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Exploring teachers' understanding and implementation of STEAM: one size does not fit all

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Introduction: In recent years, STEAM (science, technology, engineering, arts, and math) education has become an increasingly popular tool to promote student learning and engagement across disciplines. However, researchers and practitioners continue to note the lack of clarity around definitions of STEAM, its intended purpose, and the nature of discipline integration. In this paper, we explore teachers' understandings and implementation of STEAM as they participated in a teacher professional learning program.

Methods: Using a mixed-methods approach, we analyzed data from 4 years of program implementation with K-12 teachers across multiple schools and districts ($n = 61$).

Results: Participants' understanding of STEAM was deepened through their involvement in the professional learning program, with many reflecting on their initial, often shallow, (mis)conceptualizations of STEAM. Using an integration continuum developed by the authors, we identified ways in which integration varied across the STEAM lessons teachers developed, contextualizing these findings within the changing educational landscape of the COVID-19 pandemic, as teachers transitioned between remote, hybrid, and in-person instruction. Participants shared their reflections on the personal, professional, and contextual factors that supported and hindered successful STEAM integration.

Discussion: We found that, when provided with sustained, collaborative pedagogical and material support, teachers could successfully improve their understanding of STEAM and implement STEAM lessons tailored to their grade-level and disciplinary context. Our findings reinforce that teachers need support, autonomy, and flexibility to adopt an approach to STEAM integration that best fits their classroom and school context. We discuss the implications of these findings for researchers and practitioners working to provide effective STEAM teacher professional learning.

KEYWORDS

STEAM, art integration, interdisciplinary education, teacher professional development, mixed methods

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1 Introduction

STEAM (science, technology, engineering, arts, and math) education has gained increasing popularity across the globe over the last two decades (Lee and Chang, 2017; Marín-Marín et al., 2021). Studies in pre-college settings have shown that STEAM can increase students' conteeferent knowledge, increase intent to persist in STEAM spaces, generate positive attitudes toward STEAM, improve gender dynamics in the classroom, and help students connect disciplinary learning to their lives, interests, and communities (Peppler, 2013; Kong et al., 2014; Jeong and Kim, 2015; Engelman et al., 2017; McKlin et al., 2018; Lindberg et al., 2020; Wanzer et al., 2020; Hughes et al., 2022). Through professional training and support, teachers can develop instructional strategies that enable STEAM learning, such as approaches to integrating the arts and technology and the use of generative, formative assessment to allow students to explain ideas and develop new understanding (Herro and Quigley, 2016; Boice et al., 2021). STEAM instruction encourages teachers to step into a facilitator role, supporting student-led exploration, and to engage in collaborative relationships with their colleagues. STEAM education often demands that teachers utilize external resources and form connections with experts outside the school building to support STEAM implementation (Herro and Quigley, 2016; DeJarnette, 2018).

The same qualities that make STEAM an attractive avenue for authentic, integrated instruction can pose challenges for teachers. Collaborative STEAM efforts require dedicated time to plan and coordinate STEAM lessons and can be particularly challenging for teachers from different disciplines (Quigley and Herro, 2016; Herro et al., 2017; Boice et al., 2021). Finding time to effectively implement STEAM and managing the increased workload appear to be universal concerns, reported by studies across countries and cultural contexts (e.g., Park et al., 2016; Harris and De Bruin, 2018; Bertrand, 2019; Boice et al., 2021). Additionally, STEAM instruction can pose pedagogical challenges, for example, as teachers attempt to move toward a facilitator role in instruction (Quigley et al., 2019). Authentic STEAM assessment can be intimidating, as STEAM projects often involve student collaboration and require assessing the process, as well as the final product, as students iterate on their work (Opperman, 2016; Quigley and Herro, 2016; Herro et al., 2017).

In response to these challenges, the GoSTEAM@Tech teacher professional learning program was developed to support teachers' ability to implement collaborative STEAM lessons in K-12 contexts. The program, housed at the Georgia Institute of Technology, was first piloted in 2019 and implemented over subsequent years, adapting to changing COVID-19-related education policies and practices. In the program, STEM (science, technology, engineering, and math) and arts teachers, with support from university- and community-based partners, come together to design and implement STEAM lessons and initiatives in their schools. To support teachers' understandings of STEAM, researchers and practitioners collaborated to develop a working definition of STEAM within the GoSTEAM@Tech context and to create a continuum that articulates integration across the aspects of STEAM instruction. The purpose of this paper is to explore participating teachers' understanding and implementation of STEAM integration as they participated in this STEAM professional learning experience.

1.1 Defining STEAM integration

As STEAM education grows in popularity, the definition of STEAM continues to evolve. In their review of STEAM literature published between 2007 (widely considered to be the year "STEAM" was first coined by Georgette Yakman) and 2018, Perignat and Katz-Buonincontro (2019) highlight the many different perspectives on the nature of integration, role of the arts, and overall purpose of STEAM education. Though *arts integration* is a predecessor and close cousin of STEAM, some authors call for a distinction between the terms to avoid confusion and prevent the arts from being devalued in STEAM (Liao et al., 2016; Perignat and Katz-Buonincontro, 2019). When looking more closely at the meaning of the "A" in STEAM, the definitions of "arts" in STEAM range from specific visual or performing arts disciplines to the use of creativity or commonly-used teaching strategies in STEAM, such as problem-based, project-based, or technology-based learning (Perignat and Katz-Buonincontro, 2019).

The broad range of arts definitions in STEAM mirrors the varied purposes of STEAM. Ge et al. (2015) identified three purposes of STEAM in a selection of literature: using art to support STEM learning, using art to support the development of well-rounded students, and using STEM to support art. Similarly, Perignat and Katz-Buonincontro (2019) found that, within the literature they reviewed, the most common purposes of STEAM were either to advance STEM learning (especially for traditionally underrepresented populations) or to advance "domain general skills", such as creativity and problem solving (p. 34). A cross-cultural review of literature, policies, and practices related to STEAM in the United States (US) and Korea found that the purpose of STEAM differs across cultures (Lee and Chang, 2017). The authors state that in Korea, the purpose of STEAM is to increase students' intrinsic interest in math and science. Alternatively, the authors suggest that the purpose of STEAM in the US is to increase STEM scores on international assessments. Despite the differences between nations, a common purpose of STEAM in both countries is as a vehicle for enhancing STEM. This belief is pervasive across grade levels in the US with even early childhood teachers describing STEAM as a method for increasing engagement and interest in STEM amongst young students (Jamil et al., 2018). While the use of art to support the learning of a non-arts discipline is a common way of thinking about STEAM, arts advocates caution against this. Bresler (1995, p. 5) characterized this approach as a "subservient" style of arts integration (p. 5) and suggested that arts educators play a prominent role in STEAM initiatives to preserve the dignity of arts within STEAM learning, as have other scholars over the past decades (Bequette and Bequette, 2015; Liao et al., 2016; Katz-Buonincontro, 2018; Perignat and Katz-Buonincontro, 2019).

Labels like multidisciplinary, interdisciplinary, and transdisciplinary are being used in an attempt to categorize the varied definitions and purposes of cross-disciplinary work in STEAM. A transdisciplinary approach involves teaching STEAM in a way that transcends individual subjects, relying on skills from one or more disciplines to solve overarching problems (Quigley and Herro, 2016; Quigley et al., 2017; Perignat and Katz-Buonincontro, 2019). Transdisciplinary approaches often emphasize authentic, real-world connections that help students develop non-academic skills, like creativity or problem-solving (English, 2016; Bertrand and Namukasa, 2020; Caton, 2021). Interdisciplinary instruction, sometimes conflated with transdisciplinary instruction (e.g., Bertrand and Namukasa, 2020), represents the instruction of multiple disciplines to result in a new shared discipline in which knowledge and skills are deepened (English, 2016; Quigley et al., 2019). For example, the field of music technology reflects the interdisciplinary instruction of music, technology, and coding. In multidisciplinary instruction, teaching occurs in one or more disciplines to support a common theme or project, though the subjects are presented separately (English, 2016; Quigley et al., 2019). One could imagine this happening if, for example, a math teacher and visual arts teacher were to collaborate on a project in which the math teacher had their students work only on math-related aspects while the visual arts teacher had their students work only on arts aspects.

1.2 STEAM professional development

Studies indicate that STEAM professional development (PD) can grow teachers' interest in implementing STEAM (Yakman, 2017; DeJarnette, 2018). In a study by Yakman (2017), few participating K-12 teachers had started using STEAM in their classrooms before completing a STEAM PD training. After the training, 70% of participating teachers expressed that they would start implementing STEAM. An even larger percentage reported that, after the training, they felt positive or very positive about the future of STEAM education. Similarly, a study of early childhood teachers found that, after participating in two STEAM PD sessions, teachers' confidence planning and implementing STEAM lessons and their enjoyment teaching STEAM significantly increased (DeJarnette, 2018).

