abrahamson, 2009b; Trninic and Abrahamson, 2012; Morgan and Abrahamson, 2016). Gesture, in particular, is instrumental in sounding pre-semiotic processes into social interaction.

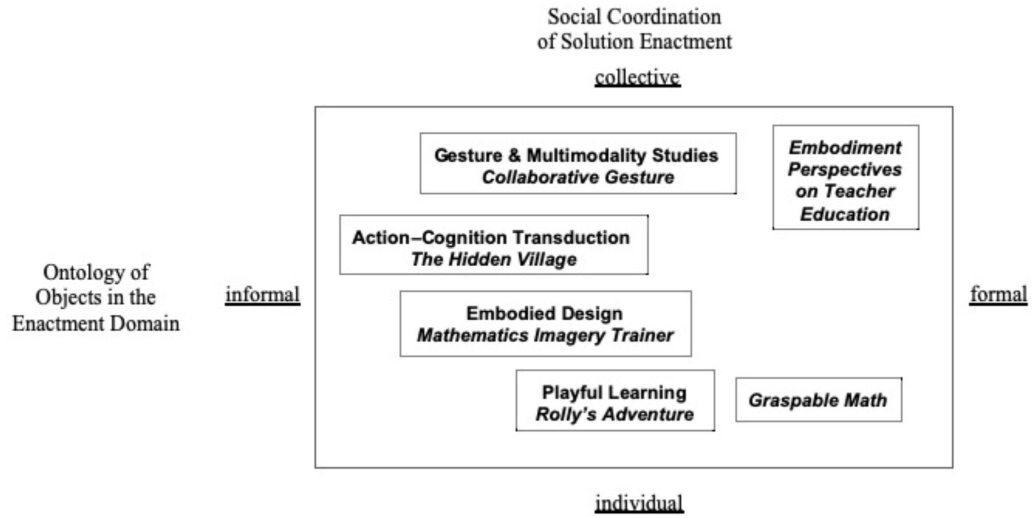

FIGURE 11 | Plotting the six embodied designs along two axes: (*x*) the manipulatives' ontological status; and (*y*) the social participation of solution enactment.

These educational potentials of the embodiment turn favor approaches such as concreteness fading (Fyfe et al., 2014) as well as sociocultural models of guided mediation (Abrahamson et al., 2012b), and a rejection of *formalisms first* approaches to curriculum design and instruction (Nathan, 2012). Approaches to instruction that foreground embodied forms of knowing have implications also for assessment of knowledge that is encoded in non-verbal form (Pardos et al., 2018). See **Appendix B** for a summative list of the design principles emanating from the six research programs surveyed in this article.

Figure 11 plots the designs exponents of the six research programs discussed in this paper with respect to two axes: (1) the ontology of objects in the enactment domain; and (2) the social coordination of the solution enactment. As the figure demonstrates, the designs differ in their foci either on pre-symbolic or symbolic objects as the things that students manipulate. For example, in the *Mathematics Imagery Trainer*, students manipulate generic acontextual icons, such as empty circles, whereas in *Graspable Math* they manipulate numerical symbolic notations, such as the digit "7." Designers' selection of interactive digital objects may reflect their philosophical and theoretical positions concerning the epistemic function of working with pre-symbolic objects, their assumptions respecting students' entering knowledge of a domain, and their instructional objectives for specific projects. These decisions can be of moment: research has demonstrated that images carry implicit semiotic content that may constrain their apparent affordances and therefore may either enhance or compromise the designers' goals for students' interactions (Rosen et al., 2018).

The designs also differ with respect to the contributions and prominence of fellow learners in the process of determining, coordinating, and enacting the physical actions that solve the problem encountered therein. For example, *Rolly's Adventure* is designed to maximize outreach—any individual child with access to a digital device and internet could play this game, whereas *Collaborative Gesture* is designed explicitly to solicit disciplinary discourse among a cohort of co-present classroom students attempting to solve a collective problem. Designers' choices respecting the collaborative quality of an educational activity are closely related to the perceived epistemic function of enactment, the available media, the instructional settings, and the desired roles of socialization. For further reviews of designers' beliefs respecting the epistemic role of movement in embodied design, readers are referred to Abrahamson and Bakker (2016), Abrahamson (2018), and Abrahamson and Abdu (2020). Notably, designs premised on a conceptualization of the mathematics learning process as the development of a new sensorimotor perceptual structure may yield different learning outcomes whether a two-handed interaction is performed by an individual student or distributed over two students (Abrahamson et al., 2011). Finally, other potential dimensions of comparison among embodied designs could include: types of technological media supporting the activities; forms and degrees of pedagogical support proffered by teachers or avatars in the learning environment; and student opportunities to discover how to enact the movement forms necessary for completing the tasks.

Whereas the perspectives presented in this paper varied in their interpretations of embodiment, they all highlighted the role of physical movement in conceptual development (Abrahamson, 2018). And yet, by and large, the field of mathematics education research has not investigated the sensorimotor production of physical movement. Being informed of research on how we learn to move in new ways could help us better design, measure, and theorize the enactment of physical movements grounding mathematics learning (Beilock, 2008, 2015; belcastro and Schaffer, 2011; Abrahamson et al., 2016a). More broadly, inasmuch as we theorize perceptual–motor activity as constitutive in the development of mathematical cognition, our field should form interdisciplinary communities of educational research that cross traditional boundaries and bring in ideas from scholars in dance, kinesiology, sports science, somatics, and related fields (Mechsner et al., 2001; Thelen and Smith, 2006; Kelso, 2016; Adolph et al., 2018; Sheets-Johnstone, 2018; Cappuccio, 2019). The movement sciences, we maintain, have much to contribute to emerging theories of conceptual development in mathematics and beyond.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the IRB/CHPS at the authors' respective universities. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

DA initiated and led the effort, with MN making significant contributions to the opening and closing sections. CW-P, CW, EO, HS, and MA wrote a segment in the central section, which DA and MN reviewed. All authors contributed to the article and approved the submitted version.

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APPENDIX A—EMBODIED DESIGN LITERATURE

Suggested further readings on embodied design include publications pertaining to the following dimension of mathematics-education theory and practice:

- "how-to" heuristic principles for building embodied designs (Abrahamson, 2009a, 2012c, 2014, 2015a);
- positioning embodied-design research projects as settings for investigating problems of empirical philosophy (Hutto et al., 2015)
- rethinking models of discovery learning (Abrahamson, 2012a; Chase and Abrahamson, 2015; Abrahamson, 2018);
- reconciling Piaget's genetic epistemology and Vygotsky's cultural–historical psychology (Abrahamson et al., 2011, 2012b, 2016c; Abrahamson, 2015a);
- developing a complex dynamic-systems reading of Vygotskian theory (Shvarts and Abrahamson, 2019);
- theorizing students' epistemic grounds for accepting cultural forms (Abrahamson et al., 2011; Abrahamson, 2014);
- situating the framework within historical approaches to intuition (Abrahamson, 2015b);
- discussing traditional and future uses of pedagogical artifacts that shape the normative enactment of disciplinary movement forms (Abrahamson et al., 2016b);
- analyzing the phenomenology of movement (Abrahamson and Bakker, 2016);
- determining the effect of context richness on movement-based learning (Rosen et al., 2018);
- investigating the role of rhythmic movements in the discovery of mathematical forms (Palatnik and Abrahamson, 2018);
- highlighting the centrality of perception in mathematics learning (Abrahamson, 2020a,b)
- pioneering the design-based research of interactive virtual pedagogical avatars with capacity for naturalistic speech and gesture (Abdullah et al., 2017; Pardos et al., 2018);
- identifying the framework's roots in Seymour Papert's educational vision (Abrahamson and Chase, in press);
- relating the framework to metaphor studies (Abrahamson et al., 2012a; Abrahamson et al., 2016a; Abrahamson, in press);
- discussing the framework in light both of dance (Abrahamson and Shulman, 2019) and somatic–contemplative practices (Morgan and Abrahamson, 2016; Abrahamson, 2018);
- dialoguing with special education (Chen et al., 2020; Tancredi et al., in press) and Universal Design for Learning (Abrahamson, 2019); and
- expanding the framework so as to include the treatment of science content (Abrahamson and Lindgren, 2014).

APPENDIX B—EMBODIED-DESIGN ACTIVITY ARCHITECTURES: SUMMARY OF PRINCIPLES, PROCEDURES, AND OUTCOMES

Embodied Design: Mathematics Imagery Trainer

Moving in a New Way

Working individually or in pairs, students tackle an interactive motor-control problem. The solution emerges as a particular attentional orientation, by which students coordinate the motor enactment of a movement form that instantiates the activity's targeted mathematical concept.

Signifying the Movement

Students adopt elements of mathematical instruments newly interpolated into the work space. Initially, they adopt the elements as means of enhancing the enactment, evaluation, or explanation of their solution strategy; yet in so doing, they shift into perceiving their own actions through a mathematical frame of reference.

Reconciling

Finally, students reflect on logical–quantitative relations between their conceptually complementary informal and formal perceptions-for-action.

Action–Cognition Transduction: The Hidden Village

Action-Cognition Transduction

Action and cognition enjoy reciprocity: Just as cognitive processes can induce motor behaviors for performing goal-directed actions, performing actions can induce cognitive states that perform reasoning, problem solving and learning.

Fostering abstr-Action

Actions that are either self-generated or externally directed can facilitate mathematical intuition and proof. The most effective actions are those that are relevant to the mathematical principles of interest.

Extended Embodiment

People explore mathematical ideas deeply when they are encouraged to collaboratively co-construct body movements.

Gesture, Collaborative Gesture, and Multimodality in STEM

Teacher Gestures

Teachers use pointing, representational, and conventional gestures to establish and maintain common ground.

Student Gestures

Learners' gestures can reveal knowledge not in speech, emerging or transitional knowledge, and how learners schematize information.

Collaborative Embodiment

The presence of multiple learners fundamentally changes the nature of gestures, as learners leverage shared multimodal resources.

Gestures During Collaboration

Learners can jointly embody ideas using gestures that build off one another, and these gestures may facilitate mathematical learning, particularly in the context of action-based technology tools for learning.

Graspable Math

Grounding of Abstraction in Perceptual-Motor Actions

Algebraic reasoning is rooted in basic perceptual processes.

Embedding Action and Perception Into New Technology Tools

Dynamic notation systems that integrate embodied, perceptual-motor training in notation can support mathematics teaching and learning.

Insight Into Students Problem Solving and Thinking

Data logged in technologies can be used to unpack mechanisms by which embodiment and action relate to student thinking, problem solving processes, and learning.

Playful Learning: Rolly's Adventure

Designing for Voluntary Mathematization

Novel non-standard mathematical representations and interactions can provoke voluntary mathematization by the player–learner.

Designing for Semiotic Enactments

Semiotic enactments can be supported by designing a game that requires players–learners to use co-speech gestures to communicate about the underlying mathematical patterns.

Learning as a Multimodal Synthesis

Understanding the processes of learning within a mathematical game requires synthesizing the player–learner's digital actions, spoken language, and physical gesture.

Embodiment Perspectives on Teacher Education

K-16 Student-Centered Teaching and Learning

K-16 teachers should teach using student-centered techniques, where students can create and share their own knowledge.

Teacher Education on Embodiment

Embodiment can be integrated via content courses and K–16 PD, where learners engage in physical or virtual play. Learning to be attuned to students' gesturing, motor-actions, and accompanied verbiage and helping students become conscious of their unconscious actions may help students build intuition and transform their actions to abstract concepts. Important for instructors to become cognizant of their own gestures and intentionally convey their gesturing to students.

Students Develop a Multimodal Voice

Embodiment provides learners access to concepts through body-based interventions and can frame teachers' formative assessments of students' reasoning that is expressed in non-verbal ways.

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ORIGINAL RESEARCH
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Development of Interdisciplinary STEM Impact Measures of Student Attitudes and Reasoning

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The integration of Science, Technology, Engineering and Mathematics (STEM) programs is a national trend. The goal of implementing STEM in schools is to prepare students for the demands of the 21st century, while addressing future workforce needs. The *Real STEM project* focused on the development of interdisciplinary STEM experiences for students. The project was characterized by sustained professional development which was job-embedded, competency-based, and focused on the development of five STEM reasoning abilities within real-world contexts. The project promoted inclusion of tasks that drew on multiple STEM disciplines, embraced the use of authentic teaching strategies, and supported development of collaboration through interdisciplinary STEM professional learning communities and engaging STEM experts from the community. The four tenets of the project are presented and research on developing and characterizing measures of student impact are provided. Key outcomes include the construction and evaluation of measures supporting interdisciplinary STEM to assess both the impact of intervention on student attitudes toward STEM and students' STEM reasoning abilities. Findings include reliability and validity evidence supporting attitude measurement and reasoning measurement as well as exploratory results that highlight a disconnection between STEM attitudes and STEM reasoning with the interdisciplinary STEM intervention examined.

Keywords: authentic teaching, collaboration, interdisciplinary STEM, reasoning, attitudes

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INTRODUCTION

The integration of interdisciplinary Science, Technology, Engineering and Mathematics (iSTEM) into schools is a national trend in the United States, apparent in the call to establish STEM designated middle and high schools (Executive Office of the President, 2010; President's Council of Advisors on Science and Technology, 2010; Tanenbaum, 2016), as well as in the creation of STEM academic/career pathways for future workforce development (National Research Council, 2013). The *Next Generation Science Standards* (Next Generation Science Standards Lead States, 2013) and the *Common Core State Standards for Mathematical Practice* (National Governors Association Center for Best Practices and the Council of Chief State School Officers, 2010; Bennett and Ruchti, 2014) provide science and engineering practices and mathematical practices that support the inclusion of STEM in schools. These practices include modeling, integrating mathematics and computational thinking into science, planning and carrying out investigations of real-world problems, analyzing and interpreting data, and designing solutions.

A problematic issue for STEM researchers and practitioners is the variety of interpretations of STEM education (English, 2016). Vasquez et al. (2013) established a continuum of increasing levels of STEM integration: disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary. A collaborative known as the *Real STEM project* has endorsed the increased push for STEM integration at the interdisciplinary (2 or more disciplines closely linked concepts/skills studied to deepen understanding) and transdisciplinary (2 or more disciplines applied to real-world problem) levels (Honey et al., 2014; Johnson et al., 2015). The Real STEM project sought to move beyond what Shaughnessy (2013) termed the STEM veneer, where approaches implemented in schools do not genuinely integrate STEM disciplines. In addition, research on the impact of STEM integration on content knowledge or interdisciplinary processes appears limited and inconclusive (English, 2016). English and Gainsburg (2016) call for research on the impact of content knowledge in STEM areas and interdisciplinary processes, including critical thinking and problem solving. Honey et al. (2014) espouse the need for the study of impact on affective factors, such as student engagement, motivation, and perseverance. The form of evidence collected to demonstrate STEM integration is also frequently lacking (Hernandez et al., 2013; Honey et al., 2014). To constructively continue the work of the Real STEM project the study reported in this paper takes steps to address gaps in research. Prior to specifying these steps some further background on the project will provide needed context.

The Real STEM project was funded by the Georgia Department of Education Innovation Fund to provide professional development. The project supported implementation of interdisciplinary STEM experiences through course modules in existing science and mathematics courses, as well as through new interdisciplinary STEM courses at the middle school and high school grade levels. The two primary student outcomes of the project were to (a) increase student engagement and persistence in STEM and (b) improve students' STEM reasoning. The intended long-term outcomes of Real STEM were to meet future STEM workforce needs by increasing student retention in the STEM pipeline and to develop STEM literate citizens who can make informed decisions about grand challenges impacting their future. Teachers participated in a 2-week summer workshop with professional development field experiences that prepared them to guide students in authentic interdisciplinary STEM research, modeling, and design experiences. As a part of these authentic experiences, teachers were mentored on collaborating with regional STEM experts to identify authentic place-based STEM challenges. The STEM research design experience was to be student-centric, with students formulating research questions within the frame of challenges identified by STEM experts. The STEM experts were to mentor the teachers and students as students explored their problem, collected the data, analyzed the data, and reported findings to an expert panel. Students were expected to view the problem through interdisciplinary STEM lenses, bringing chemistry, biology, physics, earth sciences, computational science, engineering, and mathematics to bear on the problem where appropriate. The project leadership team led the summer workshops and conducted monthly classroom observations in the partner schools.

Intervention Design

The Real STEM project provided sustained professional development in interdisciplinary STEM. Sustained professional development is job-embedded (Croft et al., 2010; Huffman et al., 2014) and competency-based (Burke, 2005), with the goal of building interdisciplinary professional learning communities (PLCs) consisting of school administrators and teachers of science, mathematics, technology, and engineering (Fulton and Britton, 2011). Mayes et al. (2018) describes a program which provided support and mentoring for teachers in four key tenets supporting interdisciplinary STEM teaching and learning. These tenets are as follows.

Tenet 1: Interdisciplinary STEM

Educators ensure that STEM is taught as an interdisciplinary approach (Stohlmann et al., 2012). We took the perspective that a meaningful STEM task must incorporate at least two of the four STEM fields. We asked teachers to start by having students view problems through all four STEM lenses, before eliminating those that did not apply. We stressed use of real-world problems, which were often interdisciplinary and occurred in complex systems.

Tenet 2: Authentic Teaching Strategies

Educators incorporate project-based teaching, problem-based teaching, and place-based education strategies to actively engage students (Boud and Feletti, 1997; Thomas, 2000; Reiser, 2006; Bell, 2010; Sobel and Smith, 2010). A primary goal of integrating STEM into a school was to provide students with the opportunity to engage in real-world problem solving through hands-on experimentation, research, modeling, and design challenges. Teachers were mentored in implementing authentic teaching strategies, including project-based learning (Buck Institute for Education, 2017), problem-based learning (Strobel and van Barneveld, 2009; Savery, 2015), and place-based education (Sobel and Smith, 2010).

Tenet 3: Collaboration

Educators create STEM PLCs within the school supported by community, business, research institute and school partnerships (Larson, 2001; Blankenship and Ruona, 2007). Interdisciplinary STEM requires a team approach to teaching in order to support authentic real-world ill-structured problems. Real STEM schools established interdisciplinary STEM learning communities that included teachers of science, mathematics, engineering/technology (when available), and an administrator. The PLCs were instructed to meet regularly to consult on implementing STEM tasks. Development of collaborations with STEM community experts was an expected outcome for the PLC team.

Tenet 4: STEM Reasoning

Educators set outcomes that go beyond student engagement to development of five 21st century STEM reasoning abilities identified by education experts (Wing, 2008; Schwarz, 2009; Householder and Hailey, 2012; Holland, 2014; Mayes et al., 2014). For interdisciplinary STEM programs to grow and be sustained they must do more than increase student engagement.

STEM programs need to have established learning outcomes, but also need to include student-centric, ill-structured problems which are difficult to connect with predetermined STEM content standards. That is, rigid synchronizing with content standards can contradict the open-ended nature of STEM tasks. The learning outcomes we highlighted are the development of student ability to think like a scientist, a computer scientist, an engineer, and a mathematician. STEM experts have different problem-solving processes which, while they overlap, are not the same. Our examination of the literature resulted in the identification of five STEM reasoning modalities which are 21st century abilities STEM experts call for students to develop:

(1) **Complex system reasoning** is the ability to analyze problems by recognizing complexity, patterns, and interrelationships within a system featuring a large number of interacting components (agents, processes, etc.) whose aggregate activity is non-linear (not determined from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures (Holland, 2014).
(2) **Scientific Model-based Reasoning** is the ability for students to construct scientific models in order to explain observed phenomena (Schwarz, 2009).
(3) **Technological Computational Reasoning** is an analytical approach grounded in the computer sciences. It includes a range of concepts, applications, tools, and skill sets that allow us to strategically solve problems, design systems, and understand human behavior by following a precise process that engages computers to assist in automating a wide range of intellectual processes (Wilensky and Resnick, 1999; Wing, 2008).
(4) **Engineering Design-based Reasoning** is the ability to engage in the engineering design process through implementation of a series of process steps to come up with a solution to a problem. Many times, the solution involves designing a product (like a machine or computer code) that meets certain criteria and/or accomplishes a certain task (Householder and Hailey, 2012).
(5) **Mathematical Quantitative Reasoning (QR)** is mathematics and statistics applied in real-life, authentic situations that impact an individual's life as a constructive, concerned, and reflective citizen. QR problems are context dependent, interdisciplinary, open-ended tasks that require critical thinking and the capacity to communicate a course of action (Mayes et al., 2014).

Purpose of This Study

The Real STEM project developed instruments to begin measuring impacts of the project on teacher practice, student attitudes, and student reasoning. In this paper we focus on the measurement of student attitudes and student reasoning. Teacher practice data is presented and analyzed in a separate article (Mayes et al., 2018). The goals of the present study begin with (a) examining the measurement characteristics of the instruments developed in order to examine STEM integration impact. This will be accomplished through piloting these instruments in school intervention settings and through careful analyses of instrument qualities and the student performances. Following completion of this goal we will have established the foundation for a second goal, (b) exploratory analyses of the effect of the Real STEM intervention on teacher practice, student cognition, and student attitudes. The focus of this report is the crucial work in support of these two main goals that represent vital developmental stages for enabling subsequent and ongoing investigation of STEM integration.

