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Creating Sustainable Computational Thinking Infusion: An Analysis of Teacher-Led Practitioner Inquiry Projects

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There is growing attention to the potential for developing professional learning experiences for content area teachers to infuse computational thinking (CT), which refers to the set of problem-solving practices related to the computer science discipline, into their classrooms. Although research has begun to document professional learning models and supports for CT infusion, an understudied area for both research and practice is how in-service teachers come to lead CT infusion efforts through determining curriculum, supporting their colleagues, and designing school and district-wide programs, once the professional development (PD) and related learning experiences are over. In this paper, we document findings from the final year of a five-year PD project, in which a subset of middle and high school content area teachers and teacher teams (*n*=12) proposed, designed, and carried out their own CT infusion projects. Using a practitioner inquiry framework, we analyze teachers' choices in project types (curriculum development, teacher PD, and activities designed to connect in-school and informal learning), motivating factors for applying for the grant, their inquiry processes, and their perceptions of project impact. We discuss suggestions for supporting teacher-led CT infusion, including taking incremental approaches that develop teacher knowledge over time, building both discipline-specific and interdisciplinary teacher communities, and engaging multiple stakeholders to build the culture necessary for CT infusion. We conclude with general implications for creating structures to sustain and extend researcher-practitioner partnerships.

Much has been written about the power and the perils of teacher professional development (PD)—researchers have documented successful PD structures and models across face-to-face, virtual, and hybrid environments (Yurkofsky et al., 2019) and critics have outlined many of the challenges to designing sustainable, cohesive, and meaningful professional learning experiences (Borko, 2004; Darling-Hammond et al., 2005). In recent years, there has been growing interest in the creation of mutually beneficial researcher-practitioner partnerships that are responsive to teaching contexts and cultures (Coburn & Penuel, 2016). However, what is often missing from the literature are concrete descriptions of how teachers sustain and grow new practices at the end of a given PD or project, particularly one involving partnerships with researchers or community organizations. How do teachers navigate the use of new forms of instruction or curriculum on their own or with limited support? How can researcher-practitioner partnerships build toward teacher autonomy?

These questions are particularly important in the context of professional learning about computational thinking (CT), which refers to a set of problem-solving practices – such as algorithmic thinking and pattern recognition – inherent to computer science that can be integrated into disciplinary teaching and learning (Wing, 2006). CT infusion is a relatively new practice in both research and P–12 settings (Kite et al., 2021; Lee & Malyn-Smith, 2020; Wang et al., 2021), which offers unique opportunities to investigate how teachers navigate new pedagogical approaches. In this paper, we focus on the final year of a five-year researcher-practitioner partnership, *Infusing Computing*, in order to document how teachers proposed, designed, and conducted practitioner inquiry projects focused on CT infusion (*n*=12). All teachers had participated in professional development for at least two years, previously infused CT into their classroom teaching, and submitted proposals to receive funds of $5,000 to $10,000 to implement self-designed CT infusion projects. As we detail in the Methods section, the idea for the practitioner inquiry projects emerged from sustained work with teachers over the course of the PD and analysis of their feedback on needs in terms of school and classroom CT infusion.

The goals of this study are to analyze the choices teachers made in terms of project formats, to describe teachers' experiences with the practitioner inquiry process, and detail teachers' perceptions of the impact that their projects had on their students, colleagues, and/or communities. Data sources include project proposals, pre- and post-project interviews, surveys, video presentations and infographics created for a teacher showcase, and teacher-collected project artifacts. We conclude with a discussion of implications for designing CT learning experiences that center teacher autonomy and expertise, as well as a broader discussion of design recommendations for concluding researcher-practitioner partnerships in ways that sustain relationships and transfer ownership of the project to teachers.

REVIEW OF EXISTING RESEARCH

We use the term *computational thinking* (CT) to refer to the concepts and processes commonly used in computer science (CS) but that are generalizable to other situations (Dong et al., 2019; Israel et al., 2015; Wing, 2006), while we use CS to refer to the study of computers, their uses, and their impact on society (Tucker et al., 2003). In recent years, organizations like the International Society for Technology in Education (ISTE) and the National Science Teaching Association (NSTA) have included CT as a crucial practice that builds problem-solving and sense-making skills (ISTE, 2019; NGSS Lead States, 2013). As new technologies, such as generative AI tools, arise, a strong foundation of CT skills can help students adapt to changing technologies and contexts. CT has also played a fundamental role in the development of new knowledge in fields like computational biology and the computational social sciences. As learners use CT to make sense of complex systems, there are also numerous possibilities for them to innovate with computational representations, design solutions using computational tools and power, engage in collaborative sense-making, and test multiple solutions to problems (Lee & Malyn-Smith, 2018).

Even as CT is increasingly recognized as a crucial skill for the 21st century, there are open questions about how and why it should be introduced within content area contexts and classrooms. As Lee & Malyn-Smith (2020) argue, CT is too often "taught in a manner disconnected from the STEM content it serves" (p. 9). Rather than teaching elements in isolation, teachers can seize opportunities to build deep and flexible knowledge of key computing concepts in connection with disciplinary content and practices (Jocius et al., 2022; Lee et al., 2020). There are other benefits to infusing CT into disciplinary teaching, including deepening students' understanding of disciplinary problem-solving and sense-making practices (Weintrop et al., 2016), providing more equitable access to computer science education for all students (Fofang et al., 2020), and supporting the development of key critical skills in collaboration and creativity (Jocius et al., 2021).

However, infusing CT into disciplinary content offers many challenges for teachers who often lack a background in or previous experience with CT or CS. Content area teachers need explicit, scaffolded, and sustained support, particularly as they take on larger roles in designing and implementing CT-infused curricula. Research (Hestness et al., 2018; Jocius et al., 2020; Ketelhut et al., 2020; Rich et al., 2021) has shown that successful CT PD has many characteristics: opportunities for teachers to leverage their existing expertise, clear connections between new understandings of CT and disciplinary pedagogical practices, collaborative reflection with content area colleagues, and opportunities to design and refine CT-infused instruction.