Despite this reported optimism, STEAM instruction can be a daunting intervention for teachers who may not have the resources, peer and administrative support, or necessary disciplinary content knowledge to implement STEAM in their classroom. Even with support, teachers can struggle to create transdisciplinary STEAM lessons grounded in problem solving and relevant to students' lives (Quigley et al., 2019). Furthermore, teachers report challenges implementing STEAM due to other teaching expectations, pacing needs, limited planning time, and restrictive school or district policies (Harris and De Bruin, 2018; Herro et al., 2019). Regardless, STEAM instruction may not require a complete overhaul of teachers' practices, but rather alterations to existing practices (Herro and Quigley, 2016).

Studies have found positive impacts of sustained teacher professional learning in STEAM on participating teachers and their students (Thompson et al., 2018; Quigley et al., 2019; Conradty and Bogner, 2020; Wong et al., 2023). A study of intensive STEAM interventions suggests that STEAM can have positive effects on teachers and the classroom environment when teachers have ample, ongoing support (Thompson et al., 2018). In particular, the authors studied the impact of ongoing support in STEAM on teachers' pedagogical discontentment, or the disconnect between a teachers' goals for their own pedagogy and their actual classroom practices. In the context of STEAM, pedagogical discontentment can occur when teachers lack adequate content knowledge or pedagogical skills associated with STEAM teaching. The authors looked at changes in K-12 teachers' classroom environments and pedagogical discontentment after 80 h of PD training and a year of partnership with STEAM coaches, with whom they collaborated two to three times each week on average. Classroom observations revealed positive changes in classroom environments to be more supportive of STEAM instruction. Additionally, there were significant decreases in teachers' levels of pedagogical discontentment, as assessed using a pre/post survey. Quigley et al. (2019) identified additional supports that allowed teachers to move from conceptualization to successful implementation of transdisciplinary STEAM, including collaboration amongst teachers, a problem-based learning approach, and flexible school and district policies to support flexible pacing and planning practices.

Importantly, teacher PD must help teachers understand and conceptualize STEAM in light of the varied STEAM approaches and definitions presented above. One study of Korean pre-service teachers revealed that, even after a semester-long course on STEAM integration in science classes, the teachers still expressed confusion about the difference between technology and engineering in a STEAM context and concern about finding suitable examples of STEAM lesson plans or resources to grow their knowledge of STEAM (Kim and Bolger, 2016). Thus, it is crucial to support teachers' understanding of STEAM before asking them to implement STEAM in their classrooms.

1.3 Program context

The GoSTEAM@Tech program was designed to support teachers in their understanding and implementation of STEAM through intensive summer PD, ongoing school-year support, and financial and material support (further described in Rao et al., 2021; Choi et al., under review[1]). During the summer PD, teachers engage in hands-on STEAM learning, visiting local community arts organizations, and collaboratively planning with other participating teachers from their school. During this time, teachers from each school develop a GoSTEAM@Tech Action Plan that articulates a STEAM unit or lesson that will be implemented during the school year. Throughout the year, teachers work to implement this plan with the support of a CEISMC coach and Innovator-in-Residence (hereafter, "Innovator"). Coaches are experienced former K-12 educators who provide pedagogical support and work closely with teachers and school administrators to facilitate teachers' ability to implement their Action Plan. One coach was assigned to each school district to promote opportunities to engage in vertical integration or inter-school

1 Choi, J., Usselman, M., Grossman, S., Boice, K. L., Jackson, J., Kessler, T., et al. (under review). Evolution of a STEAM teacher training program. *J. STEM Outreach.*

collaboration, when possible. Innovators, working 20 h per week at the school, support the development and implementation of STEAM lessons by bringing expertise from arts or technical backgrounds to the classroom. They work closely with teachers to create STEAM lessons based on teachers' standards, support lesson implementation by working directly with students, and use their existing networks to share resources or opportunities to engage with local artists or organizations. Participating teachers also have access to financial and material support to purchase relevant supplies or support fieldtrips.

Over the first 4 years of program implementation, 61 teachers participated in the GoSTEAM@Tech program, from a range of grades and disciplines (Table 1). In alignment with school district goals and the expertise of project personnel, GoSTEAM@Tech initially focused on the STEM fields of computer science, engineering, and invention and entrepreneurship, and the arts fields of performing arts (music, theater, dance), visual arts, and media arts. In year 1, STEM teachers were intentionally recruited to reflect the particular STEM focus of their district (e.g., computer science teachers were specifically recruited in schools focusing on computer science). In later years, as school-based teams increased in size, teachers were recruited more broadly across disciplines, but were still tasked with creating an Action Plan related to their district focus. As shown in Table 1, the number of participating teachers and the disciplines they taught fluctuated over the years, as teams recruited additional interested colleagues or teachers left the program and/or school. Because of the small number of arts teachers at most schools, in later years some teams did not include a dedicated arts teacher. In these cases, care was taken to place an Innovator with a strong arts background at the school to provide disciplinary knowledge.

Within the context of the GoSTEAM@Tech program, we sought to provide teachers with a clear understanding of STEAM, while recognizing the validity of different STEAM definitions and the important role of teachers in choosing a STEAM approach that works best in their classroom. During the development of the program in 2018, a working definition of STEAM integration was developed by researchers and program leadership, drawing on Bresler's (1995) levels of arts integration and the National Research Council's framework for STEM integration (Honey et al., 2014). These frameworks reflect inter- and transdisciplinary integration approaches, valuing cross-disciplinary integration in which multiple disciplines are given equal weight and applied for the purposes of creativity or problem solving. Additionally, in the absence of established STEAM integration best practices (Colucci-Gray et al., 2017; Katz-Buonincontro, 2018), we compiled a series of "high-quality lessons learned" (Patton, 2001) from the existing STEAM literature, reflected in our definition of integration. Thus, within the context of the GoSTEAM@Tech program, we define high-quality STEAM integration as "utilizing student-centered instructional pedagogies, including PBIL [problem-based, project-based, or inquiry learning], group learning, and real-world application, to increase cross disciplinary content knowledge through learning goals for students in both STEM and arts disciplines" (Boice et al., 2021, p. 5).

This definition is oriented toward a transdisciplinary approach to integration (Quigley et al., 2017), with its emphasis on both context (through problem solving and real-world connections) and content (by aiming to increase content knowledge in STEM and arts disciplines). While an important foundation for teachers' understanding, this definition was not used as a prescriptive approach to integration. Instead, the definition was shared with teachers at multiple points throughout their participation in the program and discussed in each summer PD. The PD included various workshops and activities designed to build teachers' ability to apply this definition of integration to their work designing collaborative STEAM-integrated lessons (as described in Rao et al., 2021; see text footnote 1). Importantly, teachers were encouraged to design STEAM lessons that used this integration approach, while considering their school context and possible constraints. This agency was crucial given past research on the importance of teachers' participation in the curriculum development process (Priestley et al., 2015; Baş and Sentürk, 2019). To further support teachers' conceptualization of STEAM, the research team developed the GoSTEAM@Tech Integration Continuum, designed to help teachers understand and assess STEAM integration evidenced in their Action Plans (Figure 1).

The Continuum was drafted in 2019, during the first year of program implementation. At that time, there were no established best practices in STEAM, as discussed above, and limited program evaluation data regarding integration within the GoSTEAM@Tech program. Thus, researchers and program staff were careful not to qualify different levels of the continuum as "good" or "bad." Instead, neutral language, such as "high/low" and "more/less frequent" were used, along with explicit reminders to teachers that the goal of the Continuum was to better understand what STEAM looks like *in situ*, rather than to shame or judge teachers for failing to reach levels of integration that may or may not be achievable within their school or classroom context. The Continuum was shared with program leadership and participating teachers over the course of the first and second year to solicit feedback. Initial feedback indicated that the Continuum could be a useful tool to help teachers reflect on the integration reflected in their Action Plan. Thus, the Continuum was used to support data collection around teachers' integration practices over the first 4 years of program implementation, as we will describe later.

1.4 Research question

Grounded in the emergent literature on STEAM integration and 4 years of evaluation data from a STEAM professional learning program, the purpose of this paper is to explore the following research question: To what extent does participating in a STEAM professional learning program impact teachers' (1) implementation and (2) understanding of STEAM?

2 Materials and methods

The data presented here were collected as part of an ongoing evaluation of the GoSTEAM@Tech program. The evaluation employed a mixed-methods triangulation design, using a parallel convergence model in which quantitative and qualitative data are collected and analyzed separately but results are compared to interpret the qualitative and

TABLE 1 Characteristics of GoSTEAM@Tech participants each year.