MATERIALS AND METHODS

Participants

A total of 898 students across six middle schools and six high schools participated in the attitude assessment portion of the study. The students were evenly split among males (50.2%) and females (49.8%), with a large percentage of Caucasian (62.4%) and Black/African American (24.1%) students. Hispanic/Latin American, Asian, Native American, and Other students constituted a combined 13.6% of the respondents. Three quarters of the students were at the middle school level (75.6%). The higher number of middle school students was due both to middle schools offering more sections of STEM courses than high schools, and the middle schools having larger enrollments per section.

A total of 1,315 students participated in the reasoning assessment portion of the study at four middle schools ($N = 783$) and two high school ($N = 532$) levels. The students were 51.8% males and 46.5% females (1.7% not indicating gender), with a large percentage of Caucasian (63.6%) and Black/African American (21.9%) students.

Measures of Student Attitude and Reasoning

The *STEM Student Attitude Survey* consists of six questions examining student attitudes toward the four STEM subject areas and 10 questions on their attitudes toward interdisciplinary STEM. Students ranked each item from 1 for a strong negative response to 5 for a strong positive response. An example from each section of the survey is provided below:

- Student Attitudes Concerning each STEM AREA, such as science
  Confidence: How confident were you in your ability to do well in science before class versus now? 1 Very unconfident 2 Unconfident 3 Neutral 4 Confident 5 Very Confident
- Student Attitudes concerning Interdisciplinary STEM
  Employment: I understand how STEM is important to many jobs in my community. 1 Strongly Disagree 2 Disagree 3 Neutral 4 Agree 5 Strongly Agree

The survey was developed by the project team consisting of a mathematics educator with extensive experience in STEM education, a science educator, and an evaluation expert. The survey items were derived from the Applied Learning Student Questionnaire (Georgia Governor's Office of Student Achievement, 2017) developed for the Georgia Governor's Office of Student Achievement. The survey was administered online upon completion of a STEM course. Students were asked to rate each of these areas regarding before taking the course (reflection) and after taking the course (present). The teachers were requested to have all 1,315 students participating in Real STEM courses complete the survey.

The *STEM Student Reasoning Assessment* was developed by the project team to provide a common measure for the Real STEM Project of student understanding of the five 21st century reasoning modalities promoted as course outcomes. The project team conducted research on each of the five reasoning areas, creating white papers that outlined key characteristics of the reasoning areas. Assessment items were then developed to evaluate student understanding of the characteristics. The items were vetted by the project team including the external evaluator. The assessment consists of 34 multiple choice questions: eight on scientific model-based reasoning, six on engineering design-based reasoning, five on complex systems reasoning, seven on technological computational reasoning, and eight on mathematical quantitative reasoning. The number of items included per reasoning category was determined through mapping of crucial question topics appropriate to the varied characteristics of each category. The lead teachers of the STEM courses were asked to administer the *STEM Student Reasoning Assessment* as a pre–post, but due to the variety in implementation of the STEM courses across schools, some teachers selected only to administer the reasoning assessment as a post-test and others did not administer the assessment, yielding 426 students (32%) whose pre and post tests could be matched. Sample questions from the assessment for each STEM reasoning area are provided in **Box 1**.

Design

In support of the investigation goals which include piloting and evaluating two measurement instruments, the research design involved two studies, both of which included non-experimental components and the second of which also included a quasi-experimental component. The Study 1 non-experimental dependent variable was student attitude levels, examining attitude time and attitude categories within subjects. Independent variables of student gender and student school level were used. The Study 2 non-experimental dependent variable was student reasoning ability, examining reasoning categories within subjects. The quasi-experimental component of Study 2 was a pre–post-test design with the dependent variable of STEM reasoning ability and the repeated measure of test administration. The independent variables of student gender and student school level were used. IBM SPSS (IBM Corporation, 2017) and Winsteps (Linacre, 2017a) were used for statistical and measurements analyses.

RESULTS

Evidence on measurement validity and reliability resulting from administrations of the *STEM Student Attitude Survey* and the *Student STEM Reasoning Assessment* was examined using the Rasch rating scale model and the Rasch dichotomous model, respectively, and in accordance with the two different item types of each assessment. Both of these models assume a unidimensional measurement structure and include a difficulty parameter that differentiates the item characteristics (Andrich, 1978; Rasch, 1993). These Rasch measurement models support the examination of construct validity and content validity, as well as student reliability and item reliability (De Ayala, 2009; Engelhard, 2013; Bond and Fox, 2015).

Validity Evidence

Construct validity was evaluated using item fit statistics, item measure correlation statistics, rating scale functioning, and principal components analysis (PCA) of residuals which allows examination of a dominant dimension, or unidimensionality (Bond and Fox, 2015). Item fit statistics included infit and outfit mean square (*MNSQ*) values. Items with values above *MNSQ* = 1.3 (1.4 for rating scales) indicate underfit that does not contribute to the construct measure (Wright et al., 1994; Linacre, 2017b). Those items above *MNSQ* = 2.0 also indicate underfit but to a higher degree that likely distorts the construct measure (Linacre, 2002). Although values below *MNSQ* = 0.7, known as overfit, are not considered to distort the construct measure, they may cause misleading increases in reliability estimates. To reflect item discrimination, item point measure correlation values should be positive in value, ideally above 0.50 though no less than 0.15. Rating scale functioning statistics, relevant only for the *STEM Student Attitude Survey,* were examined for favorable criteria of greater than 10 observation per each of the five categories, average category measures that increase with categories (i.e., ordered), threshold calibrations that were ideally 1.4–5 logits apart, and non-overlapping rating scale distribution peaks. PCA of residuals yields eigenvalues and corresponding percentages of variance accounted for by the principal component of the construct. For strong unidimensional structure overall variance accounted for by measures would ideally be 50% or greater, with unexplained variance accounted for less than 5% to support the construct. In addition, when strong unidimensional structure is not present, overall we are looking for variance that is no less than a 20% threshold for our unidimensional analyses (Reckase, 1979).

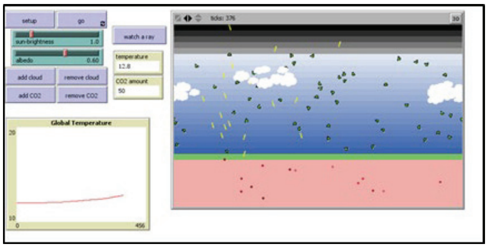
Content validity was evaluated with regard to the measurement continuum and the sample targeting. These two characteristics reflect a portion of the content validity evidence related to expectations of the distribution of item difficulties including mean and standard deviation values. The characteristics were each examined with the graphic visuospatial assistance of an item/person map, or variable map. Variable maps consist of the item difficulty measurement distribution placed on the same continuum and scale as the person measure distribution. For the *STEM Student Attitude Survey*, difficulty refers to endorsement difficulty, given that data represent a rating rather than a performance level. The variable map is made possible by the Rasch calibration of items and persons to a common logit scale. Attitude and content area items should be represented across the continuum

Interdisciplinary STEM Assessment. The Lower Coastal Plain of Georgia (LCPG) includes the 27 counties closest to the ocean. Many of you live in the LCPG or visit this area to play in the ocean. Water is everywhere on the LCPG in the form of the ocean, rivers, swamps, lakes, ponds, marshes and estuaries. All of these play an important economic and recreational role for those living on the Coastal Plain. The Georgia Coastal Hazards Portal (http://gchp.skio.usg.edu/) provides the Sea Level Affecting Marshes Model (SLAMM) which indicates the impact of potential sea level rise on the LCPG. The maps below provide information from the SLAMM model for the Savannah region. Answer the following questions on the LCPG water system.

1. *Scientific model-based reasoning:* Select all of the following traits of SLAMM that indicate it is a scientific model. (Choose all that apply)
   a. **SLAMM is based on scientific observation and data.**
   b. **SLAMM consists of objects such as sea water and coastal shores and processes such as climate change that impact those objects.**
   c. SLAMM is the only correct model of sea level rise.
   d. **SLAMM is one of multiple models of sea level rise that can be compared.**
   e. SLAMM explains all aspects of sea level rise.

11. *Engineering design-based reasoning:* Suppose you are concerned about the impact of sea level rise on a local swamp. Which of the following are good criteria and constraints for developing a measurement device for potential impacts on the swamp?
   a. Criteria: measurement device must be resistant to high humidity
   b. Constraint: measurement device cannot include toxic materials
   c. Criteria: measurement device must provide continuous data collection
   d. Constraint: measurement device must stay within budget
   e. **All of the above**

A major component of the SLAMM model is the concept of climate change. The figure below provides a picture of a model of heat energy flow on the earth. The surface of the earth is represented by the green strip; yellow arrowheads represent sunlight energy; the green dots represent CO2 in the atmosphere; the white represents clouds; and the red dots represent heat energy from sunlight absorbed by the earth.



19. *Complex systems reasoning:* Which of the following traits of a complex adaptive system does the Heat Energy Model display? (Choose all that apply)
   a. **Feedback loops: a closed loop where the output of a cycle gets returned as input for the same cycle**
   b. **Interdependence: the behavior of one of the system agents is dependent on the current state of other agents.**
   c. Dependence: the agents in the system depend on an authority or leader for direction.

BOX 1 | Continued

d. **Multi-scale hierarchical organization: within the system there are multiple levels of organization, with smaller systems within larger systems.**
e. Linear effects: where a small change in one variable always has a small effect in changing the system

23. *Computer computational reasoning:* Computer scientists use analysis and evaluation to prove whether abstractions are correct. This often involves the analysis of data. Which of the following is the result of analyzing and evaluating the data in the Heat Energy Model simulation?
    a. **Development of the global temperature graph**
    b. Number of CO_2 molecules in the atmosphere
    c. Reflection properties of the clouds
    d. Reflection properties of the CO_2
    e. All of the above

The National Estuarine Research Reserve System (NERR) gathers data on a number of water quality variables at 28 sites across the U.S., including Sapelo Island NERR in Georgia. The table provides data on the depth of water from one sensor on Sapelo Island.

31. *Quantitative Reasoning:* The line of best fit is y = 0.0566x + 2.4912 where x represents data point (date/time) and y represents depth of water. What does the line of best indicate about the trend of water depth?
    a. The water depth trend appears to be remaining constant
    b. The water depth trend cannot be determined
    c. **The water depth trend is increasing**
    d. The water depth trend is decreasing
    e. The water depth is purely the result of seasonal fluctuations

BOX 1 | Sample questions from the *STEM Student Reasoning Assessment*.

at different difficulty levels for ideal measurement, given the expectation for diverse attitude responding or diverse understanding among participants. The item measurement continuum should ideally not have significant gaps in difficulty relative to the student measures of ability or attitude. Hence, larger numbers of students and/or items typically allow for improved interpretation of the measurement continuum. Targeting refers to the overlap between item measures and person measures whereby the greater the overlap the more accurate and less error prone the measurement will tend to be. Well mirrored distributions, including means and standard deviations, reflect an appropriate matching of participants with the instrument.

Reliability Evidence

Reliability was evaluated using the item separation index, the student separation index, the item reliability coefficient, and the student reliability coefficient from the Rasch model analyses (Boone et al., 2013; Engelhard, 2013; Bond and Fox, 2015; Linacre, 2017b). The separation indices reflect the spread of student ability (or attitude) and item difficulty, respectively, to allow distinct levels. Separation levels greater than 2 for persons and greater than 3 for items are expected in order to support reliable measurement. These levels respectively represent two levels on the measurements scale (e.g., high and low performance or ratings) and three levels of difficulty. The reliability indices provide a statistic based on measures rather than raw scores, which ranges between 0 and 1. Person reliability is similar to the well-known raw-score based Cronbach alpha, though preferable to alpha due to it being based on measures. Person reliability levels above 0.80 and item reliability levels above 0.90 are expected as indicators of strong reliability evidence.

Study 1: *STEM Student Attitude Survey* Validity and Reliability Evidence

The survey items, final response means, and mean change as retrospectively reported relative to each item are provided in **Table 1**.

Table 2 provides a summary of the validity and reliability findings for the *STEM Student Attitude Survey*, indicating

TABLE 1 | STEM student attitude survey.

Item type	Item	Science		Tech		Engineer		Math	
		M	**Δ**	**M**	**Δ**	**M**	**Δ**	**M**	**Δ**
Interest	How interested were you in each STEM area before class vs now?	3.93	0.46	3.71	0.45	3.49	0.54	3.50	0.38
Confidence	How confident were you in your ability to do well in each STEM area before class vs now?	4.05	0.44	3.81	0.51	3.67	0.60	3.89	0.35
Importance	How important was understanding each of the STEM areas before class vs. now?	4.24	0.54	3.99	0.57	3.85	0.56	4.22	0.42
Persistence	How interested were you in taking classes in each STEM area before class vs. now?	3.95	0.39	3.65	0.45	3.56	0.46	3.68	0.36
Career Interest	How interested were you in a career in each STEM area before class vs. now?	3.57	0.36	3.35	0.38	3.33	0.38	3.24	0.35
College Interest	How interested were you in pursuing college degree in each STEM area before class vs. now?	3.72	0.36	3.38	0.43	3.37	0.41	3.39	0.38
Interdisciplinary STEM									
Personal Life	Learning about STEM will help me make better decisions in my life.	4.02	0.49						
Community	Knowing more about STEM will help me better understand problems in my community.	4.05	0.48						
Citizen	Understanding STEM is important to being a good citizen.	3.53	0.40						
Employment	I understand how STEM is important to many jobs in my community.	4.39	0.51						
Connection	I understand how STEM areas are connected.	4.38	0.58						
Solve Problems	I can connect what I know about STEM areas to solve new problems.	4.22	0.58						
Complex Problem I	I understand that there are many factors that must be considered when addressing a complex problem.	4.31	0.50						
Complex Problem II	I am comfortable with complex situations or problems.	3.90	0.55						
Real World	I am comfortable dealing with real world problems that don't have an obvious answer or a simple solution.	3.97	0.54						
Enjoyment	I enjoy STEM in general.	4.16	0.43						

All change values in the table were statistically significant differences at $p < 0.001$ for correlated t-tests of before to after instruction change in reported attitudes. Δ represents reported change in rating from reflection upon attitudes prior to instruction to attitudes following instruction.

TABLE 2 | STEM student attitude subject survey validity and reliability indicators.

Construct validity	Overall	STEM subjects	STEM interdisc.	Science	Tech	Engineer	Math
Items	*n* = 68	*n* = 48	*n* = 20	*n* = 12	*n* = 12	*n* = 12	*n* = 12
Fit	**6** > 1.4	**2** > 1.4	0 > 1.40	0 > 1.4	**1** > 1.4	**2** > 1.4	**1** > 1.4
Correlation	0.38 to 0.58	0.41 to 0.57	0.51 to 0.62	0.61 to 0.77	0.66 to 0.78	0.69 to 0.80	0.61 to 0.77
Functioning	**Disordered < 1.4**	Ordered **< 1.4**	Ordered **< 1.4**	Ordered **< 1.4**	Ordered **< 1.4**	Ordered **< 1.4**	Ordered **< 1.4**
Dimension.	**35.2% 8.4%**	**36.8% 11.3%**	**41.2% 8.5%**	**56.4% 10.1%**	**59.2% 8.7%**	**62.3% 7.5%**	**59.9% 9.2%**
Content validity							
Contin. Gap	**Range gap**	**Low/High gaps**	**High gap**	**Low/High gaps**	**Low/High gaps**	**Low/High gaps**	**Low/High gaps**
Targeting	0.50 (0.83) vs. 0.00 (0.38)	0.40 (0.88) vs. 0.00 (0.32)	1.19 (1.38) vs. 0.00 (0.61)	1.06 (1.71) vs. 0.00 (0.47)	0.66 (1.75) vs. 0.00 (0.49)	0.50 (1.91) vs. 0.00 (0.46)	0.68 (1.76) vs. 0.00 (0.57)
Reliability							
Item sep.	11.00	9.29	12.33	10.32	10.91	10.12	12.55
Person sep.	2.19	3.62	2.68	2.45	2.80	2.85	2.59
Item rel.	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Person rel.	0.82	0.93	0.88	0.86	0.89	0.89	0.87

Flagged values are bolded: Fit, number with item fit > 1.4; Correlation, range < 0.15, (ideal correlation > 0.5); Functioning, disordered, threshold calibrations < 1.4 logits apart; Dimensionality, PCA residuals variance accounted for <50%, unexplained variance > 5%; Continuum gaps, range of values or low values or high values (ideal should not have gaps in difficulty level); Targeting, person (M, SD) versus item (M, SD) with item M = 0.0; Item Separation < 3, Person Separation < 2; Item Reliability < 0.90 and Person Reliability < 0.80.

whether the criteria used were met or flagged (bolded items in table) as concerns. Construct validity indicators of fit, scale functioning, and dimensionality (rows 3, 5, and 6) that resulted from survey calibration indicated both strengths and limitations in the overall survey measurement characteristics (column 2).

Content validity indicators were partially satisfied but also revealed overall survey measurement limitations. Item and person reliability and separation indices (rows 11–14) were all at acceptable levels. Rasch analyses of meaningful subsets of the instrument were conducted including the STEM subject items

(1–48; column 3), subject specific items (four sets of 12 each from 1 to 48; columns 5–8), and the general Interdisciplinary STEM items (49–69; column 4). These calibrations supported relatively strong unidimensionality, particularly for STEM subject item subsets. In addition, evidence supported consistently ordered scales and strong reliability evidence. However, with fewer items per subset examined, the widths of each item distribution were limited compared with that of the entire instrument, resulting in gaps relative to student measure locations.

Figure 1 provides the variable map for the interdisciplinary STEM attitudes calibration which illustrates the match between person measures and item measures. In sum, validity and reliability evidence supported separate subject specific attitude analyses, as well as interdisciplinary STEM attitude analyses. Analysis of attitudes across all subject areas combined together was also supported, but with weaker unidimensionality evidence. That is, the potential advantage of combining items resulted in a reduction in the strength of the dimension likely because of the construct distinctions introduced by the differing subject areas.

Student Attitude Comparisons

To examine mean score comparisons from the *STEM Student Attitude Survey* statistical tests were conducted to support exploratory analyses of the resulting differences, in conjunction

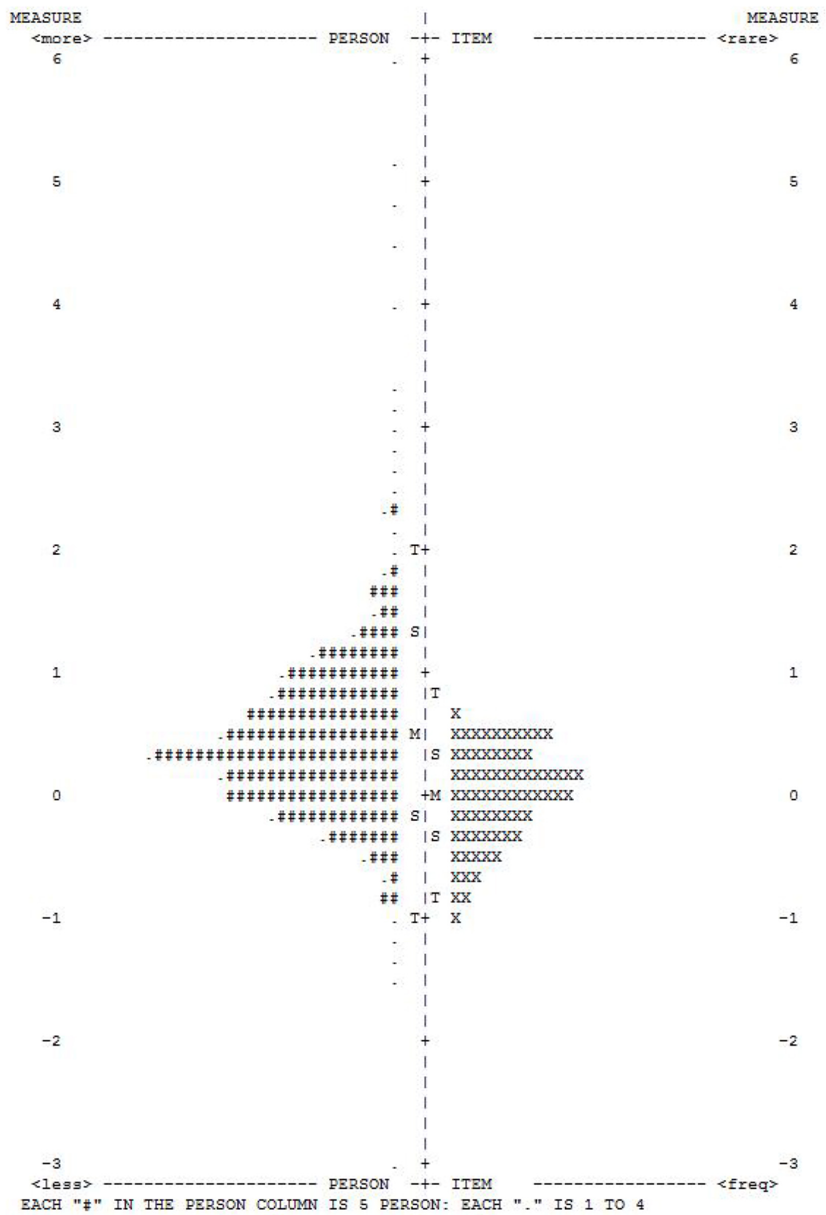


FIGURE 1 | Variable map for the STEM Student Attitude Survey calibration which illustrates the match between person measures and item measures. EACH ″#″ IS 10: EACH ″.″ IS 1 TO 9.

with difference magnitudes. Thus, responses were analyzed using correlated *t*-tests to initially identify overall differences in students' attitudes, and one-way analyses of variance (ANOVA) to examine differences in attitudes between gender and school level categories individually. Following from the research questions we used one-way analyses rather than full factorial analyses as appropriate to the category sample size variations and category response differences. Thus interaction effects were not examined with this data because of the design and group size differences. A conservative $p < 0.01$ criteria level was used to evaluate statistical significance to help prevent Type 1 errors due to the multiple comparisons. Also, difference magnitudes as effect sizes were calculated using Cohen's *d* for both within subjects (e.g., attitude change) and between-subjects (e.g., gender, school level) comparisons as we considered practical implications of findings and a standardized reference for subsequent investigations.