As the study of CT infusion is still in its nascent stages, much of the existing work has focused on theorizations of CT for disciplinary teaching (Azeka & Yadav, 2021; Lee & Malyn-Smith, 2020; Sengupta et al., 2013), teacher perceptions of CT (Chang & Peterson, 2018; Sands et al., 2019), descriptions of teacher PD programs (Jocius et al., 2022; Ketelhut et al., 2020), and initial frameworks for building schoolwide CT integration (Israel et al., 2015; Sherwood et al., 2021). What is needed in the literature is in-depth accounts of CT infusion from the perspective of teachers at multiple points in their CT learning and teaching trajectories. How do teachers envision the role of CT in their disciplinary practice? How do they adapt resources and materials to help their students with problem-solving and sense-making? What decisions do they make in terms of the form and function of CT infusion? How do they build knowledge with colleagues in school and disciplinary communities? As we describe in the following section, we draw upon theories of practitioner inquiry to unpack these questions and to explore possibilities for developing more sustainable professional learning programs for content area teachers to explore CT and CS tools and pedagogies.

THEORETICAL FRAMEWORK

The call to put teachers at the center of professional learning programs is not specific to work on CT and CS education. More broadly, many critics of existing models of PD and teacher education research have argued that teachers' professional learning experiences are often "fragmented" and "intellectually superficial" (Borko, 2004, p. 3). In addition, teachers often have limited voice in reports of research. For example, as Cochran-Smith and Lytle (1999) write,

> What is missing from the knowledge base for teaching, therefore, are the voices of the teachers themselves, the questions teachers ask, the ways teachers use writing and intentional talk in their work lives, and the interpretive frames teachers use to understand and improve their own classroom practices. (p. 2)

In response to these critiques, researchers (Cochran-Smith & Lytle, 2009) have proposed the use of practitioner inquiry, or the development of systematic processes for educators to pose questions about their work, collect and interpret data, take action, and share their learning (Dana & Yendol-Hoppey, 2019). The literature describes several related forms of practitioner inquiry, including action research (Cohen et al., 2017), practitioner research (Menter et al., 2011), and teacher research (Cochran-Smith & Lytle, 1999). These approaches share many overarching characteristics: "the practitioner is the researcher, the professional context is the research site, and practice itself is the focus of study" (Cochran-Smith & Donnell, 2006, p. 503). For the purposes of this study, we chose to use the broader conceptualization of practitioner inquiry because of how our teacher-partners conceptualized and framed their own work.

A practitioner inquiry framework has been used to document how teachers approach the integration of technology into early childhood classrooms (Johnston et al., 2019), classroom teachers' technology integration practices (Dawson, 2012), adaptations to an online professional development program (Dana et al., 2017), and the conceptualization of practitioner inquiry as a theory of action for pre-service education (Rutten, 2021). One critique of practitioner inquiry work has been the need for more empirical studies that document changes in teacher thinking and learning over time, as well as studies that address the relationships between teachers' inquiry processes and evidence of student learning (Cochran-Smith & Lytle, 2009; Darling-Hammond et al., 2005; Rutten, 2021).

What is unique to the CT infusion context is the need to build structures for teachers to engage with transdisciplinary and technology-rich teaching (Biddy et al., 2021). As teachers grapple with new tools, pedagogies, and processes, practitioner inquiry can serve as a valuable tool for reflecting on the development of rich pedagogical practices that co-develop disciplinary and CT knowledge. In this empirical study of content area teachers' choices, motivations, and inquiry processes, our aim is to center teachers' expertise in CT infusion, which was developed over multiple years of intensive work to bring CT into their classrooms, schools, and districts. As Hayes (2011) argues, this work involves explicitly unpacking and recognizing the ontological, epistemological, and methodological commitments that shade "all of the ways in which data are collected, analyzed, and reported and change is implemented" (p. 3).

In terms of our ontological commitments, our research team views our partnerships with teachers as symbiotic, with each teacher positioned as a "legitimate knower and knowledge generator" (Cochran-Smith & Lytle, 2009, p. 89). We recognize that our work is not "value neutral" (Hayes, 2011, p. 3) and that our deep engagement with teacher partners over time influenced the design of the practitioner inquiry program and our approach to this study. Epistemologically, we view knowledge as localized and co-constructed (Cochran-Smith & Lytle, 2009), and our focus is on understanding the context of CT infusion and developing solutions for impacting change (Hayes, 2011). Methodologically, as discussed in the next sections, the practitioner inquiry framework guided the design of our study, including the development of professional learning activities that allowed teachers to document and analyze pedagogical practices, as well as iterative research methods for analyzing data to highlight teachers' experiences, inquiry processes, and perceptions.

Research Questions

This study addresses the following research questions:

1. What choices did teachers make in terms of practitioner inquiry CT infusion project formats and what were their motivations for choosing their project types?

2. What were teachers' experiences with the practitioner inquiry process?
3. What were teachers' perceptions of the impact that their projects had on their students, colleagues, and/or communities?