Category	Year 1 (2019–2020)	Year 2 (2020–2021)	Year 3 (2021–2022)	Year 4 (2022–2023)
Total schools in program	9	8	9	8
Elementary	4	2	2	2
Middle	2	2	3	2
K-8	1	1	1	1
High	2	3	3	3
Total teachers in program	17	26	35	31
Teachers per program track				
Invention and entrepreneurship (District A)	6	9	11	10
Computer science (District B)	7	10	17	17
Engineering (District C)	4	7	7	4
Grade level taught				
Elementary	8	8	8	7
Middle	3	6	14	10
K-8	2	3	2	2
High	4	9	11	12
Subject taught				
Arts[a]	8	10	7	4
STEM[b]	7	11	15	18
Other[c]	2	5	13	9
Years in program				
New to program	17	15	20	10
Returning for 2nd year	–	11	8	10
Returning for 3rd year	–	–	7	6
Returning for 4th year	–	–	–	5
M years of teaching experience (SD)	9.64 (6.82)	11.00 (7.05)	11.27 (6.59)	11.32 (7.75)

[a]Arts subjects taught included music, dance, theater, visual art.
[b]STEM subjects taught included math, science, engineering and technology, computer science, and STEM.
[c]Other subjects taught included English/language arts, world languages, social studies, general education (grades K-5), special education, or gifted education. This category also included participants who served as an instructional coach, rather than a classroom teacher.

quantitative findings together (Creswell and Plano Clark, 2007). Accordingly, we use data collected using quantitative (surveys) and qualitative methods (interviews and focus groups) over 4 years of program implementation. Data from these methods were analyzed separately but concurrently at the end of each school year, and then quantitative and qualitative findings were compared to inform the interpretation and development of results.

2.1 Participants

Of the 61 teachers who participated in GoSTEAM@Tech during the first 4 years of the program, evaluation data are available for 60 (98%). Characteristics of evaluation participants reflected those of the program participants (as described in Table 1) and included teachers from a range of grade levels and disciplines. Participation rates for each data source are illustrated in Table 2. End-of-year evaluation participation rates are based on only those teachers who were still involved in the program at the end of the school year, given that some teachers left the program mid-year for various reasons (e.g., retiring, changing schools, stepping away from program due to personal reasons, etc.).

2.2 Measures

2.2.1 Survey instruments

Online surveys were sent to participating teachers when they first joined the GoSTEAM@Tech program ("Background Survey") and at the end of each year in which they participated in the program ("End-of-Year Survey"). The Background Survey was designed to provide a baseline understanding of participants' teaching practices and understanding of STEAM, as well as gather information on current and former teaching experience.

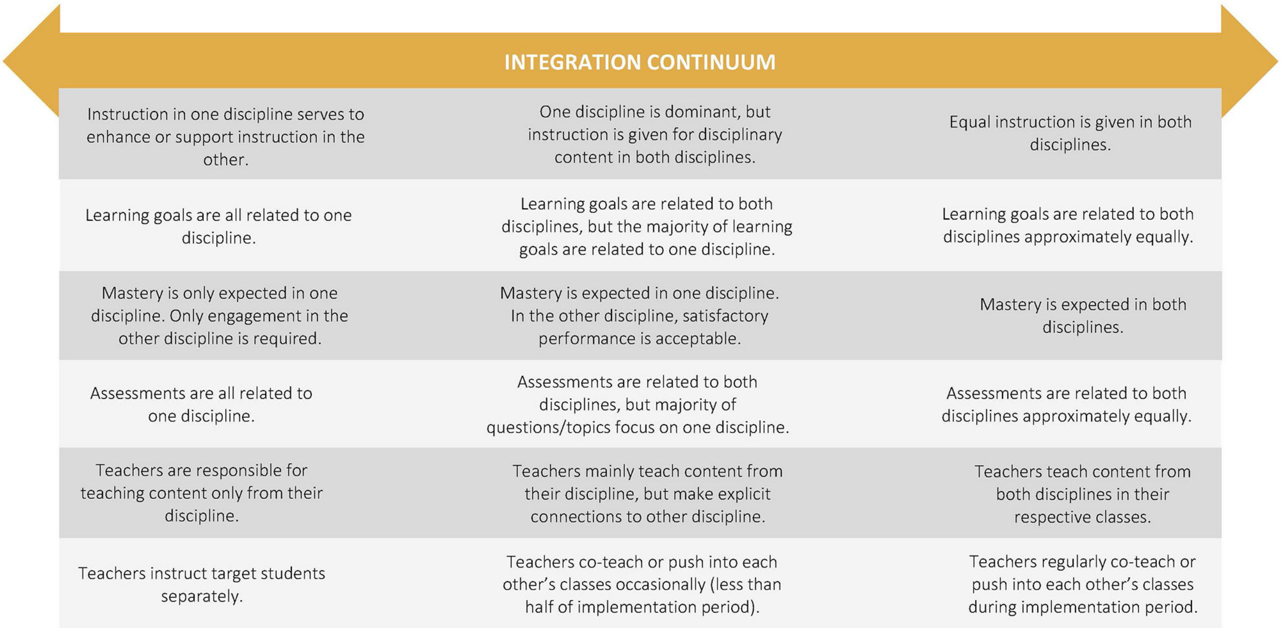

FIGURE 1
GoSTEAM@Tech Integration Continuum.

TABLE 2 Participation rates by data source.

Data collection tool	*n* respondents/*n* eligible participants (%)			
	Year 1	Year 2	Year 3	Year 4
Background survey[a]	14/17 (82%)	14/15 (93%)	19/20 (95%)	9/9 (100%)
End-of-year survey[b]	16/17 (94%)	21/26 (81%)	22/26 (85%)	23/29 (79%)
End-of-year focus group/interview[b]	17/17 (100%)	22/26 (85%)	21/26 (81%)	17/29 (59%)

[a]Only administered to teachers upon joining the program. Eligible participants include all new teachers who joined the program that year.
[b]Eligible participants include all teachers who were still involved in the program at the end of that school year.

The End-of-Year Survey also assessed participants' teaching practices and understanding of STEAM. In addition, it assessed teachers' perceptions of integration reflected in their Action Plans, developed based on Bresler's (1995) model of integration and the GoSTEAM@Tech Integration Continuum, as well as perceived impacts of participating in the program. More detail is provided in Table 3. All survey items presented here were developed by the evaluation team.

2.2.2 Focus group/interview tools

Each year, participants were invited to join a focus group with all current GoSTEAM@Tech teachers at their school. These focus groups typically lasted 45–60 min and involved two to four teachers, with some teachers participating in individual interviews based on their availability. A semi-structured protocol was developed to elicit responses from teachers about their perceptions of major components of the program, experiences implementing their Action Plans, perceptions of STEAM integration, and their experiences collaborating with other teachers. The protocol prompts were generally broad to encourage teacher reflection (e.g., "Please tell us about the STEAM integration within your Action Plan."). Each year the protocol was reviewed and revised as needed to include changes to the program or context. For example, questions were added to the protocol in 2020 to understand changes in instructional delivery due to COVID-19 disruption. Though the protocol always included items about teachers' integration perceptions and practices each year, additional questions were added in the fourth year of the program to prompt teachers to reflect on their integration practices using the GoSTEAM@Tech Integration Continuum as a guide. Teachers were shown the Continuum and told that "each row represents a different aspect of integration that may or may not be reflected within your Action Plan." Then teachers were prompted to reflect on each row of the Continuum specifically. For example, to explore integration present in instructional practices, teachers were asked "looking at the first row of the Continuum, how would you describe the level of integration of instruction?" After reflecting on each row in turn, teachers were asked "Are there any other ways in which you think STEAM integration was reflected in your Action Plan?"

TABLE 3 Survey topics.

Topic (no. of items)	Response scale	Example item(s)	Tool	
			Background Survey	End-of-Year Survey
STEAM teaching practices (6)	4-point scale from *never* (1) to *always* (4)	"I collaborate with other teachers at my school to develop interdisciplinary lessons that focus on STEAM or STEM."	x	x
Understanding of STEAM (1)	Open-ended	"How much experience, if any, do you have with STEAM? If you do have experience, please describe it." (Background Survey)/"How has your understanding of 'STEAM' changed since beginning the GoSTEAM@Tech program?" (End-of-Year Survey)	x	x
Perceptions of integration (3)	5-point agreement scale from *strongly disagree* (1) to *strongly agree* (5)	"My GoSTEAM@Tech Action Plan involved teaching content and skills related to both art and STEM."		x
GoSTEAM@Tech Integration Continuum (6)	For each aspect of the Action Plan, teachers were provided a description of low, moderate, or high levels of integration and asked to select the description that best matched their Action Plan	"Please select the choice that best describes your GoSTEAM@Tech Action Plan: (A) Learning goals are all related to one discipline. (B) Learning goals are related to both disciplines, but the majority of learning goals are related to one discipline. (C) Learning goals are related to both disciplines approximately equally."		x
Perceived impact of program (2)	5-point agreement scale from *strongly disagree* (1) to *strongly agree* (5)	"After participating in GoSTEAM@Tech, I have a better understanding of how to implement a STEAM lesson."		x

The Background Survey also included a series of items to collect information on participants' current and former teaching experiences (i.e., years of teaching experience, years of experience teaching in their current school, and subject and grades taught).