Attitudes in STEM Subject Areas

Analysis on the attitude survey items were conducted for (a) individual STEM subject areas by item, and (b) all STEM subjects items combined as a variable measuring attitude across STEM subject areas. The analysis of individual STEM subject area attitudes focused on reported change to addresses whether following the instructional experiences students tended to rate their attitude levels for each STEM subject area at a higher level than their recollection memory for their pre-instructional levels. This subject specific analysis of mean differences is presented in **Table 3** (rows 1 through 4). Note that the survey was only administered post instruction, and they were asked to reflect on their attitude prior to instruction, yielding two attitude ratings per item. This survey rating approach is known as a recollection proxy pretest, which should not be confused with a pre-test posttest design.

Analyses of attitude differences within each STEM subject area indicated statistically significant ($p < 0.001$) reported increase in mean overall student attitude ratings from before (retrospective) to after course in science, technology, engineering, and mathematics. The effect sizes for each STEM subject area change from their retrospective ratings were consistently above one half of one standard deviation, ranging from $d = 0.55$ to $d = 68$.

TABLE 3 | Self-reported change in student attitude toward four STEM subjects and interdisciplinary STEM.

	t	*df*	*P*<	Mean difference	*SE* difference	Cohen's *d*
Science attitude	−18.98	855	0.001	−2.57	0.14	−0.65
Technology attitude	−20.51	855	0.001	−2.77	0.14	−0.70
Engineering attitude	−19.77	855	0.001	−2.94	0.15	−0.68
Mathematics attitude	−16.11	855	0.001	−2.25	0.14	−0.55
Interdisciplinary attitude	−24.83	834	0.001	−5.07	0.20	−0.86

Student's t-test.

One-way ANOVAs on the individual STEM subject areas by demographic categories of gender and school level were examined. Though school level *n* was imbalanced, we conducted these comparisons to explore the developmental differences expected between middle and high school levels. With regard to gender, female students reported significantly more positive attitudes than male students about technology, $F(1,854) = 47.59$, $p < 0.001$, $d = 0.46$, and engineering, $F(1,854) = 80.63$, $p < 0.001$, $d = 0.61$, but differences by gender were not statistically significant for science, $F(1,854) = 0.003$, $p = 0.96$ or mathematics, $F(1,854) = 0.52$, $p = 0.47$. Middle school students reported significantly more positive attitudes than high school students in the areas of science, $F(1,854) = 8.57$, $p < 0.004$, $d = 0.23$, and mathematics, $F(1,854) = 57.03$, $p < 0.001$, $d = 0.58$, but differences by school level were not statistically significant for technology, $F(1,854) = 5.64$, $p = 0.02$, or engineering, $F(1,854) = 5.06$, $p = 0.03$.

Attitudes in Interdisciplinary STEM

The 10 attitude items on interdisciplinary STEM provided data on students' mean attitude about interdisciplinary STEM ratings as well as recollections of before and after instruction attitude change magnitudes with respect to being a STEM literate citizen who can make informed decisions (items 1–3), career opportunities in STEM (item 4), connection of STEM to real world (items 5–9), and enjoyment of STEM (item 10). Analysis on the attitude survey items was carried out for all the questions as a single construct measuring interdisciplinary STEM attitudes.

Table 3 (row 5) presents this analysis on the interdisciplinary STEM attitude construct. A *t*-test on interdisciplinary STEM indicated a statistically significant reported increase in recalled student attitudes from before to after course, $t(834) = 24.83$, $p < 0.001$, $d = 0.84$. There were no significant differences in interdisciplinary STEM attitudes between gender or school level categories. The statistically significant change in recalled attitudes toward interdisciplinary STEM occurred for all levels of gender and school level (all at $p < 0.001$).

Study 2: *STEM Student Reasoning Assessment* Validity and Reliability Evidence

Table 4 provides a summary of the validity and reliability findings for the Student *STEM Reasoning Assessment*, indicating whether the criteria used were met or flagged (bolded items in the table) as concerns. For the overall assessment analysis, one item (Item 6: Science Reasoning) was removed prior to this calibration after it was determined to be invalid due to multiple correct responses. This left 33 items for the overall assessment analysis. Construct validity, content validity, and person reliability levels shown in the first data column of **Table 4** indicate the need for improvements in the overall assessment's measurement characteristics. Still, the instrument showed strong item reliability and separation, as well as 30 items (91%) with productive fit to the measurement model, and 26 items (79%) with discrimination levels above the criteria of.15.

TABLE 4 | Student *STEM Reasoning Assessment* validity and reliability evidence.

Construct validity	Overall	Systems reason	Science MB	Tech CR	Engineer DB	Math QR
Items	*n* = 33	*n* = 5	*n* = 7	*n* = 6	*n* = 5	*n* = 7
Fit	**3** > 1.3	0 > 1.3	**1** > 1.3	0 > 1.3	**1** > 1.3	**2** > 1.3
Correlation	**–.03** to 0.58	0.39 to 0.50	0.46 to 0.65	0.27 to 0.61	0.45 to 0.66	0.27 to 0.63
Dimension.	**17.6%** **6.4%**	**12.1%** **24.9%**	**31.3%** **15.8%**	**23.6%** **19.8%**	**30.3%** **21.5%**	**27.3%** **14.1%**
Content validity						
Continuum	**Range gap**	**Low/High gaps**	**Low/High gaps**	**Low/High gaps**	**Low/High gaps**	**Low/High gaps**
Targeting	–0.70 (0.76) vs. 0.00 (0.65)	–0.98 (1.07) vs. 0.00 (0.22)	0.13 (1.63) vs. 0.00 (0.91)	–0.96 (1.27) vs. 0.00 (0.80)	–0.05 (1.62) vs. 0.00 (0.95)	–0.88 (1.35) vs. 0.00 (0.88)
Reliability						
Item sep.	7.26	**1.30**	6.56	5.66	7.20	6.27
Person sep.	**1.49**	**0.00**	**1.04**	**0.33**	**0.69**	**0.67**
Item rel.	0.98	**0.63**	0.98	0.97	0.98	0.98
Person rel.	**0.69**	**0.00**	**0.52**	**0.10**	**0.32**	**0.31**

Flagged values are bolded: Fit, number with item fit > 1.3; Correlation, range < 0.15, (ideal correlation > 0.5); Dimensionality, PCA residuals variance accounted for < 50%, unexplained variance > 5%; Continuum gaps, range of values or low values or high values (ideal should not have gaps in difficulty level); Targeting, person (M, SD) versus item (M, SD) with item M = 0.0; Item Separation < 3, Person Separation < 2; Item Reliability < 0.90 and Person Reliability < 0.80.

To examine measurement further by reasoning mode, Rasch analyses of meaningful subsets of the instrument were conducted, including reasoning mode specific items (five sets of items). Summary statistics are shown in the second through sixth data columns of **Table 4** for these analyses. For reasoning mode calibrations, person reliability levels were all relatively low, particularly that of systems reasoning items. Science model-based reasoning items yielded the most promising levels of unidimensionalty, targeting, and reliability, though still too low for effective use. Thus, analyses at the reasoning mode level did not improve measurement compared with that of the overall instrument, so no further analysis by reasoning mode are presented.

Figure 2 provides the variable map for the STEM Reasoning calibration which illustrates the imperfect match between person measures and item measures. The variable also shows considerable overlap among most student measures of reasoning with the majority item difficulty measures. Based on these Rasch indicators the Student *STEM Reasoning Assessment* data outcomes as an overall construct using all items together are reported as preliminary findings, with the awareness that the instrument and administration process require refinement to achieve the measurement of STEM Reasoning sought. However, reporting and examining these initial findings provides an important baseline for subsequent measurement given the favorable characteristics of the majority of items that make up the instrument. That is, the present findings stemming from the *Student STEM Reasoning Assessment* will inform our ongoing process of measurement.

STEM Reasoning Comparisons

Analyses are only reported for the overall *STEM Student Reasoning Assessment,* given the measurement findings reported above. A paired-sample *t*-test was conducted to identify statistically significant change in student understanding after exposure to the Real STEM course. Pretest and posttest statistics are provided in **Table 5**.

The *t*-test indicated that there was no significant mean change from pretest to posttest in overall student STEM reasoning ability, $t(425) = -1.41$, $p = 0.160$. One-way ANOVA was used to examine between subjects mean score comparisons by gender and school level separately. Regarding gender, male students and female students did not differ significantly on mean pre-test, $F(1,416) = 0.38$, $p = 0.54$, posttest, $F(1,416) = 0.24$, $p = 0.63$, or pre-to-post difference in scores, $F(1,416) = 1.81$, $p = 0.18$. However, high school students had higher mean scores than middle school students on the pretest, $F(1,424) = 190.33$, $p < 0.001$, $d = 1.3$, and posttest, $F(1,424) = 214.42$, $p < 0.001$, $d = 1.4$, as expected, but not on the pre-to-post difference in scores, $F(1,424) = 2.33$, $p = 0.13$.

DISCUSSION

The Real STEM project allowed for a careful examination of both the attitude and reasoning instruments under investigation, in support of interdisciplinary STEM instruction and research. Data collected and analyzed were particularly valuable because each school partner was able to implement an interdisciplinary STEM program that addressed the unique needs of their students and the configuration of their school. The resulting variation in program implementation across schools represented an important contextual element and an important challenge to address for subsequent investigations. That this was not a report of a highly controlled treatment should be considered when interpreting the findings regarding the measurement characteristics and the preliminary findings regarding students' attitudes and abilities.

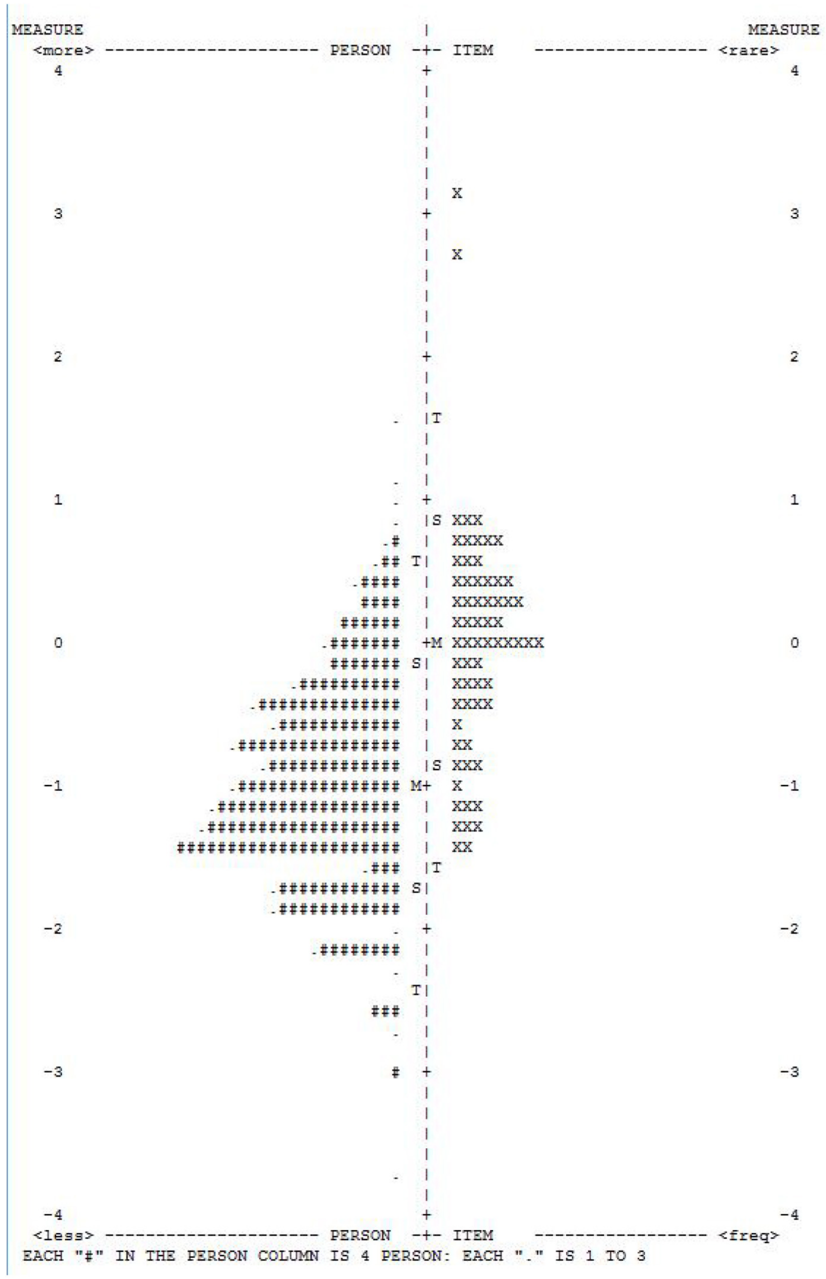


FIGURE 2 | Variable map for the STEM Student Reasoning Assessment calibration which illustrates the match between person measures and item measures. EACH ″#″ IS 7: EACH ″.″ IS 1 TO 6.

With the measurement of STEM attitudes, analyses indicated supportive validity and reliability evidence particularly for subject specific attitude measurement, as well as interdisciplinary STEM attitude measurement. In addition, data suggested the potential benefit of additional items to help address the targeting of a broader range of perspective. On the other hand, with measurement of STEM reasoning the analyses favored an overall STEM reasoning rather than a subject specific measurement. Data suggested a lower than optimal level of person reliability, which may have resulted from the diversity of the items as well as the need for additional items at lower difficulty levels. In general, however, despite the imperfections identified for further consideration, testing, and development, both the attitude and the reasoning instruments provided effective tools for examining STEM impacts.

Study 1: Impact on STEM Attitude

On the whole, findings from the ***STEM Student Attitude Survey*** **indicated that** the impact of the interdisciplinary STEM courses appeared very positive in several ways. Following instruction

TABLE 5 | Student STEM reasoning assessment.

	t	*df*	*p*	Mean difference	*SE* difference	Cohen's *d*
Pre–post difference	–1.41	425	0.16	–0.27	0.19	–0.07
Descriptive	***N***	**Mean**	***SD***	***SE***		
Pretest	426	12.54	4.67	0.23		
Posttest	426	12.81	4.98	0.24		

students reported having more favorable attitudes for the four STEM areas in all six attitude areas assessed. The course provided exposure in these areas that changed the ways students viewed them, according to what they reported. Attitude levels and change were different at moderate effect sizes, depending upon gender and school level. Female students on average reported more favorable attitudes than males toward multiple STEM areas, especially in technology and engineering. However, males on average reported no significant improvement in attitude within any of the STEM areas. Middle school students' mean ratings reflected more favorable attitudes toward STEM areas than those of high school students in most of the six attitude areas assessed. Still, both the middle and high school students' ratings reflected an increase in favorable attitudes for all STEM areas across six attitude items.

Attitudes toward interdisciplinary aspects of STEM were reported as more favorable following instruction for all 10 items that focused on interdisciplinary STEM. There was no significant difference in interdisciplinary STEM attitudes between gender categories in contrast to the positive differences found with females in some STEM areas. There was little difference between grade levels with respect to mean interdisciplinary STEM attitude rating, but both the middle school and high school students displayed improvement in attitudes toward interdisciplinary STEM on all 10 items.

Considering these findings on student attitudes relative to observations of the REAL STEM implementation across the schools supports recommendations for further inquiry supported by these findings. Based on our initial interpretation of the findings regarding student attitudes toward the four STEM areas and toward interdisciplinary STEM, we would recommend:

(1) Focused diverse learner strategies to increase engagement of all students and to address STEM attitude issues that have been observed in males (Saravia-Shore, 2008)
(2) Middle school and high school collaborations to determine best structures and methods for engaging students across grade levels in interdisciplinary STEM courses
(3) Increased interdisciplinary PLC interaction to sustain positive attitudes toward interdisciplinary STEM

Study 2: Impact on STEM Reasoning

The *STEM Student Reasoning Assessment* was developed to provide a common measure for student understanding of the five 21st century reasoning modalities. The assessment participation was voluntary and was not administered by all the included schools, due to not all schools addressing all five reasoning modalities. Although instrument validity and reliability evidence was likely affected by the implementation challenges, it indicated the need for further development of some items within the instrument. In addition, preliminary analyses identified some interesting group differences in STEM reasoning that are worth further investigation. The outcome that high school students outperformed middle school students overall in STEM reasoning is an expected relative to STEM exposure and related development of understanding regarding STEM. The school level performance difference lends support to the construct validity evidence of the instrument measures. The effect sizes of these grade level differences were relatively large, unsurprisingly. At the middle school level, on average, there was a slight non-significant drop in reasoning assessment scores following instruction, while at the high school level there was the expected increase, though non-significant, in average scores following instruction.

Overall the students had no significant mean improvement on the full interdisciplinary STEM assessment following instruction and the scores were relatively low (on average 38.8% correct) on what was shown to be a difficult assessment for this student sample as a whole.

As we consider the implementation challenges with variation across schools and the interdisciplinary STEM teaching and learning observed, our preliminary findings with STEM reasoning lead us to consider additional recommendations for further inquiry:

(1) Explicit identification of the STEM reasoning modalities on which to focus, including whether complex systems and computational reasoning will be a focus
(2) A deliberate focus on increasing engagement of female and male students within instruction and assessment to improve performance on STEM reasoning and support gender neutral learning
(3) Continuation with evaluation of STEM programs within schools to determine development of reasoning and problem-solving abilities as an academic outcome, with a focus on middle school STEM reasoning assessment
(4) An emphasis on evaluating the suitability of STEM reasoning instruments, including measurements that target student groups of interest, to effectively examine outcomes.

Student Attitude Versus Student Performance

Our expectation in examining both the measurement of student attitudes about STEM and the measurement of student performance on STEM reasoning was that there would be a strong correspondence between these two measurements overall. However, an attitude and performance correspondence were not found within this investigation. Instead, though students consistently reported improved attitudes toward interdisciplinary STEM and STEM subject areas following instruction, they did not, on average, show improvement in STEM reasoning as measured. This finding of a disconnection between attitude and performance emphasizes the importance of the many considerations to bear in mind when developing an ability instrument. These considerations include the relative difficulty and content areas of the instrument items, the variation in student abilities, the consistency of the instructional contexts and delivery, and the focus of attention during administration, among other factors. As we determine ways to enhance the *Student STEM Reasoning Assessment*, it is important to note that while average performance did not improve, nearly half of the students (48.6%) did improve their STEM reasoning score following instruction, though most of those improvements were relatively small.

Limitations of the Study

There are several factors to consider when interpreting student findings on STEM reasoning abilities. First, the *STEM Student Reasoning Abilities Assessment* was administered to students in 6th through 12th grade as a low-stakes classroom assessment. Only one assessment was used for all grade levels. As such, it is possible the degree of question difficulty and wording served as an obstacle to gauging the entire spectrum of change in student reasoning and understanding. This is evident in the fact that student scores were lower than expected on both the pretest and the posttest. Thus, the instructional treatment resulted in relatively small magnitudes of change using this assessment. These small effects would also tend to be less easily detected as statistically significant with the existing power, particularly within subgroup comparisons. These results also suggest the need to include a broader range of question difficulties within the assessment. The resulting mis-targeting of ability levels likely affected reliability findings.

Second, conditional factors may have influenced the collected data, given that the context represented a realistic instructional implementation of interdisciplinary STEM under low-stakes conditions rather than a tightly controlled experimental paradigm. As such, the test was not highly consequential for students relative to their course grades or other immediate concerns, which may have differentially affected motivation and persistence levels as well as memory recall for pre-instruction attitudes among students. These conditions may be associated with the gender–related and grade-related improvements found if these conditions affected females differently than males, and high school students differently than middle school students, for instance.