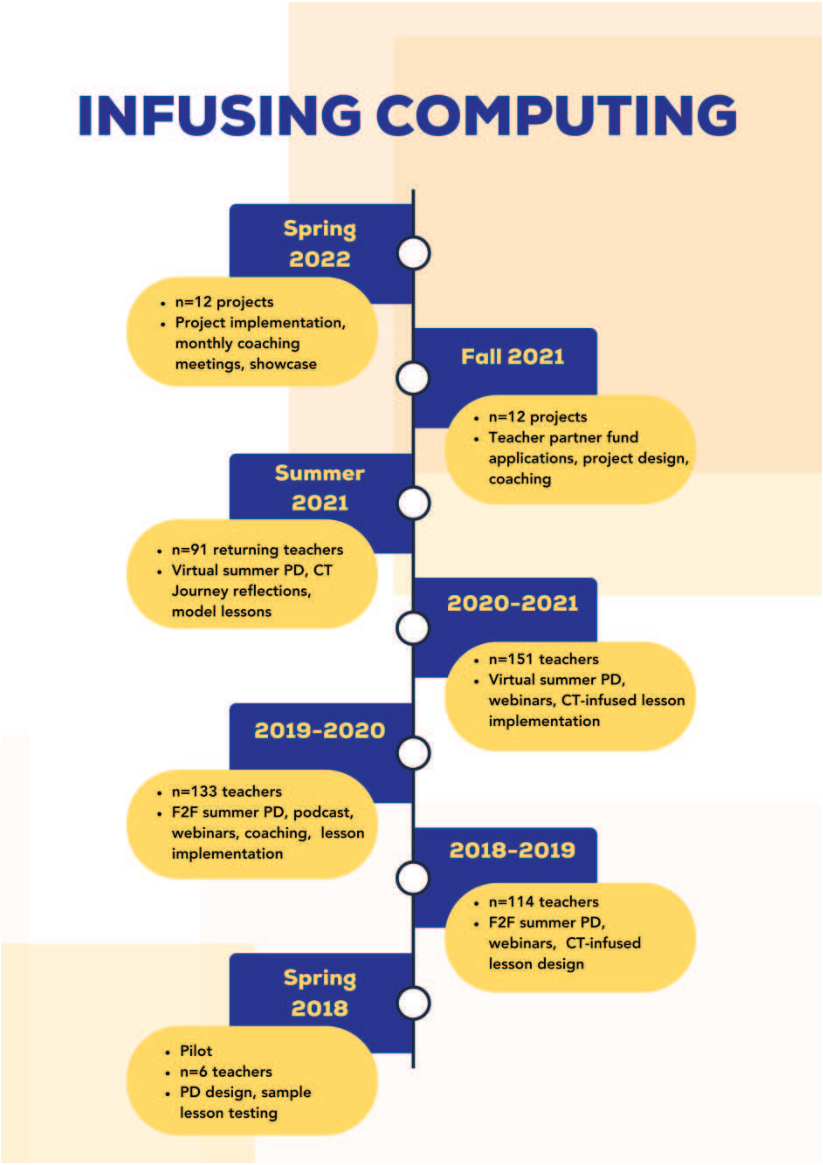
METHODS

Context: Infusing Computing

Infusing Computing was a five-year grant project that supported more than 360 content area teachers (math, science, ELA, social studies, and related arts) as they learned to infuse CT into their disciplinary teaching (Jocius et al., 2022). The project brought together middle and high school teachers from across two Southeastern states, with the goals of increasing teacher and student access to CT and CS concepts and practices, building a community of practice of teachers interested in CT (Lave & Wenger, 1991), and examining professional learning models to support ongoing and sustained CT infusion. Middle and high school teachers in any content area from both states were invited to apply by submitting a statement of interest and letter of support from their principal; participants were selected based on their demonstrated interest in CT infusion, as well as to ensure diversity in terms of teaching location (urban, rural, and suburban areas), grade levels, and content area expertise. Teachers who weren't selected initially were given priority in previous years of the project. From 2017–2021, teacher partners connected CT to disciplinary teaching practices, created CT-infused lessons and units, and documented how they used and adapted lessons in their schools and classrooms (see Figure 1).

Figure 1

Overview of Infusing Computing Project



Infusing Computing Partner Grant Program

In the final year of *Infusing Computing* (2021–2022), the project team decided to explore a method for sustainability that would go beyond offering another year of PD. Our goal was to grow CT infusion beyond the life of the grant in a way that would address unfulfilled CT and CS education needs in participants' schools and communities. After discussing different ideas with teacher partners, we developed the *IC Partner Grant* program and invited all teachers who had attended multiple workshops to apply for funds. The application required an overview of teachers' goals for a practitioner inquiry project, a plan for collecting and analyzing data to document their work, a budget, and a letter of support from the school or district. Project team members offered virtual *IC Partner Grant* application workshops and one-on-one assistance for teachers as they conceptualized their work and created data collection plans and budgets.

In total, 10 individual teachers and two teacher groups submitted proposals. All proposals were funded and received \$5,000–\$10,000 to implement their projects. Funds could be used for materials, supplies, stipends for developing curriculum or attending PD, and subsistence. All stipends were processed by the project team, and materials were purchased by the project team and sent directly to participants. Projects included CT-infused curriculum development, CT training for school and district colleagues, and after-school and community-based activities to connect and build synergy between in and out-of-school learning.

Teacher Partners

Of the two group projects, one was a collaboration between a middle school ELA and math teacher and the other was a collaboration between a middle school media specialist and ELA, social studies, and science teachers. Of the 12 individuals or groups, 41.7% (n=5) worked in middle school or K–8 settings, while 58.3 % (n=7) worked in high school settings. Teachers (n=16) represented several content areas, including science (n=7), ELA (n=2), math (n=2), social studies (n=1), English learner support (n=1), career and technology education (n=1), dance (n=1), and instructional coaching (n=1). Teachers had extensive prior teaching experience, with an average of 18.27 years and a range of 7 to 28 years. All teachers had previously attended at least two *Infusing Computing* summer workshops, with an average of 2.94 years of experience with the project (5 had attended 2 prior workshops, 7 had attended 3 prior workshops, and 4 had attended for all four years).