2.3 Analysis

Quantitative data were analyzed using descriptive statistics, such as means, standard deviations, and frequencies, to understand general trends and patterns in the data. When appropriate, inferential statistics (i.e., paired-samples *t*-tests and Cohen's measure of effect size) were used to understand change over time. The unit of analysis varied depending on the context. Individuals' perceptions and practices related to STEAM were analyzed using participants' first and last (most recent) available survey data. Practices and perceptions related to a specific Action Plan were analyzed by year, as these changed year to year based on teachers' goals and contexts. Open-ended survey responses were coded thematically to identify general themes.

Qualitative data collected through focus groups and interviews were audio recorded and transcribed. The data were coded using qualitative computer software. In the first 2 years of program implementation, the research team utilized a first- and second-cycle inductive coding strategy to thematically code the content of the data. Data excerpts were coded at multiple codes when necessary. In year 3, the codes developed in previous years were compiled to create a codebook. The codebook was used to deductively code the qualitative data collected at the end of year 3 and 4. A consensus building process was used to ensure consistent understanding of the codes, leading to the development of detailed definitions and categorization of codes. After discussing and refining the codes each year, the research team used qualitative analysis to identify patterns in the data, creating categories and subsequent themes.

To address the research question, researchers examined each years' codes and codebooks to identify codes related to STEAM integration. For instance, codes that referenced "integration," "STEAM understanding," "arts integration," or "content integration," were selected for further analysis. The corpus of the data was also reviewed for instances that may have referenced

STEAM integration in some way but may not have been primarily coded as related to integration. New codes were added, collapsed, or reassigned as necessary. To examine understanding around the GoSTEAM@Tech Integration Continuum discussed in year 4 focus groups and interviews, transcripts were qualitatively analyzed to examine the content of the responses and were categorized according to how closely the responses fit within the categories on the Continuum.

3 Results

In this section, we share qualitative and quantitative data that address the extent to which participating in a STEAM professional learning program impacted teachers' (1) implementation and (2) understanding of STEAM. We begin with findings on teachers' implementation of STEAM, evidenced through teachers' reflections on the integration present in their Action Plans and other STEAM units or projects implemented each year, as well as their perceptions of practices that may support STEAM integration. This is followed by results on teachers' understandings of STEAM, addressing how these aspects of their practice may have changed during the course of their participation in the GoSTEAM@Tech program. Throughout, we describe contextual and programmatic factors that may have impacted implementation and understanding.

3.1 Teachers' implementation of STEAM integration

3.1.1 Prior experience with STEAM

Before exploring the possible impact of program participation on teachers' implementation and understanding of STEAM, we first investigated their experiences with STEAM prior to joining the GoSTEAM@Tech program. The Background Survey prompted participants to share any prior experience they may have with STEAM education. The majority of participants (63%) were new to STEAM when they joined the GoSTEAM@Tech program. Some of these participants described past STEM or arts experiences separately, rather than describing the integration of STEM and arts disciplines. These responses were not considered evidence of past STEAM experience, as they did not reflect integration of arts and STEM disciplines. Those who were familiar with STEAM prior to joining the GoSTEAM@Tech program described participating in STEAM PD or teaching at a STEAM-certified school. Others shared examples of STEAM projects or lessons in their classrooms, describing specific subjects that they integrate into their core content area (e.g., "*I do have a little experience in incorporating technology and the arts into my lessons for history.*"; "*To fully understand music and specifically the discipline of music, I've integrated mathematics, language arts, geography, science and culture.*"). Others shared vague examples of their STEAM practices or indicated that their work with "*PBL*" was evidence of STEAM (e.g., "*General implementation of PBL and STEAM lessons in my classroom.*"). Thus, despite a substantial minority of participants describing past experiences with STEAM, not all of these respondents provided specific descriptions of their STEAM experiences.

3.1.2 Integration enacted through STEAM lessons

GoSTEAM@Tech teachers were expected to implement an Action Plan each year with their students. Thus, we explored the level of integration reflected in Action Plans and lessons to understand the nature of STEAM implementation among GoSTEAM@Tech teachers. On the End-of-Year Survey, participants were asked to rate their agreement with statements about their Action Plan for the year. Responses each year were averaged to provide a descriptive understanding of integration with the Action Plans over time. In general, participants felt their Action Plan incorporated STEAM integration, agreeing, on average, that their Action Plan involved teaching content and skills related to both art and STEM, promoted students' ability to make connections between arts and STEM disciplines, and required students to critically reflect on their STEAM projects (Table 4). The exception to this was in year 4, when participants neither agreed nor disagreed, on average, that their Action Plan required students to critically reflect on their STEAM project(s). Overall, average agreement with each statement decreased each year.

Participants were asked to further reflect on the nature of integration in their Action Plan using survey items developed based on the GoSTEAM@Tech Integration Continuum. Mirroring the trend shown in Table 4, the percentage of respondents indicating that their Action Plan reflected high levels of integration decreased over time (Figure 2). This was particularly apparent in integration ratings of instruction, with 75% of participants indicating that their Action Plan reflected equal integration in both disciplines in the first year of the program (the 2019–2020 school year), while only 10% of participants reported this high level of instruction integration in the fourth year of the program (2022–2023). Similarly, learning goals, mastery expectations, and assessment practices showed a steady decrease over time in the percent of participants who reported high levels of integration in these areas. This trend could be a true reflection of decreasing levels of integration or could reflect the increased presence or awareness of barriers to integration or changing understandings of integration over time.

The following qualitative findings are presented by year to describe participants' perceptions of the STEAM implementation reflected in their Action Plans and how this may have changed over time.

3.1.2.1 Year 1 (2019–2020): a starting point for STEAM

The first year of GoSTEAM@Tech program implementation was cut short in March 2020, as schools closed in response to the COVID-19 outbreak. However, teachers described successfully implementing Action Plans and lessons prior to school closures. The scope of teachers' Actions Plans varied from brief activities implemented in one classroom over the course of a few class periods to semester- or year-long projects involving student collaboration across classes. For example, in one fourth grade class, an art teacher and general education teacher designed a week-long Action Plan in which students used information about the relationship between balanced and unbalanced forces to create a "pendulum painter." Using the pendulum painter, students worked in groups to create a painting, hypothesizing how gravitational force would affect the motion of the pendulum, and thus the artwork. At other schools, Action Plans spanned multiple weeks, such as at one middle school,

TABLE 4 Teacher perceptions of their action plan.

"My GoSTEAM@Tech Action Plan…"	*Mean (SD)*			
	Year 1 ($n = 16$)	Year 2 ($n = 21$)	Year 3 ($n = 21$)	Year 4 ($n = 22$)
…involved teaching content and skills related to both art and STEM.	4.63 (0.50)	4.38 (0.50)	4.29 (0.56)	4.18 (0.59)
…promoted students' ability to make connections between arts and STEM disciplines.	4.56 (0.63)	4.29 (0.72)	4.24 (0.54)	4.14 (0.64)
…required students to critically reflect on their STEAM project(s).	4.56 (0.51)	4.19 (0.68)	4.14 (0.57)	3.95 (0.72)

Participants rated their responses on a 5-point scale from *strongly disagree* (1) to *strongly agree* (5).

where music and science teachers designed a semester-long Plan to help students explore issues related to water conservation. Using the coding platform Earsketch, students created songs that could be used during showering to limit water usage to just 2 min. In addition to using coding and music theory skills to compose their songs, students also used technology and design principles to make posters with LED lights, *t*-shirts, and printed pamphlets to help local businesses understand the importance of water conservation. Students work and musical compositions were displayed in a final showcase at the end of the semester. Across schools and projects, teachers noted that STEAM implementation required an awareness of other content areas, which necessitated collaboration among teachers from different disciplines. For some teachers, STEAM implementation was daunting because of the need to meet standards in their content area, while addressing standards in other areas. Timing and pacing were particular concerns for teachers trying to integrate multiple subjects, as one math teacher described, "*…my concern was how to do that and still cover all the standards. How can I incorporate both? Stay on pace but also make sure that the lessons that I present are project-based.*"

At one high school, teachers described the frequent collaboration necessary to plan, implement, and, occasionally, co-teach a technical theater experience for students in their theater, dance, and engineering classes. The performing arts teacher described the project as "*fully integrated*" because of this collaboration,