Finally, variation in the content validity of the assessment among different classrooms must be considered in relation to the units taught within those classrooms. While teachers were all provided with example modules and pedagogical support, they decided what to teach and how to teach the interdisciplinary STEM topics. Though some teachers strived to incorporate all the STEM reasoning modalities into their classroom, other teachers chose to focus on one or two reasoning modalities (e.g., science and mathematics) while focusing less on the others (e.g., complex systems, technology/computing, and engineering). All teachers were observed using an interdisciplinary STEM approach, but the STEM reasoning abilities assessment was designed to capture an interdisciplinary approach to STEM teaching that includes all four areas. The scores and any lack of dramatic performance improvement may partially reflect a tendency by educators to retain elements of a more traditional STEM class instructional approach, with less emphasis on the entire spectrum of interdisciplinary opportunities provided by the program.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Georgia Southern University Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Developing Pre-service Teachers Conceptualization of STEM and STEM Pedagogical Practices

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Science, Technology, Engineering, and Mathematics (STEM) integrated curricular approach has become the leading type of education reform worldwide. This paper presents a STEM integrated collaborative activity to enhance STEM knowledge among pre-service mathematics and chemistry teachers. Well-structured and planned on-site workshops on STEM activities were delivered to pre-service teachers while growing mathematics and science content knowledge and pedagogical practices. The qualitative content analysis research methodology was used to identify relevant topics related to post reflective questions regarding pre-service teacher perspectives on the experience gained through the collaborative practices at the STEM workshop. The results show that the workshop had a positive effect on pre-service teachers' conceptualization of STEM—through collaborative, participatory practices, an effective learning environment while bringing attention to teacher professional development and education policymakers. Key elements of this study approach included: (1) collaboration between university professors to teach and incorporate STEM in higher education; (2) unique partnership among mathematical and chemistry pre-service teachers; and (3) professional development, which is devoted and adopted into a study course.

Keywords: STEM, mathematics pre-service teachers, chemistry pre-service teachers, professional development, higher education

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INTRODUCTION

Science, Technology, Engineering, and Mathematics (STEM) has received a great deal of attention in recent years and is growing every day. Considering that STEM education is not a new concept and that it has been discussed for the past two decades, in recent years it has received considerable attention (Sanders, 2009; Bybee, 2010; Breiner et al., 2012; Kennedy and Odell, 2014; English, 2016). Many pre-university schools offer STEM courses starting from preschool and elementary education, whereas universities offer STEM degrees. STEM education encourages science literacy, innovation, and critical thinking (Siekman, 2016). Yet many countries, most definitely developing countries, are still lagging behind the growth of STEM educational skills among their students (Clark, 2014; Blackley and Howell, 2015; Kelley and Knowles, 2016). This could be because the nature and development of STEM skills in different countries are diverse and need to be enhanced in future research (English, 2016).

The development of skills through STEM education is linked to economic growth and the country's environmental and social impact (Kelley and Knowles, 2016). Global economies and societies need to integrate knowledge and skills into STEM to solve problems on an ongoing basis. The trend of future employment opportunities leads to the increasing need for at least a basic understanding and incorporation of mathematics and science. Through STEM activity practices, pre-university and university students have the opportunity to learn how to design and prepare, develop, and implement project ideas. The theory behind STEM education is that academic concepts are translated into real-world lessons when integrating STEM, representing a multidisciplinary and interdisciplinary approach to learning (Hoachlander and Yanofsky, 2011; Chalmers et al., 2017). Through STEM, students can make connections between school, community, and work (Tsupros et al., 2009). STEM implementation involves integration into teaching and learning, including one or more teachers and more than one class of students, and may have a specific time to completion (Isaacs et al., 1997; Roehrig et al., 2012).

There are multiple definitions of STEM integration (Sanders, 2009; Moore and Smith, 2014). According to Sanders (2009), STEM integration explores teaching and learning between two or more STEM subject areas. Sanders (2009) suggested that results should be deliberately designed to learn at least one of the STEM subjects, i.e., mathematics learnings in science, technology, or engineering. Moore and Smith (2014) described integrated STEM education as an attempt to unify a single course with all STEM disciplines, a lesson centered upon linking subjects and real-world problems. Moor and Smith further add that STEM integrated curriculum could include STEM content learning objectives focused on one subject, but context can come from other STEM subjects. For many years STEM education concentrated on science and mathematics as separate subjects, with little overlap and focus on technology or engineering (Breiner et al., 2012). High-quality STEM learning involves engaging students in engineering design complexities, learning from mistakes, and taking part in reconstructing, using relevant contexts to address the engineering challenges that can be directly related to student's needs. STEM learning involves studying and using correct science and/or mathematics content, engaging students through student-based pedagogies, and encouraging communication skills and teamwork (Moore et al., 2014).

The integrated STEM inquiry task of teaching and learning is even more challenging in cases where traditionally, the learners are used to guided step-by-step instructions to successfully engage in completing a task (Sergis et al., 2019). An inquiry learning in science and mathematics is considered one of the best pedagogical approaches to engage students effectively and through self-directed investigation in the learning process (Lazonder and Harmsen, 2016). Overall, using STEM integration teaching and learning approaches within the curriculum are primarily to develop the ability to live and work in a society of the 21st century and improve learning outcomes in all curriculum areas. It will be difficult for teachers who have never encountered such activities in their learning to introduce them to their classrooms (Quinn and Bell, 2013, p. 26). Teacher knowledge development does not begin or end in teacher education, but it is influenced by it (Milner-Bolotin, 2018). For this purpose, the incorporation of STEM in classrooms requires the preparation of pre-service teachers of STEM education, both for conceptual meaning and for STEM teaching practices.

This study provides STEM instructions through a series of STEM activities and shared learning experiences to pre-service mathematics and chemistry teachers. Only the effects of the post-reflective questions were discussed in this article. The goal of this study was to improve teachers' conceptualization of STEM and introduce them to STEM pedagogical practices. The need to enhance pre-service teachers' preparation to teach STEM-integrated subjects is combined with the need to investigate the effectiveness of such collaborative practices in improving teacher education programs. The study provides insights and ideas on how pre-service teachers perceive STEM education, shaping their teaching practices, beliefs, and the challenges they experience when implementing STEM education practices. Information received as needs assessment from the pre-service teachers will lead to future STEM education research and provide insight into integrating integrated STEM education in specific curriculum practices in pre-service education and continuing professional development.

STEM PEDAGOGICAL PRACTICES AND PROFESSIONAL DEVELOPMENT

Content knowledge focuses on the subject knowledge, and pedagogical knowledge focuses on practical implementation in the classroom. Ozden (2008) defines content knowledge as "the concepts, principles, relationships, processes, and applications a student should know within a given academic subject," whereas pedagogy as "the science of teaching, instruction, and training" (pedagogical practices). They are the two crucial areas of teacher knowledge that are often stressed (Shulman, 1987). The blending of the two (content and pedagogical knowledge) is called pedagogical content knowledge (PCK). PCK refers to understanding how specific topics, problems, or issues are structured, interpreted, and tailored to learners' varied interests and abilities. In recent years, technology was also added to the combination as a requisite for teachers' expertise for the 21st-century classroom (Chai, 2019). When teachers already have difficulties in their content knowledge, they are likely to experience new knowledge gaps and face challenges in pedagogical practices of integrating STEM education (Stinson et al., 2009). Stohlmann et al. (2012) suggest that what is learned from research into efficient science and mathematics instructions gives insight into effective practices in applying STEM. Walker (2007) finds that connections (*between topics, students' in-, and out-of-school knowledge, and procedural and conceptual knowledge*) and representations (*of concepts, problems, and solutions*) can also help the pedagogy of teachers. Many of these teaching approaches benefit from integrating STEM and naturally lend themselves to integrated STEM activities.

Science, Technology, Engineering, and Mathematics education practices also have the potential to shape pedagogical practices. Hands-on activities in the educational context while integrating STEM subjects is "an innovative way to reimagine education" (Peppler and Bender, 2013). According to Harlow et al. (2018), teacher support is needed to develop appropriate skills to promote STEM learning experiences, as many teachers do not have pedagogical practices to teach STEM education. Milner-Bolotin (2018) notes that it is essential to review available research evidence on teacher knowledge development during teacher education and better understand how to educate STEM teachers. Additionally, it is critical to recognize that teacher knowledge development and competencies are highly dynamic concepts. A teacher's growth is affected by many factors such as content knowledge, learning experiences, reflection, practices, and opportunities for professional development, learning attitudes, the teacher's belief in teaching as a career, and peer collaboration. Belland (2009) and Nadelson et al. (2013) explain that many teachers teach their science classes similar to how they remember them when they were students. The science content introduced mimics teaching methods of how they were taught. Belland (2009) then concludes that if accurate science-based teacher instruction is not offered correctly, teachers are likely to teach STEM in a lecture-based fashion.

As per Shernoff et al. (2017), teachers who incorporate STEM education into their teaching require several courses and workshops that show them how to integrate STEM subjects while attempting to solve real-world problems collaboratively. While there are many education reforms and research that does center upon integrated approaches to teaching STEM, there is insufficient information around STEM-specific teacher preparation programs that primarily prepare pre-service teachers for STEM implementation (Shernoff et al., 2017). Besides, because of the inequality between conventional teacher education programs and everyday life, teachers encounter difficulties in finding real-life examples to create a STEM teaching context and implement a flexible STEM curriculum. The primary responsibility for overcoming these problems rests with teacher preparation programs (Aydin-Gunbatar et al., 2018). According to Shernoff et al. (2017), teacher education programs need to improve their courses and teach those courses while preparing their pre-service teachers with the knowledge of STEM, effective pedagogy for implementing STEM, and knowledge on STEM literacy, skills, and abilities. Kelley and Knowles (2016) state that STEM teacher education programs need a thorough overview of core theories of learning, such as design thinking, computational thinking, and scientific inquiry. Pre-service teachers may also lack sufficient training to teach relevant scientific investigation, technology, design, and engineering practices. Thus, integrating integrated STEM education and engineering design processes and improving teachers' STEM content knowledge are crucial measures for introducing any STEM reforms. Teacher education programs should provide STEM courses to pre-service teachers during their study programs and professional development to support in-service teacher planning and STEM teaching implementation (Shernoff et al., 2017). Teachers' conceptualization and preparation for STEM education may be the critical factor determining STEM reforms in education (Bissaker, 2014; McDonald, 2016).

Furthermore, Chai (2019) states that the gaps in teachers' STEM knowledge and STEM teaching skills lead to STEM teacher professional development. With the introduction of new curricula to teachers, professional development often focuses on curricular training, targeting the curriculum's organizational or practical needs instead of subject content or teaching based on content objectives (Walker, 2007). It was grounded in Desimone's (2009) recommendations for teacher professional development programs to emphasize coherence, content focus, active learning, collective participation, and a substantial duration. Borko (2004) argues that teachers' professional development in many countries is insufficient, inconsistent, shallow, and does not consider how teachers learn. Many studies (Borko, 2004; Desimone, 2009; Opfer and Pedder, 2011; Fore et al., 2015) state that developing effective professional development programs, awareness of local environmental characteristics is essential. Professional growth affects teacher practices and educational programs, attitudes and behavior, performance, and productivity. However, Chai (2019) claims that teacher educators need to consider the context in STEM teacher professional development workshops or activities.

Guskey (2002) defines professional development programs as efforts to change teacher practices and beliefs. These changes are often influenced by the teachers themselves trying to find new resources and teaching strategies that best fit the students' needs. Therefore, it is essential that teacher professional development programs, both pre-service and in-service, include the most advanced practices and the most appropriate for society's needs. Educational reforms and professional development programs in Kosovo are continuously evolving. The educational reforms must receive information on how pre-service teachers in Kosovo see STEM education, conceptualize STEM and pedagogical practices. Thus, according to Yıldız et al. (2019), establishing the STEM centers in cooperation with universities will significantly contribute to creating well-educated individuals and societies in science, technology, mathematics engineering.

Context of the Study

A new pre-university education curriculum was developed in Kosovo to meet the population's needs and the wider challenges of the 21st century, creating new skills for the global labor market (MEST., 2016). The primary focus of the Kosovo curriculum framework (KCF) is to develop a *knowledge-based society*, integration in the *Digital Age*, an increase in *inter-dependencies, and mobility* as a result of globalization, inclusion in the European Union through *Learning to live together*, and *Sustainable development*. The development of knowledge, skills, routine, behavior, attitudes, and values form the main objectives of the framework.

Kosovo offers a competency-based curriculum. The KCF aims to promote integrated learning across broad areas and strengthen interconnections across different fields of learning, thus enabling students to understand the relations between all aspects of their learning. Kosovo's curriculum includes knowledge and skills, attitudes, and values to address real-world issues, integrate emerging-market curricula, and discuss new developments in society, economy, culture, or technologies. Furthermore, the curriculum gives a lifelong perspective, ensuring that the curriculum should prepare students to address daily challenges and concerns in a learning and understanding society effectively.

Creative skills, such as learning to learn, active and responsible analysis, and processing information, e-learning, along with use of digital technologies, are the focus of the curriculum approach (MEST., 2016).

According to Kennedy and Odell (2014), the current state of STEM education worldwide has developed into an immersive meta-discipline, reducing traditional barriers between STEM subjects and relying instead on developing design solutions for complex contextual problems through the use of modern tools and technologies. The Kosovo Curriculum theoretically promotes the intentional convergence of subject areas by offering more in-depth connections between science fields (MEST., 2016). However, the teachers are trained to teach one subject only, and STEM has not been mentioned in the curriculum. Similarly, initial teacher training focuses on distinct subject disciplines, as observed by Blackley and Howell (2015). In such cases, there are significant difficulties for educators and administrators in fostering integrated STEM teaching (Shernoff et al., 2017). Because of the integrated nature of STEM, it is not feasible to offer isolated courses of STEM disciplines and hope to train successful STEM teachers (Sanders, 2009). Sanders (2009, p. 22) states that introducing pre-service teachers to "the foundations, pedagogies, curriculum, research, and contemporary issues of each of the STEM education disciplines, and to new integrative ideas, approaches, instructional materials, and curriculum" is essential. This will help build pre-service teachers' STEM content knowledge and pedagogical content knowledge. For some teachers, education programs may help integrate initial training in STEM pedagogical practices (Yip, 2020). Teacher practical knowledge (Verloop et al., 2001) and educational background (Kennedy and Odell, 2014) substantially impact the teachers' integrative STEM approaches.

There is still a great deal of confusion among Kosovo teachers about STEM education and how it is best translated, applied, and implemented in practice. Kosovo teachers need professional development and experience to change STEM views as something revolutionary and distant from learning outcomes and curricula. Likewise, there is still a great deal of confusion in other nations about STEM education and how it is best applied and incorporated (Breiner et al., 2012; Blackley and Howell, 2015). When countries worldwide increase their potential in STEM education, they will have to work together to develop scientific research and build the capacity to provide quality education to students (Clark, 2014).

METHODOLOGY

The study took place at the University of Prishtina, Faculty of Education, during the academic year 2017/2018. A total of 40 (22 mathematics and 18 chemistry) pre-service teachers engaged voluntarily in the professional development workshop organized and structured by mathematics and chemistry university lecturers (authors) associated with the needs provoked during the Teaching and Learning of subject-specific courses at Master-level studies. The lecturers replicated the module developed by Dr. Sevil Akaygun and Dr. Fatma Aslan-Tutak from the Bogazici University (Akaygun and Aslan-Tutak, 2020) with their collaboration and organized STEM workshop activities to introduce practices that support STEM education.

Initially, pre-service teachers were asked to reflect on STEM knowledge they might have and STEM conceptualization. The pre-reflection was meant to enable researchers (authors) to learn how much STEM knowledge and STEM awareness pre-service teachers had. For 5 weeks in a row, the STEM professional development workshop was attended by pre-service teachers on Saturdays. In the eighth week, pre-service teachers presented and discussed their group STEM projects. During the workshop, participants had a dual role: as learners-involved in the learning process while engaging in the STEM workshop and as teachers-involved in discussions and perspectives on pedagogical processes. **Table 1** outlines the weekly activities for the STEM professional development workshop based on work of Akaygun and Aslan-Tutak (2020). All activities were completed in groups (mainly two mathematics and two pre-service chemistry teachers). After the professional development workshop, open-ended, post-reflective questions were emailed to all participants to inquire about their experiences. In response, the understanding, knowledge, and pedagogical practices gained during the collaborative practices and the benefits/challenges they faced during the STEM workshop were acquired. A total of 26 responses were collected from all participants in the workshop (incomplete responses were not considered).

A well-prepared STEM professional development workshop deepens and broadens teachers' subject matter knowledge and broadens and improves their teaching STEM practices. In this study, the STEM workshop was in alignment with the background contextual knowledge of the pre-service teachers' educational training and pedagogical strategies of teaching, the curriculum in practice, and instructional methods. The contextual information about the pre-service teachers, the educational system, and their complexity helped the researchers offer adequate resources and supporting materials for implementing and facilitating an effective teacher practices STEM workshop. The integration of their teaching subjects' curricula and teaching practices was very important. The organization of activities in small groups has enabled pre-service teachers to reflect and deeply consider integrating their fields of study with pedagogical aspects and provide them with valuable experiences that will help them and their future students.

The qualitative content analysis research methodology (Cohen et al., 2007, p. 475) was used to identify relevant topics related to open-ended reflective questions regarding pre-service teacher perspectives on the experience gained through collaborative practices in the STEM workshop. The inductive approach for data analysis was used to grasp and analyze the data from the reflective questioners. Both lecturers (authors) "diving into data details and specifics to discover important patterns, themes, and relationships starts by exploring them first and then confirming them" (Patton, 2002, p. 453). Therefore, each researcher read the answers separately and, at the same time, performed initial coding. The authors discussed the experience and results of

TABLE 1 | The activities for the STEM professional development workshop (Akaygun and Aslan-Tutak, 2020).

Week	Schedule
1	Pre-reflection on STEM knowledge
1	Activity 1: *Introduction to STEM education* Lecture on STEM education Two scientific articles on STEM education were shared with the pre-service teachers for reading and reflection (Dugger, 2010; Laboy-Rush, 2011)
2	Activity 2: *Poster of STEM Student Club Logo* Visioning of STEM through drawing (students were given A3 paper size and crayons) Reflection on the activity
3	Activity 3: *Edible Car* Guided worksheet instructed for planning, designing, and testing the speed of movement of the "Edible Car." Different foods were provided Reflection on the activity
4	Activity 4: *Ocean Color* Guided worksheet through QR code reader for planning, designing, testing ocean colors Reflection on the activity
5	Activity 5: *Building a boat* Guided worksheet for planning, designing, testing if the ship will sink or float Recycling materials provided Reflection on the activity
8	Activity 5: *Build your Project* and lesson worksheets for planning, designing and testing
8	Post-reflection questions on STEM

the first coding exercise and decided on the methodology to be followed as the final coding method. Analysis of the codes followed and constant comparative analyses were used to prevent research bias (Patton, 2002, p. 492). Patterns and themes have been reported as a list in a separate table as a useful tool for the researcher to explain each theme.

RESULTS AND DISCUSSION

The need to enhance the pre-service teachers' preparation to teach STEM integrated subjects is combined with the need to investigate the effectiveness of such collaborative practices to improving teacher preparation educational programs. In this paper, only the findings from the post reflective questions were analyzed. Our intention was not to investigate changes in knowledge before and after the workshop. Yet, we wanted to learn as many ideas and insights as possible from pre-service teachers' experiences and integrate them into our curricula. Nevertheless, it ought to mention that there were minimal and limited answers from the pre-reflections (most of which said that STEM is only a new approach to integrating science, technology, engineering, and mathematics). The coded data from the post reflective questions were organized in a table to identify themes that reflect all the issues identified in the open-question answer. Data from the questionnaire were the starting point for identifying patterns.

The data analysis for responses to the post reflective questions, *What is STEM? How do you understand STEM education? How does STEM influence the enhancement of your pedagogical practices? What are the benefits/challenges of applying and implementing STEM education?*, led to the creation of five themes (**Table 2**): (1) STEM is an instructional method for solving real-life problems; (2) STEM helps in developing 21st century skills; (3) STEM encourage the creation of positive values and attitudes, (4) STEM enables the advancement of teacher pedagogical practices; and (5) it is challenging to implement STEM in schools.

STEM Education and Real-Life Problems

The results obtained from the analysis of the data collected characterize STEM education to identify and apply concepts and content from different disciplines to solve challenging problems. Most pre-service teachers seem to agree that STEM is about preparing the best teachers and students at all levels and enabling them to compete in fast-moving science and technology. According to pre-service teachers, STEM is about involving different fields for implementing projects that need to be related to the learning outcomes envisaged in the curriculum. Others assume that STEM is a teaching method or an activity for developing the different skills necessary to solve real-life problems. The STEM education, as stated by the pre-service teachers:

> *Is a program that promotes the understanding of knowledge by interrelationships between different subjects and appropriate learning strategies that are essential to solving real-life problems.*

> *is a method that links various fields such as science, technology, engineering, and mathematics to perform a task or an activity that is compatible with the curriculum's learning outcomes. I would define STEM as an activity that integrates different fields to make teaching and learning as productive and successful as possible.*

Furthermore, the pre-service teachers stated that the:

> *benefits of STEM are many. The implementation of STEM in education brings benefits for students, teachers, and the community.*

TABLE 2 | Summary of Patterns and Themes that emerged from the responses of the reflective question: *How do you understand STEM education? How does STEM influence enhancement of your pedagogical practices? What are benefits/challenges of applying and implementing STEM education?*

Patterns (open coding)	Themes (Axial Coding)
STEM: - is a curriculum for the understanding knowledge through the interrelationships of different subjects; - an appropriate learning method; - a method for addressing real-life problems; - focused on improving learning outcomes; - an evolution to teaching method to meet the needs of students.	STEM is an instructional method for solving real-life problems.
STEM helps: - to gain new knowledge and skills; - tp develop critical thinking and creativity; - logical reflection and argumentation; - tp work together and share ideas on problem-solving; - to be a researcher; - to work together with colleagues.	STEM helps for developing the 21-st century skills
STEM: - motivates you for work; - it is a driving force for creativity and innovation; - it encourages you to grow perseverance; - it stimulates you to share ideas freely; - it enhances teamwork.	STEM encourage creating positive values and attitudes
STEM: - enables the advancement of knowledge for pedagogical practices; - had twofold benefits, training of pedagogical practices and expanding knowledge in various fields; - allowed the use of the new teaching approaches in coherence with developments in the field of education; - influences the fulfillment of curriculum requirements; - develops knowledge and skills for working in the projects	STEM enables the advancement of teacher pedagogical practices
- the encouragement, professional preparation, and institutional commitment; - teachers are not enough prepared; - lack of resources (inappropriate texts, insufficient technological equipment, lack of budget) - the management of the projects in a classroom with a large number of students; - a lack of collaborative culture among teachers of different fields; - the integrated of the disciplines of STEM can be challenging.	*STEM is challenging*

These benefits can be instantaneous during faster acquisition and exchange of cross-curricular knowledge. They can also benefit from long-term information to be used to raise awareness among all actors involved in teaching and learning. STEM helps to ensure that the knowledge gained in the classroom is applied in practices in real life.