Data Sources and Analysis

Data sources for this study included *IC Partner Grant* proposals (*n*=12), transcripts of pre-project (*n*=12) and post-project interviews (*n*=10; two teachers did not have availability during the post-project interview period), video recordings of post-project presentations (*n*=12), teacher surveys (*n*=17), and infographics created to summarize teacher-led project goals (*n*=11). First, to classify teacher projects into categories and to analyze how teachers conceptualized their work, we reviewed the project proposals and teacher surveys. Then, analysis proceeded in three phases. In the first phase, we divided the transcripts of pre- and post-project interview responses into idea units (Gee, 2011), in which each unit represented a specific and distinct idea. Three members of the research team reviewed the idea units to come to agreement on the organization of data. As all coding was done collaboratively and iteratively throughout the process, inter-rated reliability was not calculated. Then, we utilized descriptive coding (Saldaña, 2013) to identify emergent themes and codes; for example, when we noticed teachers referencing the need for scaffolding of classroom CT infusion practices over multiple timescales, we developed the "incremental CT infusion" code. Constant comparative methods (Strauss & Corbin, 1998) enabled us to confirm previously coded excerpts and to create new codes when new themes emerged.

In the second phase of data analysis and second coding cycle, axial coding (Strauss & Corbin, 1998) was used to identify dominant codes, reorganize data, and create a system for connecting themes to sub-themes. We reorganized teacher responses to create systematic understandings (Saldaña, 2013) in relation to the three research questions–project choice and motivation (*n*=47 idea units), experiences with the practitioner inquiry project (*n*=38 idea units), and perceived project impact (*n*=66 idea units). Table 1 includes themes and sub-themes from the analysis of pre-and post-project interviews, as well as descriptive statistics to describe the prevalence of sub-themes.

Table 1

Pre-Project and Post-Project Interview Themes, Sub-Themes, and Descriptive Statistics

Data Source	Theme	Sub-Themes	Example Response	Percentage of Responses
Pre-Project Interviews (n=23 idea units) and Post-Project Interviews (n=24 idea units)	Motivation for Practitioner Inquiry Project (RQ1) (n=47 idea units)	Student Access	"I just believe that we can unlock some brain power that we didn't even know our kids had"	42.6% (n=20)
		Teacher Access	"We felt like that our staff members would like to learn about it and enjoy it and then share it with the students throughout the building"	21.3% (n=10)
		School Community	"One of the big issues that we are facing, and I know a lot of other schools are facing, is morale. And we realized that computational thinking could build that morale"	19.1% (n=9)
		Disciplinary Learning	"I wanted to create an algorithm in snap again to help students create an outline to rewrite a story that involves if/then statements."	17.0% (n=8)
Post-Project Interviews (n=38 idea units)	Experience with the Practitioner Inquiry Process (RQ2)	Self-Efficacy	"When I was doing sessions in in the summer and they didn't make like too much of sense to me, but when I was in my project, it started making sense"	65.8% (n=25)
		Incremental CT Infusion	"What I did is scaffolding, where you slowly show people here's what is out there, here's how we can incorporate it into what we need"	21.1 % (n=8)
		Project Adaptations	"It was a lot of trial and error and the groups that really helped me"	13.2% (n=5)

Data Source	Theme	Sub-Themes	Example Response	Percentage of Responses
Post-Project Interviews (*n*=66 idea units)	Perceived Impact of the Project (RQ3)	Student Learning	"We had a talk about variables, that the variable at a time, tested through multiple trials. So, they got a clear idea about the scientific method--how it works, what is the dependent variable, what is the independent variable."	36.4% (*n*=24)
		Access	"Guess what? Our number of kids who want to sign up for ap computer science has gone up, so not only has this coding club helped out with getting more kids interested in computer science, we've got more kids who are being funneled into the ap computer science"	18.2% (*n*=12)
		School Community	"I wanted to have the maximum impact on the entire school. This one turned out actually to be the right one because it made such a change, and it will continue. This is not a one and done"	16.7% (*n*=11)
		Recognition	"We won one award for mentoring elementary school kids."	13.6% (*n*=9)
		Teacher Learning	"I think they really like all the little different hands-on activities that we did for each element. And we got really good PRADA connections back from them in their lesson plans"	9.1% (*n*=6)
		Awareness of STEM careers	"My students are the ones that are going to get those Boeing internships"	6.15% (*n*=4)

In the third phase of data analysis, we sorted the data by project type (curriculum, PD, or after-school) and compared themes across the three project types in relation to the research questions. We then re-reviewed the interview data, noting changes in teachers' responses from pre- to post-project interviews. We also created a document to track changes in initial project ideas through the project implementation and reflection stages.

We also reviewed all video recordings of post-project presentations, creating multimodal memos to note teacher comments as relevant to each of the three research questions. For example, when teachers who completed curriculum projects provided specific examples of student learning, we took screenshots of their presentations, transcribed their comments, and made notes about follow-up questions and comments from other participants and project team members. We used this information to triangulate findings from the interview analysis, surveys, and project proposals. In addition, we triangulated findings with additional data sources, including teacher project artifacts: lesson plans, instructional materials, and student data for curriculum projects; PD slides, handouts, artifacts, and participant data for teacher PD projects; and instructional materials, resources, websites, and participant data for after-school projects. Throughout each phase of the analysis, to ensure trustworthiness, we created analytic memos (Charmaz, 2014) and data displays (Miles & Huberman, 1994), to deepen understanding of teachers' project goals and motivations, inquiry processes, and perceptions of project impact.

FINDINGS

Findings are organized into three sections that are aligned with the research questions: teacher choices and motivation for CT infusion projects, teacher experiences and reflections on the inquiry process, and perceived impact of projects. Throughout each section, we include extended excerpts from teacher interviews, as well as artifacts collected during their inquiry projects and presentations to highlight teacher voices. All teacher names are pseudonyms.

RQ1: Teacher Choices and Motivations for CT Infusion Practitioner Inquiry Projects

Projects were classified into one of three categories based on teachers' initial project proposals: teacher PD (*n*=5), curriculum development (*n*=5), and after-school clubs or activities (*n*=2) (see Table 2). The teacher PD projects focused on different timescales and teacher participants; for example, one of the teacher teams designed a two-day mountain retreat for a group of 30 teachers at their school, another project built a group of teacher-leaders by modifying science curriculum to infuse CT, and others focused more narrowly on PD for a particular computing tool (e.g., micro:bits) or a type of CT infusion (e.g., unplugged activities). Curriculum projects focused on reinventing a particular curriculum element, such as coding for multilingual students, or on revisions to department or grade-level curriculum to infuse CT. Both after-school projects created robotics and coding communities that built on in-school infusion efforts and expanded access to students throughout their communities.