> *I would say that [the Action Plan] was fully integrated, because we taught the students together. And really looked at the standards together, at that point. …So, the full integration I would say is [during] second period because you have two masters of content teaching them at the same time. And you have students that kind of came in with separate ideas of what the class was going to be, so that's what I mean by that, is that we tackled each project together, and our timeline was together, and our physical time was together.*

In this example, not only were the classes being taught together, but students in the arts and engineering classes were expected to become proficient in each other's content to support work on an overarching project, reflecting a transdisciplinary approach to integration. For this school, the result at the end of the year was the early stages of a possible new course, which incorporated theater, dance, engineering, mechatronics, and audio/video production. GoSTEAM@Tech's emphasis on collaboration to support discipline integration was especially notable for teachers who had prior experience with STEAM. At one elementary school, teachers described previous attempts to implement STEAM projects at the school as "*haphazard*" and lacking intentional planning. One teacher from this school stated that, before GoSTEAM@Tech, "*for the most part, there was never a true planning with the arts and the content teacher.*" At the same school, a music teacher described the need to move beyond shallow interpretations of STEAM and develop a deep understand of content and standards in other disciplines. The teacher stated,

> *It's easy to say, "Oh, we can come up with a song." But do you have parameters for that song? Do you have a parameter for the standard of writing a melody that needs to match this because melodies are all about frequencies on a particular pitch level? You know what I mean? They're not thinking about it in that... They're thinking of it, oh look, rap to this. Okay, well if you're rhyming a rap, are you teaching subdivision and how it meshes with meter and subdivisions? Are you teaching them that side of the math and how it connects to the music? You know what I mean?*

The music teacher quoted above discussed a need for content area teachers to become more "*versed in the arts standards because half of the time a lot of teachers just think that arts mean visual arts.*" Similarly, at one school implementing schoolwide STEAM projects, the middle-school music teacher described a "*deeper interaction of the arts within every core subject*" as they implemented their Action Plan. These and other arts teachers expressed a certain validation from GoSTEAM@Tech's emphasis on applying the arts in a deeper and more meaningful way rather than just as an embellishment for STEM instruction.

3.1.2.2 Year 2 (2020–2021): implementing STEAM in difficult times

In the second year of GoSTEAM@Tech, the COVID-19 pandemic impacted teachers' time, resources, and collaboration opportunities, and thus, STEAM integration. GoSTEAM@Tech staff adjusted the support and expectations for GoSTEAM@Tech teachers during the 2020–2021 school year to ensure that teachers could still feel successful implementing their Action Plans while navigating the new and unprecedented challenges of the school year (Rao et al., 2021). Teachers described the impacts of COVID-19 on their STEAM implementation as they developed (or redesigned) their Action Plans for virtual instruction.

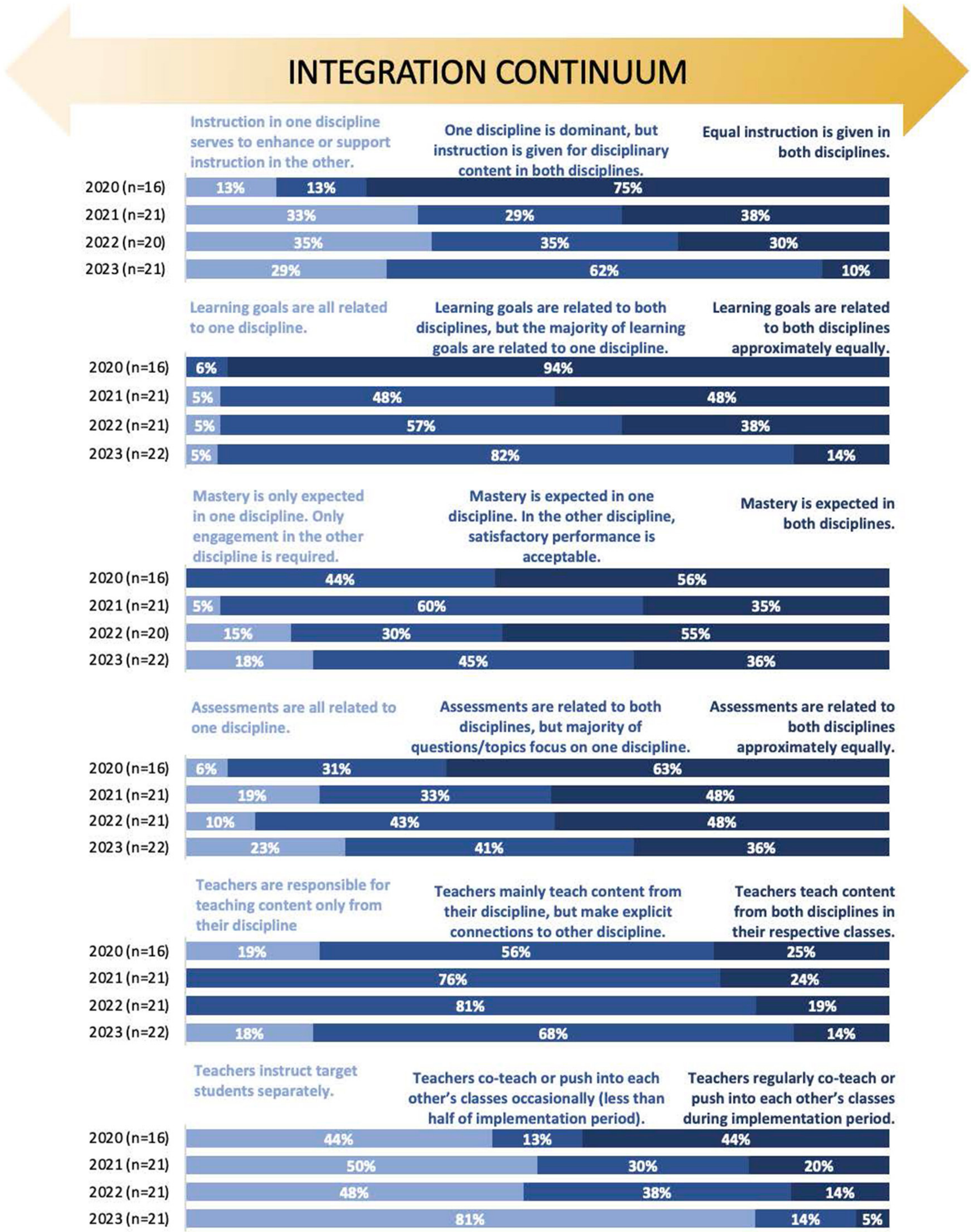

FIGURE 2
Survey responses to GoSTEAM@Tech Integration Continuum items.

While there was less evidence of co-teaching or collaboration during STEAM instruction, teachers still implemented STEAM projects within their own classrooms and collaboratively planned with their GoSTEAM@Tech teams. In year 2, teachers described a broadening approach to discipline integration to include more subjects in each STEAM project. One participant described this mindset shift, such that, rather than teaching subjects in "*isolation*," they tried to incorporate "*as many of those letters [in STEAM] in as many lessons as I can*." This could be a reflection of a change in the program to recruit a broader range of teachers to the GoSTEAM@Tech program at each school, involving teachers who taught disciplines outside STEM and arts fields. Some teachers stuck to integrating traditional STEAM disciplines, such as one teacher who implemented a "*water bottle project*" involving math, science, and music content. Students made adjustments to the size of bottles and amounts of water to develop an understanding of the *"connection between pitch, amplitude, frequency."* However, other teachers described an expansive view of STEAM that involved other, non-STEM or arts disciplines, such as social studies and language arts. For example, at the same school, a science teacher, despite some past training in content integration, described a new approach to implementing STEAM after participating in GoSTEAM@Tech that involved non-STEM or arts disciplines:

> *I have probably learned more about content integration than I have... when I was getting certified to become a teacher. You have those integration classes and they tell you make sure you mention this. I could blend the science with the social studies because I knew I could talk about soil and I could mention the soil over in this country and the soil in that country. But it was still always more in isolation. Now if I were to teach that lesson it would include a lot more than just the soil. We might bring in the music of that country, we might bring in just everything, we could look at things mathematically, we could look at things scientifically, we could look at things statistically to all be in that one lesson. And in the ideal world, that music teacher and I would be trying to work on the same concepts, if not simultaneously at least in reference.*

Similarly, one teacher, who was in the role of instructional coach, shared their efforts to support other teachers implementing STEAM, even if those teachers were not an arts- or STEM-discipline instructor:

> *"Hey, if you're teaching the Industrial Revolution, that's inventions, so have them create inventions." So that's how we can fit that. So really brainstorming with them, letting them know it's not just geared toward math and science teachers, that we can make it fit to what you do.*