Pre-service teachers indicated that the benefits of STEM education were numerous. Most of them mentioned the main interest, the integration of STEM subjects. They also confirm Chai's (2019) statement that STEM education resulted from the gaps between knowledge and skills. Pre-service teachers see the integrations of subject fields as crucial to developing students' knowledge and skills to address everyday problems and solve them. There are also responses from pre-service teachers who have defined STEM education as a necessary tool for preparing pre-university students for further studies in science, technology, engineering, and mathematics. According to pre-service teachers, the benefits of STEM are not only for students but also for the teachers themselves and the community. While STEM activities are being implemented, teachers advanced their pedagogical practices (STEM teaching, instruction, and training) and have broadened their knowledge of other STEM fields. At the same time, the community benefits from the innovative ideas that come from developed projects related to real-life problems. Our findings align with the study of Tsupros et al. (2009), which states that STEM practices also involve integrating the school and community.

Descriptions of STEM as an interdisciplinary approach aimed at "translating" academic concepts into life lessons or as an "attempt to unify all disciplines to relate subjects to real-world problems" are also given in studies by Hoachlander and Yanofsky (2011), Moore and Smith (2014) and, Chalmers et al. (2017). Thus, although for many pre-service teachers, STEM was a new concept, the involvement in the workshop enabled them to understand STEM as a multifaceted concept. In particular, STEM is recognized and related as a method for solving real-life problems.

STEM Education Develops Multiple Skills

Science, Technology, Engineering, and Mathematics integration through the implementation of engineering design activities during the workshop enabled pre-service teachers to develop valuable 21st-century skills, including being researchers, communicators, problem solvers, team workers, innovators, and competent users of the technology. They found STEM education to be the promoter of curiosity, logical reasoning, and the development of the other skills needed for problem-solving. They reflect on the fact that the benefits of STEM education are linked to the enhancement of teamwork between peers and the motivation for creative and innovative works:

Working together with colleagues has been very productive. It was challenging as well, but it also gave us a lot of fun. This experience showed us how to engage students in similar projects.

I may freely say that STEM will have a significant impact on the motivation of students. They will become researchers and become more independent. The integration of STEM fields will enable the gaining of general knowledge and skills.

In addition to gaining knowledge from specific integrated subjects, STEM aims to stimulate curious minds, reasoning, logical thinking, and collaboration skills. It is also about developing critical thinking and many other capabilities of 21st-century skills.

STEM is designed to improve learning. STEM education is also a stimulus to the development of many skills, such as the ability to use the technology, search new information, create problems on its own, and work together with colleagues from different disciplines.

In their reflections, pre-service teachers presented STEM as vital and very important for developing 21st-century skills. In their study, Moore et al. (2014) discuss the importance of STEM learning relating it to the teaching of content while developing skills, especially communication skills and teamwork. Similarly, as it was shown by Bartels et al. (2019) that pre-service teachers' attitudes support the value of collaboratively taught math and science methods courses.

Positive Values About STEM

Working in groups during the activities has made it possible for pre-service teachers to understand that STEM also influences many positive values and attitudes for STEM subjects. During the STEM activities, valuable information was exchanged between pre-service teachers. Pre-service mathematics teachers benefited greatly from working with chemistry pre-service teachers and vice-versa. They said that for the first time, they felt relaxed when sharing their knowledge and that everyone expressed their willingness and excitement to participate in the activity. Even when they have made mistakes (in measuring, selecting suitable materials, or testing the engineering design), they agreed that working as a team has built confidence in them, and they believed that they would complete the activity to the end successfully. According to pre-service teachers, STEM education is an excellent approach that allows knowledge outcomes to be achieved and enables the implementation of several positive values necessary for life.

During the activities, I realized that STEM education also has to do with the incentive for work and motivation to learn new things that are not only related to our specific subjects. I learned a lot from my chemistry colleagues. Cooperation needs to be the principal if you want to do good things in life.

Science, Technology, Engineering, and Mathematics is a tool that offers an opportunity for more self-confidence. When our car had broken down while going down the slope, I learned not to give up. We have addressed the engineering design, which was challenging for all of us, but we were perseverant until we did what "was the best."

There have also been responses regarding emotional aspects. They consider their engagement in the STEM workshop as very valuable because the cooperation with colleagues has brought fun and enjoyable times. Deemer (2004) states that teacher attitudes are often transferred to their students. Therefore, pre-service teachers' positive reflections on the STEM workshop experience are quite vital and express their readiness to apply STEM in their classrooms. On the other hand, making the necessary strategic plans for teacher candidates to develop positive attitudes about STEM (Yıldız et al., 2019) is significant for enhancing pedagogical knowledge as a 21st-century skill, and necessary competence for future teachers.

Teaching STEM as Pedagogical Practice

Teaching STEM was seen as a new approach to almost all pre-service teachers. During the first week of the workshop, they had the opportunity to read literature on STEM and practically pursued a STEM integrative approach. Pre-service teachers' participation in STEM activities is an excellent opportunity to learn to plan teaching strategies, assist with classroom management, or prepare for assessment to address students' learning needs. Thus, STEM is seen from pre-service teachers' reflections as a very effective method to develop conceptual knowledge for different subjects and advance their pedagogical practices of STEM teaching and instructions.

Both pre-service mathematics and chemistry teachers said they had theoretical knowledge of the Kosovo Curriculum's integration approach. Still, they did not have the opportunity to see how to plan and design a proper project that integrates and incorporates different fields at the same time. Pre-service teachers, some already engaged in teaching and enrolled in the previous training provided for implementing the new curriculum, have stressed that the interdisciplinary approach is documented in all curricular documents. Yet, practically minimal application there is in the classroom. It was essential for them to experience the combination of the content from different subjects and convey that content, utilizing teaching methods that differ from those by which most teachers were taught (Lynch and Fleck, 2014, p. 174).

I assume that every useful link of knowledge and information gained from all subjects has a positive impact on student's performance, so I believe that the connection of these four STEM pillars surely makes the students well qualified to work on projects. For me, as a math teacher, the benefit is twofold, the skillful advancement of new pedagogical practices and the expansion of knowledge in other fields besides mathematics.

Almost all pre-service teachers express readiness to implement STEM in classrooms after their experience, despite the difficulties and obstacles they may encounter. They see the value of attempts to continuously improve pedagogical practices through the use of new approaches and in coherence with developments in education and curriculum requirements.

I think I managed to master some of the primary elements of STEM teaching during the workshop. This experience made me feel confident about implementing this new teaching approach. Although it will undoubtedly be difficult to integrate many subjects into a specific task, with a lot of desire and will, I will do my best to apply STEM with my students.

Pre-service teachers lacked knowledge of other disciplines, and this was also noticed during the workshop. Of course, this lack of knowledge about content affects teachers during teaching. They face challenges in STEM education integration's pedagogical practices (Stinson et al., 2009). Therefore, they see more value, and the opportunity to enrich themselves with new information while collaborating with colleagues:

Although we are in the early stages and have little experience of STEM implementation, I feel confident to carry out similar projects. Everything I have learned at the STEM workshop is going to be valuable. The collaboration with colleagues is going to increase my teaching skills and knowledge for other disciplines

As in other countries, such as the United States, Australia, etc., we need to focus on learning outcomes in the curriculum and determine which subject we want to focus more on, for example, using STEM with a focus on developing knowledge and skills for problem-solving in mathematics (STEM).

From the pre-service teachers' answers, we understood that their interest in STEM was great, not only during the workshop when they were involved in the practical implementation of STEM activities. In their reflections, they expressed an interest in expanding their knowledge of STEM. They have been searching for STEM implementation practices in other countries with advanced education to better conceptualize STEM-based teaching practices.

Challenges of STEM Implementation

In general, provided that there is a lack of collaborative culture among teachers of different fields in Kosovo and that communication between colleagues is not always feasible, pre-service teachers have indicated that the discipline of STEM implementation can be challenging. Preparing for STEM implementation in the classroom is seen as challenging due to the conditions under which most schools operate. The lack of equipment and financial resources necessary for the implementation of various projects may also hinder the introduction of STEM in schools. Even the lack of organizational and classroom management skills is identified as a potential barrier for STEM adoption.

> *I think the challenges and barriers are of different and diverse natures. For STEM projects, schools need to have a budget to buy the necessary materials, and they should have computers and other tools. The desire of teachers to change and improve is not enough. Still, the encouragement, professional preparation, and institutional commitment are also critical enough to ensure that this approach to education is successfully implemented.*

> *It's hard to think about how I would manage a project in a classroom with a large number of students, especially when the school has neither the means nor space where students can work in groups.*

Pre-service teachers also stated that teachers must attend professional development for STEM education because they believe that teachers find it impossible to give up traditional lessons, especially those who are older. The Kosovo pre-service teachers' statements align with the study of Quinn and Bell (2013, p. 26), finding that changes in the classroom culture will not happen without teacher professional development. Other studies also reported a need to develop appropriate skills to promote STEM teaching and learning (Harlow et al., 2018). Since STEM education requires teachers to integrate technology, pedagogy, and content knowledge (Chai, 2019), a commitment to detailed planning and computer-aided design for each STEM-initiated project must be supported by professionals. Thus, it will be beneficial to integrate initial training in STEM pedagogical practices (Yip, 2020) for pre-service teachers and teacher professional development programs. It is difficult for all teachers to use different disciplines while teaching. Some teachers in Kosovo still have difficulties using technology. They are not prepared for this way of teaching. Thus, proper training should be provided and, of course, a forum for the quick exchange of experiences is needed. Challenges that arise during the planning and development of appropriate implementation strategies will be helpful if they are discussed with professionals, especially in the initial phase.

> *For the STEM to work, in addition to teacher training, appropriate materials and resources must be offered, which are part of the curricula of other countries that already have experience. For starters, texts or pamphlets that may help teachers to be better prepared to work with their students.*

> *Science, Technology, Engineering, and Mathematics implementation will be more straightforward in vocational schools than in high schools, as several similar projects are already underway. Nonetheless, improvements to the curricula need to be made, and more practical examples of STEM applications should be included in the textbooks.*

> *Science, Technology, Engineering, and Mathematics is not a standard that all teachers will obey. It offers different approaches and a wide range of applications. Probably this makes us confused about the things that we need to do during STEM.*

Therefore, while pre-service teachers have demonstrated commitment to introducing STEM in classrooms, there is also confusion and reluctance to implement it effectively. Such findings are similar in other countries (Breiner et al., 2012; Blackley and Howell, 2015). Nonetheless, teachers and other educational actors of STEM will be part of the education of young people, and it will be part of the culture of every classroom.

CONCLUSION

For high-quality STEM education programs, countries need to offer a comprehensive curriculum, teacher training, guidance, and assessment, integrate technology and engineering into the science and mathematics curriculum, and promote engineering design pedagogy and scientific inquiry (Kennedy and Odell, 2014). Although the current Kosovo curriculum is theoretically designed to allow for greater integration of subjects, challenges remain, mainly STEM integration education. The education system at all levels, curriculum implementation, and teaching and learning methods have brought the curriculum subject integration into silos, with insufficient integration of science, technology, engineering, and mathematics. Teachers need a lot of work to integrate content across subject areas with a variety of learning activities. However, interaction with other subjects is expected to be relatively broad and varied within the disciplines.

Science, Technology, Engineering, and Mathematics education is of significant importance for preparing pre-service teachers for curriculum integration. According to Bartels et al. (2019), pre-service teachers should be introduced to STEM and allowed to design and teach integrated STEM as early as during their studies. Modeling collaboration while offering integrative STEM activities to pre-service teachers will increase understating of STEM teaching and learning. Future teachers should be guided to consider how STEM subjects can be integrated into meaningful ways for prospective students.

This study found that pre-service teachers effectively conceptualize STEM and STEM pedagogical practices when university professors work together in STEM disciplines. The STEM workshop activities introduced helped the pre-service teachers better understand and reflect STEM concepts and practices. In future publications, we will present the results from data collected during the workshop on pre-service teachers' ability to apply STEM integration elements, such as planning, designing, preparing, developing, and implementing STEM activities. STEM teaching professional development, which is dedicated and adopted in the course of study for pre-service teachers, has shown that it could be implemented with in-service teaching in the future. The shared learning experience of STEM integration of pre-service mathematics and chemistry teachers is an excellent indication of the immediate need to redesign teacher preparation programs to better enable them to deliver integrated teaching and learning courses.

Similar to the study by Tsupros et al. (2009) and Kelley and Knowles (2016), the pre-service teachers' reflections show STEM to be crucial and related to the development of 21st-century skills and as a connection between school, community, and labor education. Joint efforts by teachers, administrators, universities, businesses, communities, and families can help meet the demand for STEM teacher education development to provide more efficient teaching and meaningful learning for students (Stohlmann et al., 2012). As pre-service teachers have shown, there is a need for more professional development training in STEM education which should be facilitated by professionals so that teachers have the opportunity to play the role of students, and at the same time, to develop the teaching competencies that are necessary for every teacher today. Effective pre-service teacher preparation programs and professional development are the only way to prepare good citizens who serve economic growth and other social developments. The reflections of pre-service teachers will also contribute to the development and adaptation of teacher training programs. Their stated challenges of pre-service teachers advocate discussions with other educational policymakers to implement STEM in schools to fulfill the competencies and development of 21st-century skills, which are the new Kosovo Curriculum's basic principles (MEST., 2016). Besides, the study supports teacher preparation to prepare for STEM teaching and a suitable environment for implementing STEM activities.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

The authors contributed equally to research conception and design, data collection, data analysis, presentation of the study, and wrote the manuscript.

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The Co-Development of Science, Math, and Language Interest Among Spanish and Finnish Secondary School Students

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The present two studies with a 3-year longitudinal design examined the co-development of science, math, and language (e.g., Spanish/Finnish) interest among 1,317 Spanish and 804 Finnish secondary school students across their transition to post-compulsory secondary education, taking into account the role of gender, performance, and socioeconomic status (SES). The research questions were analyzed with parallel process latent growth curve (LGC) modeling. The results showed that Spanish students' interest in each domain slightly decreased over time, whereas Finnish students experienced an overall high and relatively stable level of interest in all domains. Further, boys showed greater interest in math and science in both countries, whereas girls reported having a greater interest in languages. Moreover, Spanish and Finnish students with high academic achievement typically experienced high interest in different domains, however, some declines in their interest occurred later on.

Keywords: achievement, interest development, gender differences, languages, science, transitions

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INTRODUCTION

According to the expectancy-value theory of achievement motivation (EVT), interest and task values play a crucial role in shaping students' achievement and career choices, even more than ability self-concepts (Wigfield and Cambria, 2010; Wigfield and Eccles, 2002). Task values consist of interest value (liking or enjoyment), utility value (instrumental value of the task), attainment value (personal importance), and cost (the negative consequences of making a concrete choice). Task values are domain-specific; a student can be interested in math but not in languages and vice versa–(Frenzel et al., 2010). Together with other task values, interest value plays an important role in "shaping individuals' achievement-related decisions like activity choice, participation, and engagement" (Eccles, 2005, p. 109). Interest values in different domains are similar to intrinsic values (Eccles, 2005; Frenzel et al., 2010), and are often relatively stable over time (Frenzel et al., 2010; Wigfield and Eccles, 2002). However, in comparison to other expectancy-value constructs (i.e., utility value) interest value has been understudied (Chow and Salmela-Aro, 2011). When students intrinsically value an activity, they often become deeply engaged in it and can persist at it for a long time (Wigfield and Eccles, 2002;Cambria, 2010). However, little is known about the differences of interest values in different domains. Consequently, the present study examined the co-development of math, science, and language interest among Spanish and Finnish secondary school students. Moreover, the low representation of women in many STEM (Science, Technology, Engineering, and Mathematics) studies and occupations is a worldwide phenomenon (OECD, 2015), which also varies across different STEM fields. Thus, the present study examined the possible gender differences in student's interest values further.

Development of Interest in Math, Science, and Languages

Adolescents tend to become more negative about themselves and school after the transition to higher educational levels (Eccles and Wigfield, 2002; Jacobset al., 2002). Students whose valuing of different academic activities declines sharply over the school years are at risk of becoming apathetic about learning (Wigfield and Cambria, 2010).

Numerous changes in school environments during the transition to higher educational levels influence students' interest in different domains (Jacobs et al., 2002). For instance, increasing evaluations may lead students to undervalue activities and domains in which they do not do particularly well (Wigfield and Eccles, 2002). This evaluative pressure can also decrease students' intrinsic value in learning (Wigfield and Cambria, 2010). Students become much better at understanding and interpreting the evaluative feedback they receive and engage in more social comparison with their peers over time (Sáinz and Eccles, 2012; Wigfield and Eccles, 2002). As a result, many students become more accurate or realistic or even negative in their self-assessments (Jacobs et al., 2002; Wigfield and Eccles, 2002; Wigfield and Cambria, 2010; Sáinz and Upadyaya, 2016).

Similarly, boys' and girls' patterns of interest evolve differently over time, and declines in task values vary across domains (Jacobs et al., 2002). Girls' interest in math decreases in adolescence to a greater extent than boys', and girls are more likely to express greater interest in languages than in math over time (Jacobs et al., 2002). In addition, parents, teachers, peers, and school context influence the development of interest values (Frenzel et al., 2010; Wigfield and Eccles, 2002). For example, parents socialize their children's interest and engagement in different domains through various means (e.g., showing confidence in children's abilities, by encouraging their children's participation and interests in different activities) (Eccles, 2014).

Achievement as an Antecedent of Interest

According to the internal/external (I/E) frame of reference model, self-concepts and interests in one domain are closely connected to achievement in the same domain (Marsh and Hau, 2004). For instance, whereas math and verbal achievement are highly correlated, math and verbal interest values and self-concepts tend to be weakly associated (Nagy et al., 2008). Likewise, "students compare their achievement in one domain (i.e., math) with that in another domain (i.e., languages) and consider themselves as either "math persons" or "language persons" but not both simultaneously" (Marsh and Hau, 2004, p. 57). Similarly, math interest is positively related to achievement and course choices in math, but negatively associated with achievement and course choices in languages (Nagy et al., 2008).

Recently, the I/E model of reference has been extended to near-domain science domains (biology, physics, and math) and positive cross-domain effects between achievement and self-concept have been found (Guo et al., 2015). Consistent with the EV theory, prior achievement in one domain (i.e., languages) predicts interest in that domain, which in turn influences students' course selection in that domain (Marsh et al., 2005; Nagy et al., 2008).

Gender and SES as Antecedents of Interest

Math and science are often considered to be domains in which boys have a high level of achievement, values, and self-concepts, while the same is applicable for girls in languages (Durik et al., 2006; Sáinz and Eccles, 2012). The association between academic achievement and intrinsic values has been observed across different domains (Durik et al., 2006; Jacobs et al., 2002). Gender and previous academic achievement often predict intrinsic values in STEM domains (Chow and Salmela-Aro, 2011) and reading (Durik et al., 2006). Moreover, the same student may highly value languages, but may value other subjects to the same extent, such as math or physical science (Chow and Salmela-Aro, 2011; Sáinz and Eccles, 2012)

Differential interest in math, science, and language may lead to the under-representation of women in some STEM fields, as well as to the over-representation of men in most STEM fields (Eccles, 2014). In addition, high family socioeconomic status (SES) often promotes students' educational outcomes, and further influence their academic and occupational decisions (Davis-Kean, 2005; Eccles & Wang, 2015; Sáinz and Müller, 2018). Interestingly, family SES is more strongly linked to educational aspirations among boys than among girls (Guo et al., 2015), and students whose parents have higher educational attainments develop higher interest in STEM courses (Eccles & Wang, 2015; Gorard and Beng, 2009; Sáinz and Müller, 2018). However, to the authors' knowledge there is a dearth of research tackling the influence of gender and family SES on the co-development of students' interest in different subject areas.

The Present Study

Two European contexts with different educational systems and cultures facing similar problems—i.e., the lack of female participation in STEM and students' interest decline in STEM subjects across secondary schooling—were selected for this study (OECD, 2015). Interestingly, both countries are among the top-ten most equal European countries. Whereas Finland ranks fourth in the Gender Equality Index, Spain ranks the position 8th in this Index (EIGE, 2021). As in many OECD countries, jobs in the STEM fields in Finland and Spain are mainly occupied by men. These jobs are currently in high demand in the labor market, and they are characterized by being well-paid and normally associated with leadership positions (OECD, 2015; European Parliament, 2020). The present study contributes to international research on the on the co-development of gendered interest in various domains across the transition to higher education.