Table 2

Overview of Projects

Teacher/Team	Project Category	Audience
Teacher PD (*n*=5)		
Tawny (MS science)	Lead teacher PD on plugged and unplugged CT infusion	School
Natalia (HS science)	Lead CT PD for physics teachers; use micro:bits as the primary tool	District
Jay (HS math)	Lead CT PD for math teachers	School
Beatrice and Helen (MS ELA and science)	Lead a retreat for their school around computational thinking infusion	School
Stonehollow Elementary (MS library, ELAR, SS, and science)	Lead unplugged CT PD for elementary teachers	School
Curriculum Development (*n*=5)		
Tony (HS math)	Design curriculum for using TI calculators to teach Python	District
Ada (MS ELAR/ELL)	Design daily activities to bring in CT and the idea of conditional statements	District
Lina (MS science)	Develop curriculum for using coding to monitor a community garden	School
Marci (HS instructional coach)	CT-infused activities for curriculum maps	School
Abigail (MS dance)	Design CT-infused curriculum where students code dancing robots	Classroom
Connecting In and Out-of-School Learning (*n*=2)		
Olivia (HS science)	Create middle and high school robotics club to expand access to CT and CS	District
Leela (HS science)	Develop first-ever robotics team in her district and create a mentorship program to build a pipeline for CS education	Community, District

Teachers who designed teacher PD inquiry projects tended to be motivated by the desire to increase content teacher access to CT and computing education, as well as the desire to impact change within their schools or communities. In interviews, three of five teachers referenced helping their colleagues understand CT infusion as the first step in supporting student access; as one teacher noted, "We wanted to share what we had learned over the last couple of years with our students, first and foremost. But to get it to them, we had to, of course, share with our colleagues." Beatrice and Helen, who designed a school-wide CT retreat, had initially considered doing a curriculum project, but wanted to have a broader impact on their school community:

> We started thinking and talking about, well, what could we purchase? Because that's a teacher's first stop—what can we buy them that they can use in their classrooms? But then three years ago, we went on a faculty retreat and did project-based learning. It was so fun. We got to know people that we hadn't really gotten to know before and it helped our whole school, so we wanted to bring that opportunity to our teachers.

Nine of the eleven teachers/groups in this study stated that they had no prior experience with applying for teacher grants or their experience was limited to Donors' Choose projects. The two teachers that had previous grant-writing experience noted that they had been limited to the purchase of materials. As Marci, a high school science teacher who took on a new role as an instructional coach prior to beginning her project, described in her pre-PD interview,

> The problem with those other grants that don't pay for PD is that you either have people who get the awesome resource and don't know how to use it or they have to spend their time figuring it out, so it gets put on a shelf…And so that was the difference here—I felt because this allowed me to do some really intense PD with folks, whatever I do on top of it, they've already got buy-in. That is a huge thing, because we can get them all the cool stuff in the world, but if you don't teach people how to use it, they won't have the buy-in.

For Marci, the *IC Partner Grant* program offered an opportunity to build teacher access and knowledge through professional learning experiences.

Teachers who chose to focus on curriculum projects were primarily motivated by three factors: the need to increase student access to computational thinking and computing education, the potential to leverage CT and computing to support disciplinary learning, and the desire to change the school community. Ada, who works with middle school English learners, wanted to provide students with more opportunities for writing, so she developed a daily attendance question using Snap*!*, a block-based coding program introduced in the *Infusing Computing* PD workshops:

> My attendance question was based off the fact that my students say they can't write a complete sentence. I was like well damn, we're going to have an attendance question every day and through drill and kill, they're going to learn how to pick out keywords from that question and write a complete sentence. That was the end game.

Her project also incorporated the use of conditional statements and children's literature (*If You Give a Mouse a Cookie*) to help students build frames for their reading and writing. Similarly, as Abigail, a middle school dance teacher who had attended *Infusing Computing* workshops for three years, said in her pre-project interview,

> I just always had an interest in technology and I love dance. Most of the time, a lot of the things that I have ideas for, I can't implement because I just don't have the funds. So, I kind of stopped dreaming big a long time ago, which is kind of sad. When I heard about the grant, I was like, 'Oh my gosh, there's money that I can use to incorporate some of these cool ideas into my classroom.' I just immediately thought of ways to reach kids who don't necessarily like dance, but maybe like technology and could merge the two.

While teachers completing curriculum projects considered disciplinary content as essential to their work, it was not the sole consideration. Teachers expressed the need to impact change at the school level and mentioned wanting to serve as models for "other teachers."

Both teachers who chose to complete after-school projects were motivated by the desire to increase student access to computing. As each teacher stated at different points in the practitioner inquiry process, they believed that building an after-school component was the best way to impact the largest number of students. In her project proposal, Leela, who built a competitive robotics program that also included a mentoring element for elementary school students, described wanting to “enhance creativity, foster well-rounded life capabilities, including critical thinking skills and confidence, communication, teamwork, leadership and gracious professionalism.” As she reflected, “The big thing is the mentoring program of robotics kids from high school, they will continue to support elementary and middle school kids.” Similarly, as Olivia, who designed an after-school program for both middle and high school students, said in her pre-project interview, “I wanted to have the maximum impact on the entire school. This is not a one-and-done; this is going to continue with this school.” So, both teachers also saw their inquiry projects as building a foundation for their schools and communities to continue the work.