3.1.2.3 Year 3 (2021–2022): a shifting purpose of STEAM

In year 3, the GoSTEAM@Tech program staff continued the practice of allowing additional teachers, not just one STEM and one arts teacher, to join GoSTEAM@Tech. Though this practice began in year 2, year 3 marked the year in which the largest percentage of participating teachers were neither STEM nor arts teachers, instead representing disciplines such as social studies, language arts, and K-5 general education, for example. Because these teachers were not focused on primarily providing STEM or arts instruction, they brought richness to the conversation of STEAM implementation. One high-school teacher stated,

> *I'm a US history teacher and trying to understand how STEAM and STEM fit all together and that it, you know, how I could incorporate myself in there. It was a stretch at first, you know. So going through the program helped me kind of see really more big picture, how it all goes together, but I didn't have any experience before that.*

The teacher went on to describe the Action Plan that they implemented, connecting their history standards with the arts and innovation: "*The Harlem Renaissance is all about art integration, right? Yeah. It's about the music. It's about the music, the arts, poetry, all that education. In addition to the innovation that was going on during that time.*"

Some Action Plans were designed around projects that teachers described as inherently integrated. This was evident in a conversation about the work at one GoSTEAM@Tech school to continue developing a technical theater experience, started in year 1 of the program. In year 3, the corresponding Action Plan involved four teachers and integrated theater, mechatronics, physics, dance, mathematics, and audio/video technology to support set design, choreography, sound design, and costumes for a theater production. The theater teacher at the school described how teachers collaborated on the Action Plan design, but implemented STEAM separately in their individual classes, with each GoSTEAM@Tech teacher working "*in everybody's independent content, we were all addressing the standards through what our project was.*" This is a notable difference from the co-teaching that occurred during year 1, when this school first attempted a technical theater experience, and perhaps reflects the involvement of more teachers and post-COVID time and space constraints. However, the theater teacher described the inherent need for integration in the Action Plan "*because theater is such a multidisciplinary activity that you're hitting a lot of things all once.*" They also described a subservient use of the arts to support STEM (Bresler, 1995), stating "*… and I always explain that, I find the arts is a vehicle for, to apply STEM-related processes and thinking.*"

The conversation around STEAM implementation in year 3 focused heavily on leveraging STEAM to promote creativity and engagement. One high-school teacher described a student-led approach to decision making throughout their STEAM project to promote "*… all of this is creativity, you know, and I try to give them as much freedom as possible, when those decisions are made.*" An elementary teacher described the utility of STEAM integration to highlight student interests and "*gifts.*" This teacher stated,

> *Some students are, you know, have different gifts when it comes to art and art integration or different interests when it comes to art. So it just gives you that ability to look at art and its addition to the classroom in more than just one stagnant way.*

STEAM provided a creative outlet for students to "*truly express themselves in ways that they never, that they possibly never would've thought of by simply having a conversation to write or just write something down.*"

During STEAM projects, teachers leveraged students' interest and creativity to help them demonstrate their learning in creative and generative ways. Teachers recognized the opportunity for students to explain and demonstrate new knowledge in more engaging ways in STEAM projects, compared to traditional assessments, as one middle-school teacher explained,

> *And it, again, it lets them know that no, we're not just going to give them paper, pencil tests, or computerized tests to, you know, to be able to say they've mastered it, but give them different ways of showing it. And when you can show kids that STEAM, all of it is involved in everything that we do, you know, to me, it just makes it where it's not another activity or chore, but it is, it brought it, their understanding of it, altogether.*

Another elementary school teacher highlighted the use of STEAM to help students represent their learning through an animated timeline developed in Scratch, an online coding software. The teacher noted the engagement and interest from students in the project,

> *But for them to actually take, you know, some of the things that they're seeing on the paper that I give to them do more research. And then they were able to animate a timeline of the information that we were learning. So every time we learned something new, we would add that to our timeline and the kids would, you know, during lunch, "Can I get on? Can I get on Scratch?"*

The use of STEAM integration to promote student creativity and engagement is interesting when situated in the context of a post-pandemic school year. In year 3, teachers described navigating increased standardized testing, demands for remediation, and pressure to cover standards quickly. Teachers' contrasts between traditional forms of assessment and instruction with STEAM implementation seems to indicate an appreciation for STEAM as a mechanism for teaching that emphasizes student creativity, agency, and engagement.

3.1.2.4 Year 4 (2022–2023). STEAM in theory and in practice

As in year 3, teachers discussed various purposes of implementing integrated STEAM lessons. One secondary science teacher described using their Action Plan to move beyond their prescribed standards to build students' awareness of injustices facing their community:

> *This project allowed me to dig into like the environmental justice portion. There's not necessarily enough standards, so I was able to like to collaborate and just do some refresh on, just like the history behind environmental injustices, and how certain spaces and some places are not given enough resources to access the things that are like the basic necessities for life, and have my kids kind of use art and things like that to raise awareness to those injustices and stuff... If I didn't do GoSTEAM@Tech, I would not have like stretched my mind to think outside of just teaching according to the standards.*

Sometimes teachers who worked collaboratively on the same Action Plan described different purposes of the Plan. For example, at one elementary school, one teacher described the Action Plan as a way to incorporate engaging projects that would help students better understand issues in the local community. This teacher stated, "*...all the activities, like for me it also allowed me to be more creative because I felt that with everything that they did, they had to have some type of project.*" Another teacher at the school described an additional purpose of their Action Plan to promote STEM learning, stating, "*we incorporated the technology, the math and everything, had to measure everything within their community, showing everything that they learned within STEM.*" Similarly, a high-school engineering teacher used their Action Plan to promote STEM learning. In this Action Plan, a small group of students designed and constructed an instrument in their mechatronics class. While the project had an "*art output*" (i.e., the instrument), the project itself was designed to teach the mechatronics standards and did not emphasize arts standards or content. These varied purposes of STEAM reflect a nuanced awareness of how to use integration to support students' agency to address injustice, implement problem-based learning approaches, and achieve discipline-specific learning goals. However, these examples also highlight a de-emphasis of the arts compared to the first years of the program, in which focus groups frequently involved the discussion of specific arts standards and goals reflected in Action Plans.

During the fourth year of the program, the GoSTEAM@Tech Integration Continuum was used in focus groups to guide discussion of the nature of integration reflected in teachers' Action Plans. Mirroring the survey results for year 4, participants described low or moderate levels of integration in each domain of the Continuum (referencing the far left and middle columns of the Continuum shown in Figure 1). When describing their Continuum ratings in focus groups, teachers noted a gap between the level of STEAM integration they hoped for in theory and the level of integration they achieved in practice, illustrated by the quotes shared in Table 5.

Looking at the Continuum in focus groups resulted in discussion of how integration is also reflected in student collaboration and interactions. For example, one teacher described their "*ideal plan*" for integrating music, technology, and theater into an Action Plan, in which students from different disciplines would work collaboratively on a school play. Scheduling constraints prevented students in different classes from collaborating, though they were still able to develop projects that integrated music and technology that were used in the school play. In their description of integration reflected in their Action Plan, one teacher from the school defined "*true*" integration as students learning together across disciplines with instruction occurring simultaneously in an integrated context,

> *...but I think it's because, like we didn't really do a true integration where like his students working side by side with my students. Like I guess the ideal plan would be we're all in the music tech lab together, finding the sounds, mixing the sounds together, et cetera. ...It's not the true GoSTEAM@Tech integration that I think people are looking for.*

The focus group findings shed light on the decreasing trend in integration ratings on the survey each year (Figure 2) by illustrating that, ideally, teachers would have liked to provide equal integration across disciplines, but this was not always possible in practice, primarily due to the content expertise of the teachers and constraints of instruction (i.e., scheduling, limited collaboration, or subject area priority). Thus, in year 4, teachers seemed aware of what was required for high levels of STEAM integration, but faced challenges that prevented them from achieving this.

3.1.3 Practices that supported STEAM implementation

In describing the integration reflected in the STEAM projects they implemented, teachers describe practices that supported or

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TABLE 5 Focus group excerpts illustrating continuum ratings.