The Educational Systems in Finland and Spain

Compulsory comprehensive education in Finland lasts for 9 years, until the students are 18 years old. After that,

TABLE 1 | Sample characteristics for the Spanish and Finnish samples.

	Spanish sample (n = 1,317)			Finnish sample (n = 804)		
Waves	**Time 1**	**Time 2**	**Time 3**	**Time 1**	**Time 2**	**Time 3**
	Early adolescence		**Mid-adolescence**	**Mid-adolescence**		
Grades	8	9	10	9	10	11
Age	13	14	15	15	16	17
Gender	52% females			47.71% females		
SES	26% high SES, 54% intermediate SES, and 19% low SES			34% high white collar SES, 49% low white collar SES, 17% blue collar SES		
Origin	74% born in Spain			99% Finnish native speakers		

The dark bars indicates the transition points to higher educational stages. Whereas in the Spanish sample, a pseudo-transition happens between time 2 and 3 (the last course of compulsory secondary education), in the Finnish sample the transition to post-compulsory secondary education happens between time 1 and 2.

approximately 50% of adolescents' transition to senior high schools and approximately 41% go to vocational schools (School Statistics, 2010). Average academic achievement in the ninth grade is the minimum requirement for admission to senior high school. Both senior high schools and vocational schools take 3–4 years to complete, after which time students may apply to higher education institutes. Meanwhile, compulsory comprehensive education in Spain lasts for ten, until students are 16 years old. After that, either senior high school or vocational education take 2 years to complete. Spanish senior high school students have to choose one out of the three available tracks: science and technology, humanities and social sciences, or the arts.

The present study examined the following research questions: 1) How does Spanish and Finnish secondary school students' interest in math, science, and languages (e.g., Spanish or Finnish) co-develop during their transition to high school? 2) To what extent students' academic achievement, gender, and family socioeconomic status (SES) predict the parallel development of math, science, and language interest in among Spanish and Finnish students?

STUDY 1

Methods

The data were drawn from the Spanish *Expectancies* study, in which secondary school students participated. Consent was obtained from students after getting prior permission from both parents and educational authorities. The first survey (Time 1, age = 13) was carried out at the end of grade 8. The second (Time 2, age = 14) and third (Time 3, age = 15) surveys were gathered at the end of the third and fourth years of compulsory secondary school (grades 9 and 10, respectively). A total of 1,317 students (703 males, 604 females) from 10 public secondary schools in Madrid and Barcelona participated in the study (see **Table 1**).

The majority of participants (74%) were born in Spain. Students most often lived with both parents (69%). The occupational distribution of parents was: 24% of the fathers and 14.4% of the mothers worked in higher-level white-collar occupations (e.g., doctors, lawyers), 63.5 and 57.3% worked in intermediate-level white-collar occupations (e.g., clerks, teachers) or in blue-collar occupations (e.g., taxi drivers, police officers), and 4.1 and 25.2% were unemployed, homemakers, or retired. Approximately 36% of the fathers and 39% of the mothers had university degree, 56% of the fathers and 55% of the mothers had completed secondary education, while only 2% of the fathers and 3% of the mothers had completed only primary school.

Attrition analyses were conducted by comparing the students who participated in the study at each measurement time (N = 417) with those who had missing data at one or more measurement times (N = 592). Students who participated in the study at each measurement reported higher level of interest in math (M = 4.03, SD = 1.71) and science (M = 4.50, SD = 1.76) at Time 1 than those who did not (M = 3.34, SD = 1.574, t (5.07) = $p < 0.001$ for math; M = 4.12, SD = 1.87, t (2.47) = $p < 0.001$ for science). In addition, students who participated at each measurement reported higher math interest at Time 2 (M = 4.10, SD = 1.82) than students who did not (M = 3.53, SD = 1.81, t (2.66) = p <.01). Moreover, students who participated at each measurement reported higher final grades in math (M = 5.63, SD = 1.93), Spanish (M = 6.05, SD = 1.89) and science (M = 6.09, SD = 2.22) than students who did not participate at each measurement (M = 4.58, SD = 1.93, t (6.42) = p <.001 for math; M = 4.95, SD = 1.89, t (6.86) = p <.001 for Spanish); M = 4.61, SD = 2.14; t(6.0) = $p < 0.001$ for science).

Measures

Intrinsic value (Times 1–3) was measured with the Task Value Scale translated into Spanish, which consisted of three items (Eccles and Harold, 1991). Participants were asked to rate separately the intrinsic value of math, Spanish and natural sciences (physics and chemistry in Time 2 and 3) using a 7-point scale (1 = not at all; 7 = very much). Sample items read as follows: "How much do you like. . .?", "In comparison to other subject areas, how much do you like...?", and "How much would you like to work with. . .". Cronbach's alpha reliability was 0.86 for math, 0.87 for Spanish and 0.93 for natural sciences.

Academic performance was measured with self-reported final grades (Time 1) ranging from 1 (lowest) to 5 (highest) for math, natural sciences, and Spanish.

Demographics. Gender was coded 1 = girl, 2 = boy. Family SES was coded as 3 = High, 2 = Intermediate, and 1 = Low.

TABLE 2 | Correlations, means, and variances for the Spanish sample.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Math Interest[a]	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2. Math Interest[b]	0.63***	—	—	—	—	—	—	—	—	—	—	—	—	—
3. Math Interest[c]	0.58***	0.65***	—	—	—	—	—	—	—	—	—	—	—	—
4. Science Interest[a]	0.24***	0.16***	0.22***	—	—	—	—	—	—	—	—	—	—	—
5. Science Interest[b]	0.37**	0.49***	0.47***	0.38***	—	—	—	—	—	—	—	—	—	—
6. Science Interest[c]	0.38***	0.42***	0.55***	0.25***	0.60***	—	—	—	—	—	—	—	—	—
7. Spanish Interest[a]	−0.11**	−0.10*	−0.06	0.16***	−0.01	0.00	—	—	—	—	—	—	—	—
8. Spanish Interest[b]	−0.17***	−0.12**	−0.10*	0.01	−0.05	−0.06	0.51***	—	—	—	—	—	—	—
9. Spanish Interest[c]	−0.12**	−0.07	−0.06	0.01	−0.05	−0.01	0.44***	0.46***	—	—	—	—	—	—
10. Math Performance	0.51***	0.40***	0.40***	0.46***	0.28***	0.33***	−0.01	−0.09*	−0.02	—	—	—	—	—
11. Science Performance	0.26***	0.20***	0.28***	0.12**	0.30***	0.29***	0.09*	−0.03	−0.01	0.52***	—	—	—	—
12. Spanish Performance	0.13***	0.11**	0.12**	0.12*	0.15***	0.19***	0.34***	0.15***	0.09	0.46***	0.51***	—	—	—
13. Gender	−0.12***	−0.11**	−0.09**	−0.12**	−0.10**	−0.11**	0.17***	0.15***	0.13***	−0.04	−0.01	0.12**	—	—
14. SES	0.07*	0.05	0.05	0.12*	0.04	0.08*	0.03	0.02	0.02	0.15***	0.14***	0.24***	0.04	—
M	3.71	3.69	3.49	4.33	3.84	3.53	4.17	3.99	3.92	2.43	2.68	2.66	1.46	2.02
Var	2.89	3.30	3.31	3.19	3.38	3.63	2.32	2.25	2.25	1.70	1.73	1.59	0.25	0.38

Note. ***p *< 0.001;* **p *< 0.01;* *p *<.05*
[a]*Time 1*
[b]*Time 2*
[c]*Time 3.*

Analysis Strategy

To capture the parallel development of students' interest in math, science, and Spanish, the results were analyzed with parallel process latent growth curve (LGC) modeling (Muthén and Muthén, 1998-2018). In these models, the mean levels of math, science, and Spanish interest (intercept), their linear growth (linear slope), and individual variation across these scores were estimated. The intercepts were specified by setting the loadings of the three observed values of math, science, and Spanish interest to 1; the linear slope was specified by setting the loadings of the three observed values to 0, 1, and 2. The residual variances of the observed variables were able to be freely estimated. The linear slopes of each growth curve were regressed to the intercepts of each growth curve. The statistical analyses were performed using Mplus (Version 8; Muthén and Muthén, 1998-2018) with the missing data method and MLR estimator. Goodness-of-fit was evaluated using four indicators: χ^2 test, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and the Standardized Root Mean Square Residual (SRMR). Next, students' gender, SES, and performance in math, science, and Spanish were included in the model as covariates to predict the interest intercepts and slopes. In the final model, all the statistically non-significant associations were fixed to zero.

RESULTS

Parallel Process LGC Model for Students' Interest in Math, Science, and Spanish

The means, variances, and correlations between all the variables are shown in **Table 2**. The fit of the final parallel LGC model was good: χ^2 (18, N = 1,317) = 168.6, p = 0.00, CFI = 0.95, TLI = 0.93, RMSEA = 0.04, SRMR = 0.04 (**Table 3**; **Figure 1**). The variances of both the initial levels and linear slopes of the interest variables (except Spanish) were statistically significant, indicating significant individual differences both in the initial status and in the developmental trends of the interest variables. Only the variance of Spanish interest slope was non-significant, indicating that the decreasing linear development was similar for all the students. Moreover, the initial level of science interest positively predicted the linear slope of math interest (*s.e.* = 0.32, p <.01), and the initial level of math interest positively predicted the linear slope of science interest (*s.e.* = 0.57, p <.001).

Next, students' gender, SES, and performance in math, science, and Spanish were included in the parallel process LGM as covariates. In this model students' math performance positively predicted the initial level of math interest, and negatively predicted the initial level of Spanish interest (**Table 4**). However, when students reported high math performance, their math interest decreased and Spanish interest increased more rapidly later on. Spanish performance, in turn, positively predicted the level of Spanish interest, and negatively predicted the initial level of math and science interest (**Table 4**). However, when students reported high Spanish performance, their subsequent interest in Spanish decreased, and subsequent interest in science increased more rapidly later on. Students with high science performance experienced a high initial level of science, which, however, decreased more rapidly later on. Moreover, male students reported higher initial interest in math, whereas female students reported higher initial level of Spanish interest. In addition, students from lower SES families were initially more interested in Spanish, whereas Spanish interest increased more among students from higher SES families[1].

[1]However, further analyses indicated that these results were due to a suppression effect as no statistically significant correlation emerged between family SES and Spanish interest. When the analyses were run without the performance variables in the model, the effect of family SES on Spanish interest was non-significant (*s.e.* = 0.05, p *ns* for intercept; *s.e.* = −0.06, p *ns* for slope).

TABLE 3 | Latent growth components of the parallel process LGC model (standard errors in the parentheses).

	Spanish students			Finnish students	
	Math interest	**Spanish interest**	**Science interest**	**Math/Science interest**	**Finnish interest**
Growth components					
Means					
Intercept	3.73 (0.05)[a]	4.16 (0.05)[a]	4.29 (0.06)[a]	3.92 (0.06)[a]	4.05 (0.06)[a]
Linear slope	−0.10 (0.03)[b]	−0.13 (0.03)[a]	−0.37 (0.04)[a]	−0.03 (0.03)	−0.01 (0.02)
Variances					
Intercept	2.12 (0.19)[a]	1.09 (0.08)[a]	1.58 (0.25)[a]	2.08 (0.14)[a]	1.58 (0.11)[a]
Linear slope	0.24 (0.10)[c]	0*	0.70 (0.14)[a]	0.23 (0.03)[a]	0.21 (0.05)[a]
Residual variances					
Interest (Time 1)	0.78 (0.18)[a]	1.18 (0.09)[a]	1.67 (0.26)[a]	0.39 (0.03)[a]	0.45 (0.03)[a]
Interest (Time 2)	1.21 (0.09)[a]	1.12 (0.09)[a]	1.53 (0.11)[a]	0*	0.10 (0.10)[a]
Interest (Time 3)	0.86 (0.18)[a]	1.27 (0.09)[a]	0.18 (0.06)[b]	0.43 (0.)[a]	0.44 (0.03)[a]

Note. [a]$p < 0.001$; [b]$p < 0.01$; [c]$p < 0.100$* = *fixed to zero.*

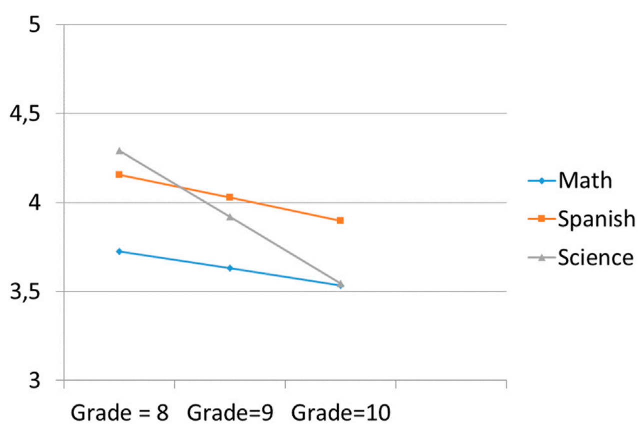

FIGURE 1 | Parallel Development of Spanish Students' Interest in Math, Science, and Spanish.

STUDY 2

Methods

The data were drawn from the Finnish Educational Transitions (FinEdu) study, in which all the ninth-grade students in a medium-sized town with a population of 88,000 in Central Finland were recruited (see **Table 1**). The first survey (Time 1, age = 15) was carried out at the end of the students' ninth grade and before the transition to high school (academic track) or vocational school (vocational track). Two measurements were carried out during post-comprehensive education: the first was half a year after the transition to post-comprehensive education (Time 2, age = 16) and the second was 1 year later (Time 3, age = 17). A total of 871 students (456 males, 415 females) from nine secondary schools and, later on, from 13 post-comprehensive schools participated.

Consistent with the general population in Central Finland, the majority of participants (99%) were Finnish-speaking (Kuopion Lukiokoulutus, 2009). Students most often lived with both parents (62%), or with their mother or father, either as a single parent (25%), or living with her/his new spouse (11%), or with somebody else (1%). Approximately 27% of the fathers and 20% of the mothers worked in higher-level white-collar occupations (e.g., doctors, teachers); 16 and 49%, respectively, worked in lower-level white-collar occupations (e.g., clerks, salespeople); 36 and 17%, respectively, had blue-collar occupations (e.g., cooks, bus drivers); 11 and 4%, respectively, were private entrepreneurs; 1 and 2%, respectively, were students; 3 and 2%, respectively, were retired; and 5 and 6%, respectively, had some other status (e.g., unemployed).

Attrition analyses were carried out to examine attrition between the measurements by comparing students who participated in the study at each measurement time ($N = 435$) with those who had missing data at a certain measurement time ($N = 443$). Students who participated in the study at each measurement time showed higher interest in Finnish at Time 1 ($M = 4.24$, $SD = 1.61$) and Time 2 ($M = 4.24$, $SD = 1.76$) than those who did not ($M = 3.82$, $SD = 1.93$, $t = -2.32$, $p <.05$; $M = 3.87$, $SD = 1.66$, $t = -2.12$, $p < 0.05$). Moreover, students who participated in the study at each measurement time showed higher interest in math and science at Time 1 ($M = 4.09$, $SD = 1.88$) than those who did not ($M = 3.56$, $SD = 1.95$, $t = -2.62$, $p < 0.01$).

Measures

Interest (Times 1–3) was measured with the Task Value Scale (Niemivirta, 2002), which was developed based on the EV theory (Eccles and Wigfield, 2002). Participants rated interest in math, sciences, and Finnish separately using a 7-point scale (1 = not at all; 7 = very much).

Academic performance was measured with the grade point average (GPA) of the final comprehensive school report (Time 1), on a scale ranging from 4 (lowest) to 10 (highest).

Demographics. Gender was coded 1 = girl, 2 = boy. Family SES was coded 1 = blue collar, 2 = lower-level white collar, 3 = higher-level white collar.

RESULTS

The results were analyzed similarly as in Study 1. **Table 5** shows the means, variances, and correlations between all the variables. The parallel process LGC model was constructed for students' interest in math and natural sciences and in Finnish. The fit of the final parallel LGC model was good $\chi^2(10, N = 857) = 44.30$, $p = 0.00$, *CFI*

TABLE 4 | Antecedents of the latent growth components of the parallel process LGC model (standardized estimates, standard errors in the parentheses) among Spanish secondary school students.

	Math interest		Spanish interest		Science interest	
	Intercept	*Slope*	*Intercept*	*Slope*	*Intercept*	*Slope*
Math Performance	0.67 (0.04)[a]	−0.29 (0.08)[a]	−0.29 (0.05)[a]	0.31 (0.15)[c]	0*	0*
Spanish Performance	−0.13 (0.04)[b]	0*	0.58 (0.04)[a]	−0.98 (0.29)[b]	−0.21 (0.06)[a]	0.22 (0.7)[b]
Science Performance	0*	0*	0*	0*	0.82 (0.05)[a]	−0.48 (0.08)[a]
Gender	−0.09 (0.03)[b]	0*	0.16 (0.03)[a]	0*	0*	0*
SES	0*	0*	−0.14 (0.05)[b]	0.34 (0.14)[c]	0*	0*

Note; [a]*p < 0.001;* [b]*p < 0.01;* [c]*p < 0.05.0* = fixed to zero; gender: 1 = male, 2 = female.*

TABLE 5 | Correlations, means, and variances for the Finnish sample.

	1	2	3	4	5	6	7	8	9
1. Math/science interest[a]	—	—	—	—	—	—	—	—	—
2. Math/science interest[b]	0.71***	—	—	—	—	—	—	—	—
3. Math/science interest[c]	0.54***	0.49***	—	—	—	—	—	—	—
4. Finnish interest[a]	0.07	−0.08*	0.03	—	—	—	—	—	—
5. Finnish interest[b]	0.07	0.01	0.05	0.63***	—	—	—	—	—
6. Finnish interest[c]	0.06	0.02	0.24***	0.55***	0.50***	—	—	—	—
7. GPA	0.28***	0.16***	0.33***	0.24***	0.17***	0.30***	—	—	—
8. Gender	0.19***	0.23***	0.16***	−0.34***	−0.29***	−0.37***	−0.19***	—	—
9. SES	−0.03	0.06	−0.04	−0.00	0.08	−0.05	0.34***	0.06	—
M	3.88	3.84	3.91	4.02	4.00	4.03	8.03	1.53	2.01
Var	3.61	3.68	3.61	3.03	2.88	2.88	0.72	0.25	0.46

*Note. ***p < 0.001; **p < 0.01; *p <.05;*
[a]*Time 1*
[b]*Time 2*
[c]*Time three.*

= 0.96, *TLI* = 0.94, *RMSEA* = 0.06, *SRMR* = 0.03). The results showed that Finnish students experienced a relatively high level of math/science and Finnish interest, and both remained stable over time (**Table 3**; **Figure 2**). The variances of both the initial levels and linear slopes of the interest variables were statistically significant, indicating significant individual differences both in the initial status and in the developmental trends of math/science and Finnish interest. In addition, a high initial level of math/science interest negatively predicted the linear trend of Finnish interest, whereas a high initial level of Finnish interest negatively predicted the linear trend of math/science interest (**Figure 3**).

Finally, students' gender, GPA, and SES were included in the parallel process LGC model as covariates. The final model fit the data well: $\chi^2(23, N = 876) = 85.65, p = 0.00, CFI = 0.95, TLI = 0.93$, $RMSEA = 0.06$, $SRMR = 0.04$ (**Table 6**). The results showed that boys had a higher initial level of math/science interest, whereas girls showed a higher initial level of interest in Finnish. Moreover, students who had a higher GPA showed a higher initial level of math/science and Finnish interest; which however, slightly decreased later on.

DISCUSSION

The present study contributes to STEM education in Spain and Finland since it is the first to investigate the co-development of math, science, and language interest among Spanish and Finnish secondary school students across the transition to post-compulsory education, and taking into account the role of gender, academic achievement, and family SES. In both studies, students following an academic/vocational track were followed. The results showed that Spanish students' interest values in all three domains decreased across the school years, whereas Finnish students' interest values remained relatively stable. In addition, students with high achievement showed a higher initial level of math/science and language interest.

Development of Spanish and Finnish Students' Interest in Math, Science, and Language

The results showed first, that Spanish students' interest in math, science, and Spanish language slightly decreased over time. However, Finnish students' interest in math/science and Finnish language remained relatively stable over time. These differences may be related to the educational stages of the students from both samples. While Finnish students faced a transition to secondary education between Time 1 and Time 2, all students in Spain went through a pre-specialization stage during Time 3, regardless of whether they were or not going to pursue vocational training or high school the following year. While math and Spanish are compulsory subjects at this educational stage in Spain, science domains such as physics are optional, which may show as decreases in Spanish students' physics interest.