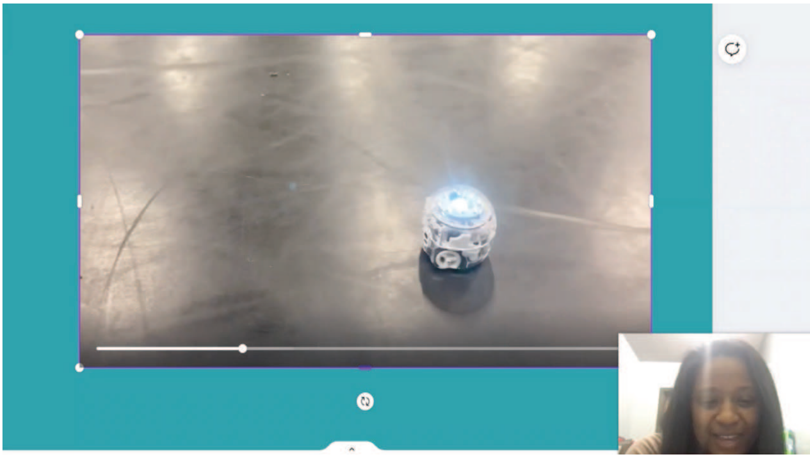
RQ2: Teacher Experiences and Reflections on the Practitioner Inquiry Process

Throughout their post-project interviews, *IC Partner Grant* showcase presentations, and post-project surveys, teachers reflected on the practitioner inquiry process. Teachers referenced multiple points, including the processes of conceptualizing their projects, collecting data, analyzing, and revising, in which they engaged in critical reflection and synthesis of data. Reflections on the practitioner inquiry process primarily related to three themes: incremental CT infusion, project adaptations, and self-efficacy.

Four of the five teachers who completed curriculum projects referenced the idea of incremental CT infusion, or gradually introducing CT concepts, practices, and dispositions over time with either students or colleagues. For example, Abigail originally designed a multi-part project; in Part 1, her students coded a choreographed Ozobot dance that aligned with their physical movements and then in Part 2, they programmed a micro:bit to count dance steps. In her presentation, Abigail shared samples of students’ code and videos of their work with Ozobots (see Figure 2). To document the impact of her work, she collected pre- and post-project data about her students’ knowledge of CT concepts and their beliefs about CT.

Figure 2

Screenshot from Abigail's Partner Grant Showcase Presentation



In her post-project interview, Abigail reflected on the experience and described how inquiring into her own practice led her to reconsider how to infuse CT into her classroom:

> In order for it to work the way I want it to--it would have to be infused into everyday learning for the whole year. I have actually been thinking about that a lot lately, and how just in the dance period, how can I get these kids motivated to actually do some work? So, thinking about life skills, employability skills, and then kind of putting that under the umbrella of CT—I actually thought about that earlier today, like how I can start with pattern recognition and use it for learning these patterns? I think it needs to be infused more…I didn't do a good job of connecting those dots and so, I'd like to infuse it the whole year.

Similarly, Ada, who also completed a curriculum project in her ESOL classroom, described the need to "be consistent" and "dedicated for the duration of the entire school year." Teachers specifically mentioned that using the CT vocabulary and capitalizing on opportunities to recognize CT in daily lessons was crucial for student understanding. As Lina, a middle school science teacher who also completed a curriculum project, said, "I continuously tell them that, this is the algorithm you have to follow, this is the decomposition, how we have to break it into steps, those kind of things—we tried to tell them every class period." This idea of repetition, and gradually building expertise over time, was common to all teachers completing curriculum projects.

Teachers who completed all three types of projects referenced numerous adaptations that they made over the course of their practitioner inquiry, from narrowing down the focus of their work to adapting based on student and teacher interests to testing out their work with particular groups before expanding it. For example, in her presentation, Abigail described "focusing" only on the Ozobot project and saving the micro:bits for the end of the school year, while Ada adapted her attendance questions throughout the year based on her ongoing analysis of learners' responses and their writing development. Olivia had originally planned her after-school program based on her experiences working with high school students and ended up having a much larger group of middle school students in her club. She also had to switch materials due to COVID-19-related microchip shortages. As she said in her post-project interview, "I ended up with mostly middle school kids. Plus, I did not expect to be teaching with the Spheros, so you know that that was a learning curve for me, but it turned out to be very rewarding." Like other teachers, she was able to make adjustments based on changing learner needs, conditions, and technologies.

All of the teachers in the study also referenced shifts in their own self-efficacy and the self-efficacy of their participants as it related to CT. Lina, who had attended the *Infusing Computing* PD all four years, described how the practitioner inquiry project gave her the opportunity to build her students' self-efficacy "little bit by little bit," which mirrored her own process for learning to infuse CT. In her post-project interview, Marci, an instructional coach who developed a PD for teacher-leaders in her district, mentioned that the practitioner inquiry process caused her to slow down and reflect on her own learning:

> Actually, in doing the survey, I realized that I have some gaps, particularly in–how do I assess students in this? The project was really focused on lesson planning, so there's definitely room for growth in terms of implementation, whether it's where I observe teachers or co-teach with them, so in doing some of these lessons or working on the assessment piece. That's definitely a huge piece of it.

Teachers also referred to shifts in their students' or colleagues' self-efficacy. Marci went on to describe the growth in her teacher-leaders' abilities to understand and describe CT to their own school-based colleagues. While her group began without any pre-existing knowledge of CT, by the end of the process, "they were able to train all the other teachers and felt comfortable with it, can explain it and where it relates to their curriculum."

Across each of the themes related to teachers' inquiry processes (incremental CT infusion, project adaptations, self-efficacy), teachers referred to their experiences with CT infusion and PD as supportive of their work. For example, Marci said, "I had gone through the summer sessions, so I wasn't really building the plane as I flew it. I knew what I was going to do and had time to reflect and figure out how this could really apply." Teachers also referred to their own learning processes as incremental, describing how their approach to CT infusion changed over time and deepened as they engaged with their practitioner inquiry projects and shared their work with students and colleagues.