Continuum domain	Illustrative quote(s)
Instruction	*"I would say we focused basically on science because we had to get the science grades, but we incorporated the other disciplines when needed. . . . but science was the major discipline that we focused on because we had to make sure that they, we taught each standard that they had to learn for science."* *"I think the challenge becomes, teachers being able to lift both disciplines. . . . I think, like, I said, we're doing some of this stuff. But again, I would love it if we were able to push all the way to the right, because I think we're trending more in the middle."*
Learning goals	*"After talking about it over the summer, we just realized it's hard.... It's just not part of the standards that they would teach."*
Mastery	*". . . mastery is expected in one discipline. The others, satisfactory acceptable."* *"I mean, we expected it to be across the board, mastery in everything. But that's just not what happened."*
Assessment	*". . . they were assessed, but it was within each individual discipline."*
Teaching content	*"I think sometimes we can get so focused on what we're supposed to be teaching, that bringing in other subjects intentionally may seem foreign because of the- the standards that need to be taught."* *". . . teachers teaching their own content. So, kind of, we were kind of focusing on our area."*
Teacher collaboration	*". . . physically, I think it would be column one, but interactively, . . . it'd be columns two and three. We talk and pass, and we have a group chat. . . and as I walk down the hallway. I hear things and things that I can implement in my class. . ."* *"Collaboration is valued, but it doesn't always happen in an integrated way."*

hindered their ability to implement STEAM instruction, including collaboration and developing content knowledge outside their domain to promote integration. Though these came up in focus group conversations, we also asked participants to rate the frequency with which they engaged in teaching practices that support STEAM instruction using surveys to measure possible changes over time. We compared participants' responses before the program (as reported on their Background Survey) and after the program (as reported on their final End-of-Year Survey, during the last year they participated in the program). Before the program, participants reported engaging in some STEAM teaching practices more regularly than others, but almost all participants reported in engaging in each of the practices at least "sometimes" after the program (Figure 3).

A paired-samples t-test revealed statistically significant differences in some items before and after participating in the GoSTEAM@Tech program (Table 6). The large effect sizes associated with these differences indicate that the differences are likely meaningful in practice, in addition to being statistically significant. Encouragingly, the items where a significant difference was found are also the ones that describe teaching practices specific to the integration of STEAM disciplines.

These survey results reinforce qualitative findings, indicating that teachers engaged in certain teaching practices to support STEAM integration, and that collaboration was especially important for successful STEAM implementation. The reports of frequent engagement in STEAM teaching practices are interesting considering that teachers, on the whole, reported lower integration levels in their Action Plans over time, as shown in the GoSTEAM@Tech Integration Continuum ratings.

3.2 Teachers' understanding of STEAM integration

We analyzed quantitative and qualitative data to describe teachers' understanding of STEAM during their participation in the GoSTEAM@Tech program. Using data from participants' most recent End-of-Year Survey, we investigated perceived changes in their ability to implement and assess a STEAM lesson. On average,

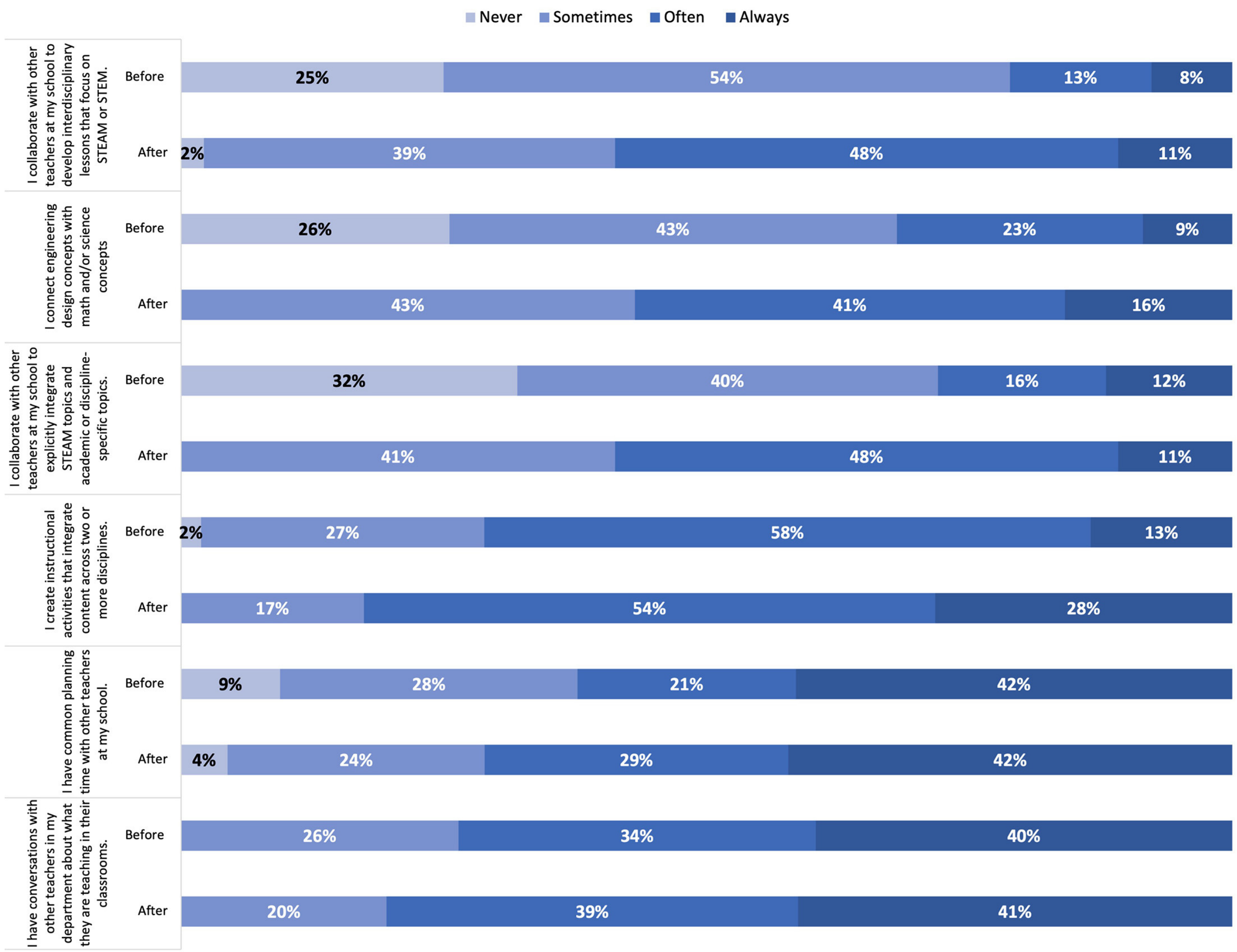

FIGURE 3
Frequency of STEAM teaching practices before and after program.

teachers agreed (a 4 on a 5-point scale) that, after participating in GoSTEAM@Tech, they have a better understanding of how to implement ($M = 4.47$, $SD = 0.58$) and assess a STEAM lesson ($M = 4.36$, $SD = 0.64$). This finding is reinforced by focus group data, in which teachers described an evolving understanding of STEAM. Following the first year of the program, teachers were already reconsidering prior conceptions of STEAM and described new perspectives and evolving definitions of STEAM. Teachers credited the summer PD with helping them develop their understanding of STEAM, particularly because of the exposure to other disciplines and new ideas for STEAM integration, as one high school computer science teacher described after their first year in the program, "*for me, that was very impactful because I didn't even think about doing those things with music technology and computer science.*"

Each year, teachers continued to describe the impact of GoSTEAM@Tech on their understanding of STEAM as a mechanism for authentic instruction that connects disciplinary learning to real-world issues, reflecting a transdisciplinary approach to STEAM (English, 2016; Quigley et al., 2019). One performing arts teacher stated in year 1, "*GoSTEAM@Tech allowed me to shift my focus to more of what is authentic teaching.*" Similarly, in year 2, a middle-school music teacher stated that the program helped them understand "*enrichment as opposed to just using the arts to enhance everything else. . . . It's not just about music for the sake of music. It's about everything and how it all comes together for one purpose.*" In year 3, teachers understood STEAM as a powerful tool for engaging students in design-based thinking, problem-based inquiry, and project-based learning. One teacher stated,

> *. . . it really does engage students in a way, and it makes them learn while having fun. And I think, you know, that's the biggest thing. I think they genuinely are learning and they're enjoying the learning that they're doing and they're taking ownership of their learning.*

Engagement was central to teachers' understanding of STEAM in year 4 as well, with one teacher stating, "*GoSTEAM@Tech's just made me more mindful in my teaching each day trying to*

TABLE 6 Changes in average teaching practice frequency.

Item	*Mean* (*SD*) Before	*Mean* (*SD*) After	*t*(*df*)	Cohen's *d*[a]
I collaborate with other teachers at my school to develop interdisciplinary lessons that focus on STEAM or STEM.	1.90 (0.75)	2.67 (0.74)	5.93 (38)*	0.81
In my courses, I connect engineering design concepts with math and/or science concepts.	2.03 (0.88)	2.78 (0.76)	5.35 (35)*	0.84
I collaborate with other teachers at my school to explicitly integrate STEAM topics and academic or discipline-specific topics.	1.89 (0.89)	2.68 (0.66)	4.21 (37)*	0.93
I create instructional activities that integrate content across two or more disciplines.	2.85 (0.70)	3.08 (0.66)	1.65 (39)	–
I have common planning time with other teachers at my school.	2.85 (1.10)	3.05 (0.93)	1.27 (39)	–
I have conversations with other teachers in my department about what they are teaching in their classrooms.	3.15 (0.83)	3.20 (0.76)	0.34 (39)	–

Responses were rated on a 4-point scale, from *Never* (1) to *Always* (4). Responses of "not applicable" were not included in the analysis.
[a]Cohen's *d* is provided only if paired-samples *t*-test was statistically significant.
*$p < 0.001$.

find more innovative ways to make the lesson more engaging for the scholars."