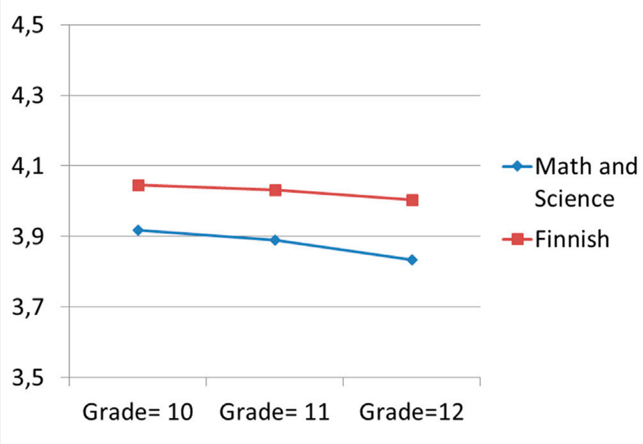

FIGURE 2 | Parallel Development of Finnish Students' Interest in Math and Science, and Finnish.

These findings may also be explained by the students' age and school experiences: at the beginning of the study, Spanish students were slightly (e.g., 2 years) younger than Finnish students. In line with other studies, younger students (e.g., here Spanish students) tend to report higher interest than older students in different domains, which may decrease more rapidly over time (Jacobs et al., 2002; Upadyaya and Eccles, 2015). Given their broader school experience, older students (*e.g.*, Finnish students) develop a more stable perceptions of their domain interests (Wigfield and Eccles, 2002; Wigfield and Cambria, 2010). Similarly, Finnish students' high level of performance in all PISA competence assessments across time could be another indicator of the stability in the Finnish students' interest in the target domains (OECD, 2015).

In addition, transition to high school may show in students' interest in the different subject areas (Jacobs et al., 2002; Wigfield and Cambria, 2010). In Finland the transition to post-compulsory secondary schooling took place between the first and second measurement, when students had already selected their academic/vocational track and might know their academic strengths/weaknesses relatively well. This may show as stability in students' domain interests. Importantly, these results suggest that more changes in students' domain interests occur during the earlier stages of their education (Jacobs et al., 2002; Wigfield and Eccles, 2002). The "pseudo-transition" that Spanish students undergo at the end of compulsory secondary schooling (Time 3) may also have an impact on their interest in different domains, when the choices of available subjects are limited and may diminish students' interest values.

Interestingly, when Spanish students reported high science interest, their math interest decreased less later on. Similarly, when Spanish students reported high initial math interest, their subsequent science interest decreased less. These findings may be due to the fact that whereas math and science are near-domain scientific subjects, math and language are not that close (Nagy et al., 2008). Therefore, students who show an interest in math tend to not show an interest in language, and vice versa.

Among the Finnish students, high math/science interest also predicted decreases in Finnish interest, whereas a high level of

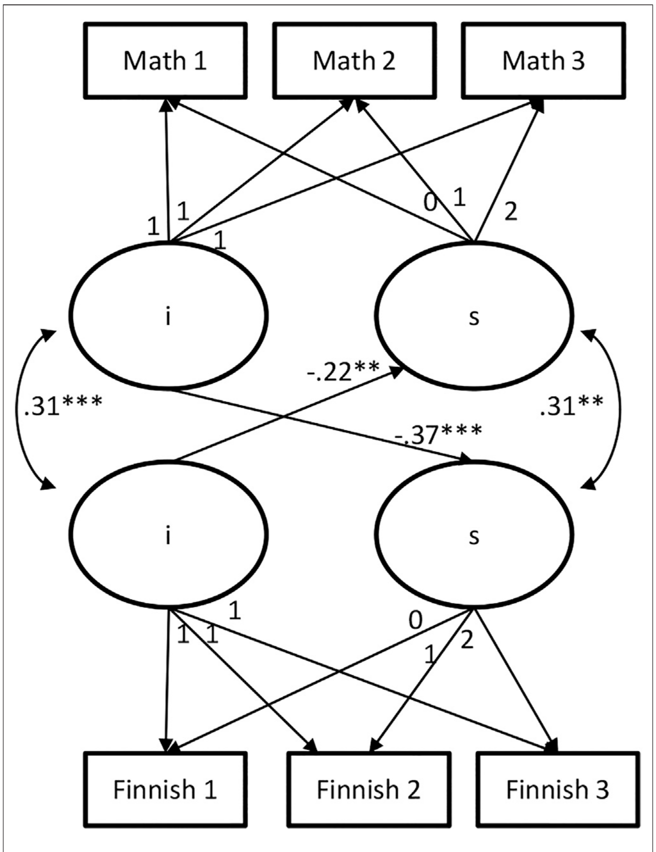

FIGURE 3 | The Parallel Process LGC Model of Math/Science Interest and Finnish Interest Among Finnish Students. Note.***p* < 0.01; ****p* < 0.001. I = intersect, s = slope.

TABLE 6 | Antecedents of the latent growth components of the parallel process LGC model (standardized estimates, standard errors in the parentheses) among Finnish secondary school students.

	Math/Science interest		Finnish interest	
	Intercept	***Slope***	***Intercept***	***Slope***
Gender	0.33 (0.04)[a]	0*	−0.41 (0.04)[a]	0*
SES	0*	0*	0*	0*
GPA	0.52 (0.04)[a]	−0.22 (0.08)[b]	0.30 (0.05)[a]	−0.15 (0.05)[a]

Note: [a]*p < 0.001,* [b]*p < 0.01;* [c]*p < 0.05.0* = fixed to zero; gender: 1 = girl, 2 = boy.*

Finnish interest predicted decreases in the level of interest in math/science (Nagy et al., 2008). The changes associated with school specialization may have greater effect on Finnish students and may have led students with high math interest to experience decreases in their language interest and vice versa. Following the I/E frame of reference (Marsh and Hau, 2004), students might consider themselves to be either "math/science persons" or "language persons," but not both. Similarly, Spanish students with university aspirations may have different pattern of interest from those with vocational aspirations. This parallel development of math, science, and language interest provides an opportunity for cross-domain comparisons. Over time, the parallel development of interest in different domains was very similar both among Finnish and Spanish students.

Factors Influencing Students' Math, Science, and Language Interest

In line with the EVT (Wigfield and Eccles, 2002), the results for Spanish students showed that girls reported higher interest in Spanish and lower interest in math than males. Similarly, Finnish boys reported higher math/science interest, whereas girls showed higher language interest. Male students often attach greater personal importance to math than female students (Sáinz and Eccles, 2012), while female students attach more value to languages than male students (Durik et al., 2006; Jacobs et al., 2002). These findings also show that even secondary students brought up in the most gender-equal societies (e.g., Finland) deploy gender differences in their interest in science and languages.

Further, some findings confirmed the assumptions of both the EVT (Wigfield and Eccles, 2000) and the I/E model of the reference (Marsh and Hau, 2004). In line with the reciprocal effects between achievement and task values in math and language (Marsh and Hau, 2004; Nagy et al., 2008), high GPA predicted high math/science and Finnish interest, which, however, slightly decreased later on among Finnish students. These findings also confirm assumptions of the EVT (Jacobs et al., 2002; Wigfield and Cambria, 2010). In addition, among Spanish students achievement in one domain predicted high interest in the same domain (Marsh and Hau, 2004; Nagy et al., 2008). Students with high Spanish achievement reported high initial interest in Spanish and low initial math and science interest. However, when Spanish students reported high performance in any of the three target domains, their subsequent interest in that same domain decreased (Jacobs et al., 2002), whereas their subsequent interest in the rest of domains increased more rapidly later on. These findings could be associated with students' need to increase the motivational value of those subject areas where they had lower achievement. Similarly, among Finnish students high GPA predicted high initial interest in math/science or Finnish, which decreased more rapidly later on. These results add to the previous findings by showing that students' performance shapes the co-development of students' interest in different academic domains (see also Eccles, 2005; Wigfield and Cambria, 2010).

Cultural reasons may explain the different patterns of SES influence on the development of students' interest in Spanish language. Spanish society is more heterogeneous in terms of a higher percentage of immigrant population than Finnish society. This results in a much higher heterogeneity in the classroom, which may enhance the importance of the role of Spanish language in the curriculum of secondary education and increase students' interest in Spanish over time (García-Ruiz, 2011).

Limitations

The present study has several limitations. First, the results can be generalized only for the same age group, educational stage, domains, and countries. More cross-cultural studies would be needed to further examine students' motivation and interest in math, science, languages, and other domains, and in countries with different socio-cultural contexts. Even though the interest value measures used in this study were based on the same background theory, the differences in the results may be due to the use of different items. In the future studies the use of parallel items measuring students' motivation would be crucial. In addition, it is possible that various homogeneous subgroups of students exist reflecting different developmental trajectories of math, science, and language interest. More person-oriented studies will be needed in the future to further examine these possible subgroups (Chow and Salmela-Aro, 2011).

In addition, among Finnish students math/science interest was measured with one combined item, which might explain some country differences in the results. In the future studies it would important to examine the interest in these two academic subject domains separately (Wigfield and Eccles, 2000). Moreover, the attrition analyses indicated that students who participated in the study at each measurement time reported slightly higher motivation in both data sets. Thus, it is possible that the results suffered from a selection effect which should be noted when generalizing the findings. Finally, while Finnish students were going through middle adolescence and transiting into high school and vocational training between the first and the second measurement time, the Spanish students were going through early adolescence and experiencing a pseudo-transition into high school or higher vocational training across the third time (the last course of compulsory secondary education), making the educational transition the students were facing at each country slightly different. Future studies should better address these differences.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by IRB (Institutional Review Board) at the UOC and University of Helsinki. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MSI and KU have conducted the analyses and written the article. KS has given feeddback to the last versions of the article.

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Inclusive Instructional Practices: Course Design, Implementation, and Discourse

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As national efforts strive to make STEM more inclusive, it is important to identify instructional practices that maximize effective learning for all and provide students from different demographic and educational backgrounds equal opportunities to excel. Here, we present a guideline for inclusive instructional practices based on findings from 1) cognitive psychology about learning and memory, 2) social psychology about creating inclusive discourse, and 3) discipline-based education research (DBER) about effective learning practices in STEM higher education. Our aim is to promote equity across STEM education by providing researchers and instructors across different STEM fields with concrete suggestions for implementing inclusive instructional practices in their courses.

Keywords: stem education, inclusivity, equity, underrepresented students, instructional guideline

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INTRODUCTION

Testing the effectiveness of instructional practices in undergraduate STEM requires empirical assessments across multiple disciplinary and institutional contexts (C. A. Brewer and Smith, 2011; National Academies of Sciences and Medicine, E, 2016). Investigations into student outcomes include comparisons of performance measures such as exam scores, final grades, concept inventory scores, student behaviors, or affective factors (e.g., the extent to which students identify as scientists) (see National Research Council, 2012 for overview of different measures used in DBER research). Over one hundred studies have examined the impacts of evidence-based learner-centered pedagogy, also referred to as active learning, on measures of aggregated class performance outcomes (Freeman et al., 2014). However, of these studies, few focused on the effects of active learning pedagogies on underrepresented students in STEM specifically, or have considered the reduction or closure of performance gaps as stand-alone measures worthy of explicit focus (e.g., Haak et al., 2011; Ballen et al., 2017; Casper et al., 2019; Theobald EJ. et al., 2020). Under-represented groups in STEM are those whose representation in STEM fields is smaller than their actual representation in the society (e.g., African-Americans constitute 13% of US population but they earned only up to 8% of STEM B.S. degrees in the last 20 years (Rivers, 2017)). Studies that explicitly tracked the performance of under-represented students showed that across different STEM disciplines, active learning pedagogies had a disproportionate positive impact on their performance (Theobald EJ. et al., 2020). However, these studies were still limited in number and context. Therefore, as one of the next frontiers of STEM education, it is incumbent upon the STEM education community to examine and identify inclusive instructional practices in order to support national efforts to promote and retain those historically underrepresented in STEM. We consider inclusive instructional practices as a collection of historically-, socially-, cognitively-, and culturally-sensitive instructional practices implemented in classrooms in order to create equitable learning opportunities for students from different demographic and educational backgrounds. For example, for designing historically-sensitive instructional practices in the United States, one ought to consider the fact that a number of demographic groups were deprived of educational resources over several generations. These historical injustices led to current circumstances in which some demographics are more likely to live in neighborhoods and to attend K-12 schools which are under-resourced, leading to lower academic preparation as students enter higher education (Chetty and Hendren, 2018; Fahle et al., 2020).

We provide a guide for inclusive instructional practices using theoretical and empirical findings from diverse fields. Specifically, we draw from cognitive psychology to discuss learning and memory; social psychology to inform our thinking on creating inclusive discourse; and discipline-based education research to apply effective instructional practices in higher education STEM. There are theoretical reasons for believing the efficacy of these previous findings would be transferrable across different STEM fields, even when empirical studies are limited. We have organized this inclusive teaching practices guide around three major aspects of a STEM course: design, implementation, and classroom discourse. The individual practices fall largely into two groups, as we have labelled: 1) General Category [GC]: generally effective teaching practices which have been shown to benefit all students including underrepresented students; and 2) Targeted Category [TC]: effective teaching practices which particularly benefit underrepresented students by addressing specific aspects that serve as barriers to academic success that are unique to underrepresented students (Schwartz et al., 2016). Targeted practices do not benefit underrepresented students by hindering the performance of over-represented students (Powers et al., 2016), but rather, the extent of their positive effects is larger for underrepresented students, as they target the barriers that are more pronounced for these students. Both categories of inclusive instructional practices are required to create an equitable learning environment which helps students from different backgrounds to thrive, and some practices may span both categories.

GUIDELINE FOR INCLUSIVE INSTRUCTIONAL PRACTICES

(1) Course Design:

- [GC] Have all students understand what they need to do to succeed, regardless of their background. The absence of this information in course materials rewards students who are aware of the "hidden curriculum," who are better prepared for college courses, and are more familiar with the culture, expectations, and assessment methods of higher education (Anyon, 1980; Margolis, 2001; Smith, 2013; Basyiruddin, 2020). For example, effective study habits, which encompass the strategies students use to learn, understand, and retain course content, can be underdeveloped among incoming STEM students (Blasiman et al., 2017). Students (and instructors) commonly rely on ineffective study strategies aimed at short-term goals, such as passing an exam, rather than meaningful understanding of the material (Kornell and Bjork, 2007). Clarifying how to study effectively and actively will encourage success for all students, rather than those who entered the course with existing knowledge of the material or advanced study habit strategies.
- [GC] Have all students understand different components of their course grade, their weights, and how the final course grade is calculated to ensure grades are providing meaningful and effective feedback to students (Quinn, 2013; Feldman, 2018). Lack of a clear grading scheme makes it challenging for students to use the grade they receive in each component of the course as a measure of their learning, and to prioritize investment on learning different aspects of the course. For example, curving grades without clarifying the scheme renders the scores uninterpretable to students, particularly those less familiar with the curving practice. This practice discourages these students as they underestimate their performance in the course (Seymour and Hunter, 2019).
- [GC] Have all students recognize the resources available to them, and how they can best use each of these resources. Without clearly enumerating all the available resources and how students can use them, resources will be utilized by students who are more aware of the university environment and better prepared for college courses, particularly STEM courses (Cotten and Wilson, 2006). For example, students from different backgrounds have different ideas as to what is meant by "instructor office hours", and how they can benefit from them. For students who did not have office hours in their precollege education may perceive instructor office hours as a place for them to demonstrate what ***they have already learned***, as opposed to a place for instructors to provide additional individual help with what ***they have not already learned*** (Jack, 2019).
- [GC] Provide supplementary materials and instructions that will support students with gaps in their preparation, as well as tools to allow students and instructors to identify such gaps. Communicate in advance when students should seek out and use these resources (Rath et al., 2007). Many STEM courses are based on pre-requisite foundational knowledge. For introductory courses, this knowledge should be provided in high school courses. However, significant gaps in the quality and quantity of high school courses equate to gaps in foundational knowledge (Reardon et al., 2019). Previous work shows gaps in incoming preparation is the main reason for demographic performance gaps in introductory STEM courses (Salehi et al., 2019; Salehi et al., 2020). Without providing supplementary materials to address these gaps in preparation, the STEM courses tend to target the well-prepared students and discriminate against students who came from under-resourced schools with regard to STEM education (Seymour and Hunter, 2019).

        - Note: Supplementary materials can be offered in different formats. For example, instructors can: 1) suggest a companion course for students to complete alongside the main course (Fullilove and Treisman, 1990; Batz et al., 2015); 2) dedicate one of the instructor office hours or TA sections to less prepared students; 3) offer an explicit list of external resources (e.g., free online educational videos) that cover course pre-requisites. In providing these resources, one should be mindful of efficiency of supplemental materials in order to balance between inside- and outside-class workload. Many of the students without proper incoming preparation are from less-privileged backgrounds and may work a paid job to cover the cost of their education and/or support their family. This makes their time outside classroom more limited.
- [GC] Design instruction based on the "deliberate practice" approach. As Ericsson et al. (1993) showed in different contexts, acquiring expertise requires: 1) decomposing expertise into subskills, acknowledging that some subskills must be mastered before learning other ones; 2) designing learning activities that directly address each of those subskills through practice; 3) engaging learners in those activities; 4) providing specific, timely, nonthreatening, and actionable feedback about learner's performance; 5) allowing the learner to repeat the activity using the feedback to improve that subskill. To design the course based on deliberate practice approach in STEM courses, the instructor can:
    - Clarify and decompose the learning goals to the point that corresponding learning activities directly address each goal. Identify more challenging learning goals and dedicate more resources to them.
        - *Note: this is particularly an important activity for the instructor to engage in as they prepare their course materials, as it helps them overcome their "expert blind spots" of difficult topics that they may overlook.*
    - Provide students with frequent practice and feedback opportunities. Design learning activities that the individual can engage in between lecture sessions to practice those learning goals (Wood et al., 1994; Willoughby et al., 2000; Preszler et al., 2007; Thomas and McDaniel, 2007; Dunlosky et al., 2013). Without the opportunity to repeat and improve, less prepared students will struggle compared to those who have received more academic preparation.
- [GC] Explicitly align learning activities that students complete in class with their formal assessments. Consequential, high-stakes exams are not the time to test more complex questions than what students have been exposed to in class, though research has never explored the extent to which instructors assess this way (Morris et al., 1977; McDaniel et al., 1978; Ericsson et al., 1993; Morgan et al., 2007; Thomas and McDaniel, 2007; Wormald et al., 2009; Jensen et al., 2014). Alignment will provide students with different levels of academic preparation more equal opportunity to study effectively and perform well on tests. The mismatch between cognitive difficulty of the assessments and learning activities students engage in during the course (e.g., homework) mean students have to "read the instructor's mind" to prepare for exams. Underprepared students are at a disadvantage if assessed this way, particularly as they may often come from different backgrounds and cultures than the instructor. If the course learning activities match the course assessments, then student investment in these activities will help their performance on the assessments. The mismatch, on the other hand, leads to performance on assessments that is more reflective of students' prior preparation (and/or creative use of resources to which select students have access) than of knowledge and mastery of material from class.

(2) Course Implementation:

- [GC] Check that all students clearly see how each learning activity maps to a specific learning goal that defines in operational terms what they should be able to do. This will benefit students by providing a roadmap for monitoring their own learning and understanding which resources to use to address challenging material.
- [GC] Include frequent low stakes formative assessments/ quizzes that give students (and the instructor) feedback about student learning. Feedback is essential for students to improve their learning and for instructors to adapt their teaching. Using various formative assessment methods during class, such as polling tools or worksheets, provides frequent feedback to students and instructors about how well students are understanding the topics covered in lecture sessions.
- [TC] After communicating the course syllabus and roadmaps to success in the course, survey the students for the challenges they expect to encounter in the course, and work with them on finding support and/or accommodations where suitable (Meaders et al., 2020).
- [TC] Actively reach out to students who indicate performance struggles and explore how you can help them.
- [GC and TC] Encourage supportive and educationally productive group work in class. Set norms for interactions during group work to avoid dominance of individuals, and ensure every student is comfortable contributing. Group work benefits students' learning if done properly; if not deliberately structured, it can be unpleasant for some students and generally ineffective. To encourage successful group work:
    - Create well-defined activities for groups that include both individually-completed and group-completed components.
    - Randomly assign tasks to ensure the rotation of roles in groups such as who reports back from each group or who records notes. Although "cold calling" on individuals to answer questions about the work has been shown to be more equitable and improve performance of at-risk groups, it can be stressful on individuals (Dallimore

et al., 2013; Cooper et al., 2018). This can be reduced by calling on individuals to present "what your group thinks", rather than their individual answer.
    - Intervene if individuals are dominating the group interactions or interrupting others, or if some members are excluded from the group discussions.
    - Provide students with an opportunity to think individually before group activities or answering in-class polls (Rowe, 1969; Nicol and Boyle, 2003; Nielsen et al., 2012).
- [TC] Consider the cost of learning technologies and resources required for your course and try to minimize and/or provide support for the cost as much as possible. For example: 1) choose a free desktop or mobile application or website (e.g., Poll Everywhere) for formative assessments instead of clickers, which cost money; 2) If any component of the course (e.g., textbook or assignment platforms) costs money, explore potential resources for students who need help to cover the costs and explicitly list those resources in the course syllabus.