RQ3: Teachers' Perceptions of Inquiry Project Impact

The third research question focused on teachers' perceptions of the impact of their project, as evidenced by analysis of post-project interview data, presentations, and project artifacts. Teachers primarily categorized impact in six ways: access, awareness of STEM careers, student learning, teacher learning, school community, and recognition. First, teachers completing all three project types described the value of their work in expanding access to CT and CS education throughout their schools, districts, and communities. Leela, who developed her community's first robotics team, integrated a mentorship component in order to grow a pipeline of students interested in pursuing robotics. As she said in her post-project interview, "The high school kids were able to motivate lots of elementary and middle school kids, and they are so eager to join robotics in upcoming school years." In the final showcase presentation, Leela's students shared their work and described the impact that the project had on their perceptions of computer science and their academic trajectories, as well as the value they saw in mentoring younger students. Similarly, Olivia, who established a middle and high school robotics program, said,

> Guess what? Our number of kids who want to sign up for AP computer science has gone up, so not only has this coding club helped out with getting more kids interested in computer science, we've got more kids who are being funneled into AP computer science,

> so in a of couple years, we're really going to be able to build on this program.

Similarly, teachers completing curriculum and teacher PD projects noted the value of expanding access to more students and colleagues, as well as the value of having materials, including codable robots, hardware, and software, that could be "reused for years after years."

In interviews and the showcase presentations, teachers completing curriculum and after-school projects unpacked the impact of their work in relation to student learning. During her showcase presentation, Olivia, for example, shared that student interactions with physical objects were crucial to helping them learn how to program. As she said,

> And as I was digging into their work…with the tools—it's more hands-on, they can see it move, it's three-dimensional, it's not just on a screen, right? So, when they're writing a program with the Sphero, it's moving forward, backwards, left, right, in a circle–it's making a picture of something on the lights or flying.

Similarly, Lina described engaging her own students in inquiry as they completed their plant and soil CT-infusion projects; during her presentation, she shared examples of student work and learning throughout the process. As she mentioned in her interview, "I said, let's just analyze what happens if we put these seeds in, let's see what is the difference, what patterns we see. We found out that actually it grew better than it grew in water, so that was a big eye-opener for the students."

Three teachers also described how their projects helped grow student awareness of a range of different STEM careers. For example, Leela detailed how "the program changed things" for two of her students, one of whom had rethought his plan to begin working after graduation and planned to earn a credential to work with automatic models, while the other had developed an interest in pursuing bioengineering as a career pathway. This was also evident in other teachers' descriptions of how infusing CT and CS education in traditional K–12 settings could create more equitable opportunities for their students to participate in a high-tech workforce. In her post-project interview, Natalia, a high school physics teacher who designed PD on micro:bits described her frustration with the static nature of her curriculum, as well as her desire to push to prepare students for 21st-century jobs: "Why am I teaching physics from 100 years ago to prepare people for jobs that already didn't exist, that were starting to go out 50 years ago? I consistently challenge my students. I'm consistently adding what they actually need." She noted that her project allowed her to expand access to CT and CS across her school context.

All five of the teachers completing PD projects also described the impact of their work as it related to teacher learning during their post-project interviews. Jay, who led a PD on CT infusion, described how working through state standards supported teacher learning:

> And there were teachers from special education and there was one teacher from history, so they took their own state standards and deconstructed and then they were able to identify, okay, this is where I can apply the pattern recognition, this is where I can apply the abstraction.

Similarly, Marci detailed the surprise of her teacher-leaders as they realized how many connections to CT already existed within their district curriculum:

> It did surprise me how many elements of PRADA [model for CT concepts; Dong et al., 2019] were in our lesson plans and how little revisions we really ended up needing to do. I figured there would be a few, but there were a bunch which was really cool. Also, the teacher leaders in the beginning were hesitant, like, 'I don't know if I want to do this, or you know we weren't paying me, I definitely wouldn't be doing it.' By the end of it, they were so happy about the project and just excited.

Collaboration with colleagues helped teachers to reimagine CT infusion across multiple disciplines. For example, as Olivia described, "Being able to work with a history teacher and dance teacher and art teacher and just the collaboration that happened over all of that span of time really solidified my understanding of how this is really possible across every curriculum."

Teachers also described the desire to scale up their work to create lasting change in their school communities. For example, Lina, who redesigned her school's science curriculum to embed CT across all units, considered multiple project types before deciding on one that would "have the maximum impact on the entire school…This is not a one and done." Other teachers, including Leela and Natalia, presented evidence of the impact of their work on the school community at the final showcase, including testimonials from their colleagues and information about professional learning opportunities, such as plans to attend Amazon's Future Engineers program and supporting more teachers in their districts certified to teach computer science.

Finally, five teachers described how recognition of their work within their districts and communities was important for them, their colleagues, and their students. Olivia described her work in infusing CT and with her inquiry project as changing her "path in my career." After 26 years of teaching high school science, she earned her teaching certification in AP computer science and planned to teach CT and CS at the middle and high school levels. She also took on a new role as an instructional coach during the inquiry project process. She also said that the data she collected helped her to make a case for more CS education resources: "This gave us the data to say, here's what we're doing and here's proof that it works–could you continue supporting us?" Similarly, Tawny, a middle school science teacher who brought in other colleagues to design CT-infused curricula, said the inquiry process was successful in "opening up more doors," such as leading district-level PD. Others, like Beatrice and Helen, referenced how the recognition they received from school and district leaders led to greater interest in CT-infused pedagogy from their colleagues. Finally, teachers described the impact of the recognition on their students. Leela, for example, described the impact of recognition on her students' confidence and self-efficacy as they received awards for mentoring younger learners, were featured in district publications, and presented at school board meetings and the *Infusing Computing* showcase.