Teachers who participated in multiple years of the program reflected on their understandings of STEAM before joining GoSTEAM@Tech, noting the work involved in changing their understanding over time. One teacher, upon finishing their fourth year in the GoSTEAM@Tech program, stated, *"I think for a long time we were operating just by saying, 'we're STEAM,' and not really knowing, as a school, not really having much knowledge around what that looked like."* Another teacher in their third year of the program described their initial understanding of STEAM as an "*add-on.*" In the subsequent years, through the projects and professional learning, the teacher explained, "*[STEAM]'s definitely kind of infused its way into my general curriculum, but it's been a process in getting there.*" Indeed, teachers in year 4 were cognizant of the "*intentional planning*" necessary to integrate multiple disciplines within the STEAM projects. This speaks to a heightened awareness of the depth of STEAM instruction that GoSTEAM@Tech teachers developed, as well as teachers' honest reflections on the effort and work it took to implement a deeper, more integrated STEAM approach in their practice.

4 Discussion

The purpose of this study was to understand the extent to which participating in a STEAM professional learning program impacted teachers' (1) implementation and (2) understanding of STEAM. Results suggest that most teachers entered the program with no prior STEAM experience or, after participating in GoSTEAM@Tech, noted that their previous STEAM efforts lacked intentionality, understanding, or support. By the end of their time in GoSTEAM@Tech, teachers reported regularly engaging in practices to support STEAM implementation, such as collaboration and content integration, and felt the program had positively impacted their understanding of how to implement and assess a STEAM lesson.

Each year of GoSTEAM@Tech, teachers described Action Plans and STEAM lessons that they implemented, reflecting various levels of discipline integration and varied purposes of STEAM. The GoSTEAM@Tech Integration Continuum was used to identify how teachers were integrating different disciplines in their instructional and assessment practices. In year 1, teachers reported high levels of integration using the Continuum and described in-depth knowledge and appreciation of arts standards. In the following years, Continuum ratings dropped, with teachers reporting lower levels of integration. However, they continued to engage in integrated STEAM instruction. Beginning in year 2, focus group data revealed an intent to include STEAM instruction in as many disciplines as possible, often facilitated by technology tools. This likely reflected a programmatic change to involve teachers from multiple disciplines in the GoSTEAM@Tech program. In years 3 and 4, teachers began to describe the purpose of STEAM more broadly, emphasizing the role of STEAM in promoting engagement and allowing their students creative freedom. Teachers also described assessment practices in STEAM that allowed for a holistic, generative approach to assessment. Thus, while the Continuum ratings of content integration in years 3 and 4 reflected lower levels of integration, teachers described goals for STEAM that transcended disciplinary instruction. Particularly in year 4, teachers spoke of an aspirational vision of a "*fully integrated*" STEAM project or "*true*" integration, involving collaboration (among teachers and occasionally among students) across disciplines, real-world problem-solving, and student agency and engagement, reflecting the qualities of a transdisciplinary approach to STEAM (Quigley et al., 2019). Taken together, these findings could reflect that the program helped teachers develop a deeper understanding of STEAM and intentionality around integration, though their ability to provide integrated STEAM instruction in the manner they aspired to varied. Another, not mutually exclusive, explanation could be that the program and its participants developed a better understanding of the barriers to highly integrated, collaborative STEAM instruction (further summarized below) and adjusted lesson plans accordingly. While perhaps unsatisfying for those looking for one clear definition of effective STEAM integration, our findings reinforce that teachers are capable of adopting an approach to STEAM integration that best fits their classroom and school context.

Teachers described individual and contextual factors that impacted their ability to implement a transdisciplinary model of STEAM they hoped for. Similar to prior research, teachers in this study described the need for collaboration and coordination across subjects (and teachers) to implement STEAM effectively (Quigley et al., 2019; Caton, 2021). Teachers experienced challenges when working across content areas in collaboration with other teachers from different disciplines, a problem shared by teachers in other studies and contexts (Quigley and Herro, 2016; Herro et al., 2017). In addition, teachers described a lack of time to coordinate and implement STEAM, but also external pressures to improve student achievement through standardized testing, especially following the COVID-19 pandemic. As reported in the literature, these pressures, largely out of control of the teachers, create challenges for teachers to effectively implement STEAM lessons (Herro et al., 2019). In focus groups, the teachers expressed appreciation for the support of the GoSTEAM@Tech program in providing and advocating for shared planning time amongst teachers, introducing them to new tools and strategies for integrating subjects beyond their own content areas, and providing resources to assist with STEAM implementation.

With sufficient support, teachers reported positive effects on their teaching and classroom environments, suggesting STEAM as an impactful intervention (Thompson et al., 2018). STEAM instruction was not without effort, and teachers described undergoing a "*mindset shift*" necessary to adjust their teaching practices and develop their own content knowledge necessary for STEAM instruction. Teachers described becoming more flexible, receptive, and open to being facilitators of student learning, particularly in years 3 and 4 as they reflected on a transdisciplinary purpose of STEAM instruction. Indeed, later in the program, teachers identified STEAM as a creative way for students to express their knowledge in STEAM topics. They also described STEAM as an authentic way for students to generate knowledge and be assessed, mirroring past research on integrated STEM education (Brown, 2021). Project- and problem-based learning approaches were referenced by teachers, especially through the implementation of their Action Plans. Through the identification of projects with real-world relevance in the lives of students, and the support of robust PD, the teachers described increased confidence to further implement STEAM in their respective schools.

There are a number of limitations of this study. While teacher focus group and survey data from multiple years of program implementation provided insight into teachers' perspectives on their STEAM experiences, we have limited data on what Action Plan implementation looked like in the classroom. COVID-19 limited our ability to observe classrooms and, when observations were attempted, scheduling constraints often prevented observations from occurring. Thus, the available data are self-reported, though this was useful for exploring teachers' perceptions of the program impact and experience. Other limitations come from the use of the GoSTEAM@Tech Integration Continuum. This tool was developed in 2019, with the support of program staff and participating teachers, to understand content integration within teachers' Action Plans. Using the Action Plan as the unit of measure for the Integration Continuum may not have captured the extent to which STEAM integration was happening in the classroom. Additionally, because Action Plans were collaboratively designed and implemented, multiple teachers within the same school could have varied perspectives of integration reflected in their Plan, based on their role in implementation. Furthermore, the language in the Continuum reflects a binary understanding of integration of just two disciplines. While this reflected the early structure of the program to include one arts teacher and one STEM teacher per school, it was not a good representation of the program structure in later years, or of projects with more than two disciplines represented. In focus group discussions of the Continuum with teachers in year 4, the binary language did not appear to hinder anyone's understanding or use of the Continuum to describe their Action Plan. In the future, broader language may be needed to appropriately capture all disciplinary connections. Additionally, future iterations for the Continuum could assess teachers' use of project- or problem-based strategies in STEAM and their intended purpose of STEAM instruction to provide a more detailed understanding of transdisciplinary STEAM integration. As we interviewed teachers across years, we noted their interchangeable use of "STEAM integration" and "arts integration." This reflects conversations among scholars around the muddied distinctions between arts integration and STEAM, and could indicate that perhaps these concepts are not distinct in teachers' minds (Liao et al., 2016; Perignat and Katz-Buonincontro, 2019). With continued refinement, the GoSTEAM@Tech Integration Continuum may prove to be a useful tool to help teachers reflect on or plan for content integration in STEAM, in addition to its value as a research tool.

Based on our findings, we note a continued need to support teachers interested in engaging with STEAM instruction by providing a thorough definition of STEAM integration, while giving teachers the autonomy and flexibility to develop integrated STEAM lessons that are appropriate for their context. Collaboration and resources to help teachers develop knowledge outside their content area are vital for successful STEAM integration. Education leaders must be ready to provide structural, financial, material, and content knowledge support to teachers to promote their adoption of integrated STEAM instruction. Our results suggest that effective STEAM PD cannot adopt a one-size-fits-all approach to STEAM, as teachers need to adapt STEAM lessons to their unique classroom and school environments. With a clear conceptual grounding in STEAM and support for implementation, teachers can successfully implement integrated STEAM instruction across grade levels and disciplines.

Data availability statement

The datasets presented in this article are not readily available because of restrictions of the funding agency. Requests to access the datasets should be directed to KB, katherine.boice@ceismc.gatech.edu.

Ethics statement

The studies involving humans were approved by Georgia Institute of Technology, Central Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KB: Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. MA: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. JJ: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. TK: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. JC: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. SG: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. MU: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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