(3) Class Discourse:

- [TC] Avoid language and examples that imply a particular group of students is the main audience of your course. For example, an instructor who apologizes for the price of the expensive textbook required for the class, but then encourages students to "just have your parents pay for it," is problematic for many reasons. Some students are paying for their own education, and many others are generally concerned about their finances (Harrison and Tanner 2018). In this example, the instructor's language is excluding those students and subtly communicating that their financial situation is of no concern to them. Spend time reflecting on the diverse backgrounds and experiences of your students and acknowledge this diversity in the class discourse.
- [TC] Emphasize the importance of an inclusive learning environment and the roles of the teaching team and students:
    - List expectations of how students should treat one another in class in order to foster an inclusive environment and encourage students to review and modify the expectations.
    - Call out unacceptable comments or behavior (see microaggressions below).
    - Be open to learn from your students about your implicit biases and/or exclusive behaviors by providing them the platform to give feedback.
- [GC and TC] Work to encourage a growth mindset (Claro et al., 2016; Yeager et al., 2016). Avoid references to "talent", stress the overriding importance of focused effort to achieve mastery, and emphasize that this applies to everyone (Lin-Siegler et al., 2016). Beware the common conflation of "talented" with "privileged" and therefore educationally better prepared.
    - Share your own ***personal*** challenges in mastering a topic, methods you found to overcome them, and ***general*** challenges and strategies to learn. This will emphasize expertise in STEM topics is not the product of inherent talent or intelligence, but rather the product of repeated and deliberate practice.
    - [TC] Communicate your belief in students' capability to learn and succeed. Previous studies have shown this disproportionately benefits underrepresented students (Cohen et al., 1999).
    - Emphasize hard work over innate ability (Aronson et al., 2002; Good et al., 2012), but also be sensitive to needs for the right kind of hard work. Remember that less prepared students may not know how to study effectively, and everyone benefits from explicit guidance.
    - Emphasize errors as natural and instructional (Bell and Kozlowski, 2008). Explain not just the correct answers but the reasons why an answer is wrong and how to fix it, along with what can be learned from the wrong answer. Provide students with opportunities to "redo" so that in the process they learn from their errors and can improve their grades.
- [TC] Emphasize the responsibility of the instructor as a facilitator of students' growth and learning. Students are in class to learn new skills, not to show off previous skills (Canning et al., 2019).
- Be vigilant and willing to intervene in response to microaggressions aimed at a student (Harrison and Tanner 2018). Microaggressions are brief, sometimes subtle comments that put down others based on their perceived personal characteristics, such as gender, sexual orientation, or underrepresented status (Sue, 2010).
- Discourage students from contributing "questions" that are actually just attempts to show off, not actual questions on the course material. Instructors who reward this behavior likely discourage students who have meaningful questions from asking them, and may make students feel like they are inferior and do not belong; which is a consequence of the "question that is not a question".

FUTURE DIRECTIONS IN INCLUSIVE STEM EDUCATION

We hope the guideline presented here contributes to improving equitable STEM education by providing researchers and instructors with concrete actions for improving the inclusivity of their courses. While this guideline is not a comprehensive literature review, we offer practical suggestions based on previous works to promote inclusive instructional practices. We acknowledge that there remain many detailed research questions still to be explored. While previous research has shown active learning disproportionately benefits underrepresented students, future work will explore what particular components of active learning courses benefit underrepresented students, features define successful implementation, and through what mechanisms are these effective–and for whom?

Addressing these research objectives requires better measures of incoming student preparation, and better measures of learning within a class. These are critical factors that currently serve as limitations to research, if the objective is to measure learning in response to different instructional practices over the course of a semester. While obtaining accurate measures of preparation and knowledge is challenging, researchers can use multiple measures of content-specific assessments and concept inventories that are tailored to specific classrooms (Salehi et al., 2019). A second important advance needed in education research is to collect and analyze data that go deeper than simply the overall class level; to examine the dependencies across different demographic groups (e.g., Ballen, Salehi et al., 2017; Casper et al., 2019). For example, if the outcome of an instructional practice results in the relative underperformance of a group on the basis of, for example, gender or race/ethnicity, we should question the inclusiveness of the practice rather than question the capacity of the students. Third, instead of relying on broad descriptions such as "active learning" or "flipped classroom", researchers should report the instructional practices used in their study in much more detail, and with precision, including the details of implementation (Driessen et al., 2020). Detailed descriptions will power robust metareviews of active learning components that are inclusive. Fourth, there is a need to better understand the contextual factors that influence inclusiveness of instructional practices by testing them across disciplinary and institutional contexts (Kanim and Cid, 2020; Thompson et al., 2020). To achieve this requires expanding the pool of research subjects beyond students at selective, research-intensive universities, which have dominated contemporary DBER studies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SS had written the first draft and other co-authors equally contributes to revising the draft.

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Achieving Multidimensional Educational Goals Through Standard-Oriented Teaching. An Application to STEM Education

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Socially and in relation to the individual, schools' mission for STEM education is not limited to the teaching of knowledge and cognitive skills. Although they form an important basis for dealing with today's challenges in a self-confident and responsible manner, they alone are not enough. Positive attitudes towards learning are additional important prerequisites for lifelong learning and participation in society. However, national educational standards still focus mainly on developing cognitive competencies. They hardly take into account multidimensional educational goals that combine both cognitive and non-cognitive outcomes. At the classroom level, in everyday school life, addressing both is one of the greatest challenges. Introducing standard-oriented curricula may have the potential to shift teachers' professional perception also to non-cognitive educational goals. We argue that, in order to foster multidimensional educational goals, they need to be more clearly addressed at the policy, teacher training, and teaching level. One important research agenda within STEM education for the next years will be to examine and discuss the connection between the implementation of standard-oriented teaching, the achievement of multiple educational goals, and teachers' professional competence.

Keywords: interest, motivation, social-emotional learning, standard-oriented teaching, cognitive and non-cognitive outcomes, mathematics and science education, teachers' professional competence

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INTRODUCTION

Both, socially and in relation to the individual, the mission of schools for STEM education (science, technology, engineering, and mathematics) is not limited to the teaching of (content) knowledge and cognitive skills. However, in daily school life, the focus of teaching is mostly on strengthening achievement development and performance (Schiepe-Tiska, 2019). Little room is given to explicitly strive for other learning goals such as developing interests or social-emotional learning. If anything, these goals are addressed implicitly or they are perceived as side effects to reaching cognitive learning goals. Hence, schools often do not provide resources (e.g., instruction materials, specific courses or activities) or create conditions (e.g., training teachers, devoting teaching hours, receiving school administration support), that would promote striving for other learning goals (Schiepe-Tiska et al., 2021). The global Coronavirus pandemic in 2020 has made this obvious again, as the main interest in public awareness had been on how much learning losses students would experience due to school closings. However, although cognitive learning outcomes form an important foundation for dealing with today's challenges in a self-confident and responsible manner, they alone are not enough. They need to be complemented by so called "non-cognitive" factors as additional and important school outcomes (e.g., Schiepe-Tiska, Rozcen et al., 2016; OECD, 2018a). Together, cognitive and non-cognitive outcomes can be summarized under the term of *multidimensional educational goals*.

In STEM education, reaching multidimensional educational goals is particularly important at the end of compulsory school as this is a decisive phase of identity development. At this point, students develop clear ideas about themselves, and clarify their relation with others and the world in general. Thus, in addition to questions about ones' own interests or ideas about occupational choices, the examination with social and political participation becomes more relevant (Blossfeld et al., 2015; Schiepe-Tiska, 2019).

International large-scale assessments such as the *Programme for International Student Assessment* (PISA) also have adapted the perspective of cognitive and non-cognitive outcomes for mathematics and science (OECD, 2017; OECD, 2018b). This was an important step as PISA aims to provide an internationally embedded, realistic view of countries' reached learning outcomes (i.e., benchmarking), that are oriented at defined standards (i.e., monitoring). At the country level, these frameworks provide opportunities to engage in normative discussions about cultures' central objectives that are important for our current understanding of the world—regarding education in general and STEM education in particular. These discussions, in turn, are reflected in present school practices and teaching policies.

For instance, the poor performance of Germany in PISA 2000 introduced a change in its educational policy perspective (Klieme et al., 2003). While before it was mainly oriented towards a defined curriculum (input orientation), the question of which learning goals should be achieved (output orientation) came more into focus. One of the goals had been to give teachers more space and freedom about how to reach different learning goals. Consequently, standard-oriented curricula were introduced, which may have the potential to shift teachers' professional perception to non-cognitive educational goals in addition to cognitive outcomes. For the next years, an important research agenda within STEM education will be to examine and discuss the connection between fostering multidimensional educational goals, the implementation of standard-oriented teaching, and teachers' professional competence.

We draw on these developments and argue that more balance between cognitive and non-cognitive learning goals is needed—at both the system and the school level. We introduce the concept of multidimensional educational goals and apply it to STEM. Using the example of Germany, we will outline how a change in educational policy perspective—from input to output—may facilitate this balance. We will discuss the potential and challenges of standard-oriented teaching for pursuing different learning goals. Moreover, we will briefly present a current research project studying these relationships, which will be linked to PISA 2022 in Germany.

MULTIDIMENSIONAL EDUCATIONAL GOALS IN STEM

Multidimensional educational goals provide a framework in which both, cognitive and non-cognitive outcomes, are presented. In contrast to cognitive outcomes, non-cognitive outcomes are characterized as constructs that are not identified with traditional indicators of cognitive capability or intellectual functioning (Rieger et al., 2017). According to multiple reviews and studies, these factors are essential for success in education as well as in occupation (Almlund et al., 2011; Kautz, et al., 2014) and they are important prerequisites for lifelong learning and an active participation in society (e.g., Prenzel, 2012; Schiepe-Tiska, Roczen et al., 2016). They shape the identity and personality of students and thus—together with cognitive outcomes—influence decisions about educational pathways (e.g., Parker et al., 2014). This is particularly relevant as the United States as well as Europe report an increasing need for STEM professionals at different levels of expertise (Cappelli, 2015; Cedefop, 2017). This trend is still growing with the worlds' change due to technological progress and digitalization.

Hence, in STEM education, non-cognitive outcomes are not only determinants of cognitive learning outcomes, but important educational goals themselves (see also Blossfeld et al., 2015; Schiepe-Tiska, Roczen et al., 2016). They influence whether students engage actively and of own accord in situations where science and mathematics competencies are necessary. Science provides the most profound explanations we have about our material world and the ability to reason mathematically and understand computational thinking concepts is important for keeping up with the worlds' change driven by new technologies. Hence, students need to recognize how important and significant STEM education is for their daily life *and* the society. Only when they feel meaningfully connected to STEM they are willing to engage with STEM and address ethical and political dilemmas such as climate change, develop critical orientations and thinking skills, and value scientific approaches to inquiry (cf. OECD, 2018b; OECD, 2020).

In the research tradition of science education, non-cognitive outcomes are mostly summarized under the umbrella term *attitudes*. Attitudes are an individual's affective, cognitive, and behavioral reactions towards an object or phenomenon (Rosenberg and Hovland, 1960). In science, they can be differentiated into *attitudes towards science* and *scientific attitudes* (Gardner 1975; Klopfer 1971; Osborne et al., 2003). Attitudes towards science refer to the affects, beliefs, and values students hold about an object such as school science or scientists themselves (Tytler and Osborne, 2012). They include constructs such as interest in and enjoyment of science, perceived value of science, or attitudes of peers and friends towards science (see also Schiepe-Tiska et al., 2016). Scientific attitudes refer to how students think about science. They display dispositions to look for material explanations and to being skeptical about many of these explanations (Osborne et al., 2003). For both facets, however, there is still no consensus about how many sub-constructs exist, how these can be classified, or how they can

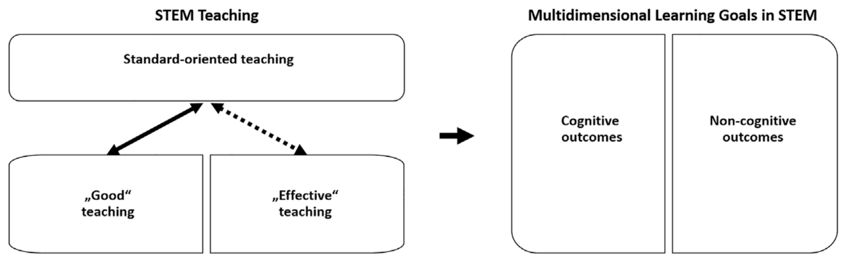

FIGURE 1 | The relationship between Standard-oriented teaching and Multidimensional Goals in STEM education.

be labeled and interpreted (see Kerr and Murphy, 2012 for a similar argument).

In contrast to science, in mathematics, the importance of attitudes is more hesitantly accepted (Hannula et al., 2016; Schukajlow et al., 2017). The most examined non-cognitive characteristic is mathematics anxiety (e.g., Strohmaier et al., 2020). It is a common phenomenon across countries, cultures, and ages and it massively influences students' mathematics achievement and their willingness to engage with mathematics beyond the school context (e.g., OECD, 2013; Schiepe-Tiska and Schmidtner, 2013). Other non-cognitive outcomes such as interest in mathematics or mathematics self-concept/self-efficacy are additionally important but less often examined. However, for example, for high-achieving students in mathematics, these motivational-affective characteristics explain why and how these students translate their potential into performance (Ziernwald et al., 2021).

From a practical perspective, one major challenge for STEM teachers when pursuing multidimensional learning goals is that they can influence or compete with each other. For example, in depth analyses of Germanys' PISA 2015 data showed that science teaching, providing students with cognitive activating learning opportunities, such as explaining ideas or drawing conclusions, as well as doing experiments was related to higher levels of science competencies as compared to teaching that is little cognitive activating and does not allow conducting own experiments. However, for enjoyment and interest, the picture was more differentiated. Only teaching that offered cognitive activating learning activities and the possibility of doing experiments more often was related to higher science enjoyment and interest. Cognitive activating science teaching with rare opportunities for doing experiments was less related to science enjoyment (Schiepe-Tiska et al., 2016). Hence, a balanced consideration of cognitive and non-cognitive learning goals is needed.

STANDARD-ORIENTED TEACHING

National educational standards formulate subject-specific and interdisciplinary cognitive basic qualifications that students in a country should have acquired by a certain point in their school careers (e.g., KMK, 2003; KMK, 2005). These standards mainly formulate cognitive learning goals but, in part, they also refer to non-cognitive outcomes.

One of the main learning environments to address multidimensional educational goals in STEM systematically is the classroom (see **Figure 1**). Normative, pedagogical principles and current standards play an important role in schools and describe features of "good" teaching (Berliner, 2005). For example, good science teaching is oriented at the idea of inquiry-based science teaching, in which students experiment and solve authentic science problems while learning the underlying scientific principles and developing corresponding concepts (Bruner, 1961).

In Germany, national educational standards were introduced as part of the educational reform in response to Germanys' poor results in STEM in the first participation in TIMSS and PISA (Baumert et al., 2001; Beaton et al., 1996). These standards are formulated for different levels of educational qualification. For example, in mathematics, the standards for the intermediate school leaving certificate state that "the mission of school education goes beyond the acquisition of cognitive skills. Together with other subjects, mathematics teaching also aims at personality development and value orientation" (KMK, 2003, p. 6). This multidimensional formulation of learning goals in relation to standard-oriented teaching is in line with initiatives in other countries such as United Kingdom, Canada, the United States, or Switzerland (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010; EDK, 2011; Department for Education, 2014; Ontario M. o. E., 2006).

Germanys' national standards represent not only a joint, mandatory framework for quality assurance of STEM teaching but also for the development of STEM teaching (KMK, 2010). Consequently, introducing the standards aimed at shifting the focus in teaching from being exclusively on the input, (i.e., learning and subject content) to more predefined, explicitly stated learning goals (i.e., output). Hence, the standards define requirements and liabilities that should be achieved at a particular point in time (Klieme et al., 2003), but in contrast to conventional curricula they are less detailed and do not prescribe in detail which topics have to be covered and how these topics have to be sequenced in particular (KMK, 2010). In theory, these standards can give teachers more freedom to choose how to reach learning goals as they "do not define the intervention methods or materials necessary to support students" (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010, p.4). Hence, they offer possibilities to focus on achieving cognitive and non-cognitive educational goals (KMK, 2010).

Orienting teaching at defined standards (in Germany called *competence-oriented teaching*), describes a new dimension of "good" teaching (Helmke, 2017; Müller et al., 2013; see **Figure 1**). However, it has rarely been tested empirically whether it is also a criterion for "effective" teaching (Berliner, 2005), that enables the achievement of multidimensional goals. Moreover, how standard-oriented teaching is related to other criteria of high effective teaching has also rarely been examined. One challenge is that, up to now, no consistent definition of standard-oriented teaching besides its focus on learning outcomes and the organization of learning as a cumulative process exists (Lenski et al., 2017). One suggestion for approaching a definition is made by Drieschner (2009), who describes four characteristics of standard-oriented teaching: 1) it establishes links between learning contents and real-life problems, 2) it encourages an active examination of a specific subject area, for example by enabling students to find several solutions or to formulate their own questions, 3) it reinforces social learning activities, and 4) it provides learning materials that are appropriate for students at different competence levels. However, again, the focus is more on reaching cognitive learning goals rather than taking a multidimensional perspective.

DISCUSSION AND FUTURE DIRECTIONS

The world of the 21st century is characterized by rapid developments - above all in technology. In order to deal with the resulting environmental, economic, and social challenges, it is educations' responsibility to equip future generations for the growing complexity as well as for dealing with increasing uncertainties (OECD, 2018a). Hence, education should not only focus on the development of subject-specific knowledge, but simultaneously on a broader set of skills, attitudes, and values. In STEM, a balanced pursuit of both cognitive and non-cognitive educational goals should be a central aim. In order to foster such multidimensional educational goals, they need to be addressed at different levels.

At the educational system level, although multidimensional goals are to some extend included in countries' national standards, standards' focus is still on developing knowledge that can be applied to different contexts and rather disregard non-cognitive learning goals (KMK, 2003; KMK, 2005). School laws and policies may name different non-cognitive goals more specifically, but they are still rather abstract declarations of intent and often a hodgepodge of characteristics (see also Blossfeld et al., 2015). Germanys' current PISA results reflect this flaw: Although, students' mathematics and science competencies were stable above the OECD-average (Reinhold et al., 2019; Schiepe-Tiska et al., 2019), enjoyment and instrumental motivation in both—mathematics and science—were below the OECD-average and declined between two PISA cycles (Schiepe-Tiska and Schmidtner, 2013; Schiepe-Tiska et al., 2016). This was also true for science self-efficacy. In order to enable a systematic development of multidimensional goals, first, they would need to be defined, classified, and specifically named for different developmental stages in countries' national educational standards.

At the school and classroom level, concepts of how to foster these goals explicitly together with and in addition to cognitive outcomes are needed. The teachers' mission is to transfer these goals into practice. For that, standard-oriented teaching can offer a fruitful and promising framework as it gives teachers more open spaces for designing their teaching and focusing on different learning goals. However, in order to enable them for pursuing multidimensional goals, awareness needs to be created by including them as mandatory part in teacher training curricula. Teachers need to be trained in identifying and evaluating multidimensional learning goals and to develop their diagnostic competences beyond students' achievement. Researchers could support teachers in that by developing suitable instruments focusing on identifying and evaluating multidimensional goals. Needless to say, teachers' own development of professional competence should be organized under the perspective of a multidimensional development so they can function as role models for their students.

In addition, specific recommendations and examples on how to implement striving for multiple goals in daily (subject-specific) classrooms are missing. One opportunity for the design of standard-oriented teaching, that may support teachers in addressing multidimensional goals, are tasks (Besser et al., 2013). Tasks play a prominent role particularly in STEM education (Knoll, 2003). In mathematics instruction, they represent central learning opportunities (Reiss and Hammer, 2013) that determine the course of instruction almost completely (Kuger et al., 2017). In science, (textbook) tasks play a somewhat less central, but still important role and are often used as lessons' supplements (Wendt et al., 2017). Tasks offer numerous possibilities to focus on real-life problems, initiate active and in-depth examinations, as well as social learning processes. Hence, they have the potential to offer learning opportunities addressing different cognitive and non-cognitive outcomes (e.g., Rellensmann and Schukajlow, 2017). However, an analysis of current German mathematics and physics textbook tasks showed that the theoretical opportunities for the motivational potential of tasks remain unexploited (Heinle et al., 2021).

From a research perspective, thus far, there is no evidence to what extent multidimensional goals are considered in current teaching practice. Our research project *"Classroom Experience, Characteristics & Outcome: Multidimensional educational goals and the views of students and teachers"* (Ceco) draws on this gap and examines the relation between multidimensional educational goals, standard-oriented teaching, and teachers' professional competence in mathematics and science by using a multi-method design (Ceco Team, 2020). We will investigate to what extend teachers consider different learning goals defined in PISA and nationals' educational standards while preparing and teaching their lessons and how this relates to the selection and design of tasks they use for learning vs. examinations. Linked to PISA 2022, Ceco supplements the international design of the PISA study in Germany with specific components at the input, process, and outcome levels. Two ninth grades as well as their mathematics and science teachers will be sampled additionally.

They will be visited in a mathematics and science lessons to assess teaching characteristics as well as motivational-affective learning goals in particular. In addition, tasks will be analyzed regarding their orientation on competencies defined in PISA and Germanys' national standards as well as their cognitive activating and motivational potential. The results will provide the opportunity to compare rather distal teaching and learning characteristics from PISA with more proximal characteristics in daily school life. Moreover, the link with PISA will enable examining aspects of achievement, motivational, and socio-economic heterogeneity of classes related to standard-oriented teaching and multidimensional learning goals.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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