DISCUSSION

In examining teacher-led CT infusion projects through the lens of the practitioner inquiry framework (Cochran-Smith & Lytle, 2009; Dana & Yendol-Hoppey, 2019), this study has documented how individuals and groups of in-service teachers (*n*=12) came to lead computational thinking infusion efforts within their schools and communities. Specifically, we examined teachers' motivations for their projects, their experiences with the practitioner inquiry process, and their perceptions of the impact of their work. Using a practitioner inquiry approach enabled us to co-construct knowledge in an "explicitly democratic, collaborative, and interdisciplinary" process (Hayes, 2011, p. 3) that aimed to create sustainable change at the end of a long-term research project, *Infusing Computing*.

Teachers' Choices in CT Infusion Practitioner Inquiry Projects

First, we found that teachers were motivated to design projects that would increase teacher or student access to CT and CS education, support disciplinary learning goals, and build school communities. These findings are in alignment with existing literature that focuses on integrated CT learning (Fofang et al., 2020) that address disciplinary learning (Weintrop et al., 2016) and build the school cultures necessary to support CT infusion (Lee & Malyn-Smith, 2020). Teachers who chose to design teacher PD projects were more likely to want to create change and increase access to CT within their schools or communities, while those choosing curriculum projects were more likely to focus on disciplinary learning goals. This finding aligns with literature on classroom-based action research that suggests that teachers are motivated to create pedagogical change in the classroom setting, with the broader goal of building positive school cultures (Diana, 2011). Further, in alignment with research on CT infusion as a new pedagogical practice that requires sustained and multi-faceted professional learning experiences for content area teachers (Caskurlu et al., 2021; Ketelhut et al., 2020), teachers completing all three types of projects expressed the need to build the tools and structures needed to make a lasting impact that would grow over time.

Teachers' Reflections on the Practitioner Inquiry Process

The idea of building CT infusion practices that would persist over time was also a salient theme in teachers' reflections on the practitioner inquiry process. As our teacher-partners recognized, an incremental approach to CT infusion was most effective in supporting learning about and building self-efficacy related to CT. For example, rather than treating classroom CT infusion as a one-time learning experience, incremental infusion helps students see how CT supports problem-solving within and across a variety of disciplines and real-world situations. This aligns with curricular frameworks (Kong, 2016; Sengupta et al., 2013) and research on CT infusion (Azeka & Yadav, 2021; Weintrop et al., 2014) that highlight the importance of scaffolding learners toward progressively more complex CT tasks that simultaneously build disciplinary knowledge. Teachers who designed PD also referenced the importance of building their own and their colleagues' self-efficacy and skill sets with CT infusion over time, which allowed for adaptation to changing school cultures and conditions. This shifts the perception of CT infusion from a one-time activity that is an add-on to the "regular" curriculum to a core component of a transdisciplinary curriculum that builds students' abilities to solve complex disciplinary problems.

Teachers' Perceptions of Inquiry Project Impact

Finally, this study documents teachers' perceptions of the impact of their projects as expressed through interviews, presentations, and in project artifacts. Teachers felt their projects were successful in increasing student and teacher access to CT and CS education, exposing students to STEM career choices and opportunities, scaffolding teacher and student learning, building school and community support for CT and CS, and enhancing confidence through external recognition. In particular, teachers referenced the importance of building toward school contexts to support CT and CS education, as well as the value of recognition at the school, district, and community levels. As Israel et al. (2022) found, one barrier to CT infusion is low teacher buy-in, primarily due to limited resources, lack of schoolwide supports, and uncertainty about the academic benefits for learners. In this study, teachers who participated in practitioner inquiry had myriad opportunities to reflect deeply upon their own CT-infused teaching practices and the benefits for learners in their classrooms, build school and community buy-in, and receive recognition for their work. Other studies have documented the importance of building broader support at the schoolwide level for CT infusion practices, particularly in the elementary grades (Israel et al., 2015; Sherwood et al., 2020); however, more work is needed to better understand the ways in which structures function at the middle and high school levels. Further, more research that focuses on ways to engage all stakeholders (e.g., administrators, families, and community members) to build support for CT and CS education would make a valuable contribution to the literature.

Limitations

One limitation of this study is that it focuses only on the group of teachers who chose to apply for the *IC Partner Grant* program, and not on the other teachers who attended *Infusing Computing* PD and chose not to apply. It is our hope that our future work can highlight the conditions under which teachers are motivated and supported to pursue CT infusion and practitioner inquiry work in their schools and classrooms. We also hope to examine longitudinal case studies of teachers who participated in the project for all five years to trace their development and to contribute to gaps in the knowledge base regarding the sustainability and forms of CT infusion over time.

Conclusion

As Hayes (2011) argues, an action research or practitioner inquiry approach aims to create "sustainable, dependable change, which can be less interesting from a research standpoint than the implementation of novel solutions and the study of changes immediately following" (p. 13). While there have been many advances in our knowledge about CT integration and computer science education in recent years (Lee et al., 2020; Sands et al., 2018; Yadav et al., 2017), the mechanisms, barriers to, and supports for sustainable, dependable change in classrooms and schools remains an understudied topic. While these mechanisms may not always be "novel," it is essential to consider the long-term impact of programs and document solutions to create sustainable practices. We believe that this study offers one example of how research projects can build teacher autonomy and create structures for sustaining new pedagogical practices even after a research project ends.

The findings of this study can be used to support teachers and teacher educators who aim to build a culture of CT infusion within a PD, school, or district context. For those interested in designing learning experiences involving CT-infused disciplinary curricula, taking an incremental approach to gradually build learners' CT knowledge holds promise for both student and teaching learning. In addition, creating communities that are both discipline-specific (e.g., a group of math teachers) and interdisciplinary (e.g., a grade-level team) can serve as valuable supports for teachers to expand their professional communities and to examine new ideas from fresh perspectives. Further, we believe that a crucial, and often overlooked, element of CT infusion is taking up an inclusive approach that explicitly integrates multiple stakeholders, including administrators, parents, and community members. These efforts can build the broader support for CT infusion that is necessary for long-term implementation and sustainability. It is our hope that future research will continue to center and highlight teachers' voices as they engage in the complex work of building knowledge about CT infusion over time and across contexts.

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