A COMPARISON OF ONLINE AND FACE-TO-FACE PROFESSIONAL DEVELOPMENT FOR INCREASING THE ART AND SCIENCE CONTENT KNOWLEDGE OF NOVICE AND EXPERIENCED ELEMENTARY SCIENCE TEACHERS

Sage Andersen, The University of Texas at Austin
Bradley S. Hughes, University of California, Irvine
Corresponding Author Contact Information:
Sage Andersen
The University of Texas at Austin
George I. Sánchez Building, Room 4.404L
1912 Speedway, Stop D500, Austin, TX 78712 Email: sage.andersen@utexas.edu

ABSTRACT

This study compared two versions of the same elementary science professional development (PD) and curriculum program that were offered face-to-face and completely online, while keeping all content consistent between the two. Using quantitative analyses of pre- and posttests of content knowledge (CK), we evaluated the extent to which the online version of the PD compared to the face-to-face PD for increasing the earth science and art CK of upper elementary teachers required to teach an earth science and art integrated curriculum. Additionally, we explored how the impact of PD modality (online vs. face-to-face) on teachers' CK learning outcomes differed for novice and experienced teachers. Findings revealed significantly higher CK learning gains for teachers who participated in online PD compared with face-to-face PD, but with a small effect size. Subgroup analysis revealed that compared with experienced teachers, the novice teachers had significantly higher CK gains from participating in the online PD compared to the face-to-face version with a large effect size. We also discuss the implications for the design of large-scale online teacher PD.

Keywords: *professional development, teacher learning, content knowledge, science teacher education, online learning*

INTRODUCTION

In the current study, we focus on the role of professional development for increasing the art and science content knowledge (CK) for elementary science teachers to enable them to effectively teach science through the arts, which would support reform efforts that promote more equitable science learning experiences for students. Intensive professional development (PD) activities that engage teachers in learning over extended periods of time

(Boyle et al., 2005; Goldenberg & Gallimore, 1991; Guskey, 2002) have been shown to be effective in promoting teachers learning CK, which in turn improves instruction and student achievement (Gess-Newsome et al., 2019; Roth et al., 2011).

Despite this, teachers are less likely to enroll in long-term and intensive PD programs (Zhang et al., 2008), citing issues related to balancing the demands of work and family and the travel time to such programs (Vrasidas & Zembylas, 2004). These issues are compounded by the fact that intensive PD programs require large amounts of funding and human resources (Odden et al., 2002), which can lead to issues of scalability and sustainability (Higgins & Bonne, 2011). This has generated a growing interest in the potential of online courses to support teacher professional development (e.g., Butler & Leahy, 2010), which can address issues related to the scalability of PD, including cost, convenience, scheduling flexibility, accessibility, and the ability to reach more isolated populations (Alqarni, 2015; Marrongelle et al., 2013).

However, there is limited research comparing the impacts of online PD to more traditional face-to-face models, particularly when the content of the PD is the same. Furthermore, it is important to consider whether online PD is effective for *all* participating teachers, particularly those who are in the early years of their teaching career and require additional support for developing their CK.

This study focused on a National Science Foundation (NSF) grant-funded PD program that sought to prepare upper elementary teachers for interdisciplinary integration (Davis & Stephens, 2022) of the arts into earth science education and our efforts to make the PD program more sustainable and accessible to teachers via online course delivery. In the earlier face-to-face version of this PD program, participating teachers engaged in an immersive PD over one week (40 hours) during the summer. The goals of this PD were to train both novice and experienced teachers to teach earth science through inquiry and the arts, which necessitated that teachers develop or deepen their CK related to earth science and the elements of art used to teach earth science content in the curriculum. To achieve more sustainable dissemination of the program long term, we transitioned the program from face-to-face PD to fully online PD.

In the current study, we sought to evaluate the extent to which the online version of the PD compared to the face-to-face PD for increasing the earth science and art CK of upper elementary teachers required to teach an earth science and art integrated curriculum, when the content of the PD was held constant from face-to-face to online. Moreover, recognizing that the participating teachers varied both in the number of years teaching (and therefore in their prior levels of CK) and the extent to which they may have experience with online learning, we also sought to explore how PD modality (online vs. face-to-face) impacted teachers' CK learning outcomes and how this differed for novice and experienced teachers. In the following review of the literature, we first describe the reform context in science education that laid the foundation for the design of the focal PD program, including its focus on developing teachers' art and science CK. Next, we describe the theoretical foundations related to how teachers learn through professional development that guided the design of both versions of the PD program, including any implications when designing for novice and experienced teachers.

LITERATURE REVIEW

Importance of Developing Elementary Teachers Art and Science Content Knowledge

Recent reforms in science education based on decades of research that have been outlined in *A Framework for K–12 Science Education* (National Resource Council, 2012) and codified in the Next Generation Science Standards (NGSS; https://www.nextgenscience.org) call for a more integrated approach to science instruction that more authentically mirrors how scientists and engineers engage in their work to develop new understandings and solve problems for the natural and designed world (NGSS Lead States, 2013). While the NGSS promotes integration across STEM disciplines (i.e., science, technology, engineering, and math), proponents of the arts suggest that integrating the arts with science (as well as all STEM subjects, often referred to as STEAM) may be supportive for student learning in science (Daugherty, 2013). Arts integration has been shown to foster students' ability to think creatively and opens up new pathways for students' critical thinking and innovation (Hadzigeorgiou, 2016). Additionally, arts integration can create more equitable opportunities for all learners, particularly learners from linguistically minoritized communities, to communicate what they know and to actively co-construct new knowledge with their peers (Bube, 2021; Corrigan et al., 2022; Hardiman et al., 2014; Hughes et al., 2022).

Integrating the arts with science is particularly important at the elementary level since integration has been shown to ensure more time is spent on science learning, which is a common issue in elementary classrooms (Davis & Stephens, 2022). Further, elementary science learning sets the stage for students' science identity development (Davis & Stephens, 2022; Peters-Burton & Knight, 2022) and because many students at the elementary level are still learning to speak, read, and write in the language of instruction (e.g., English), they are particularly supported through the multimodal nature of learning science through the arts (Grapin, 2019).

Research has demonstrated that teachers are better able to teach integrated STEM or STEAM instruction when they hold a deeper conceptual understanding of the integrated content they need to teach (i.e., their own content knowledge) (Loewenberg Ball et al., 2008; Shulman, 1987). For example, when teachers specialize in science and hold deeper CK, they teach the science content more accurately and with more interactive and engaging methods for students (Sanders et al., 1993) and are more confident in their ability to effectively enact integrated STEM instruction (Margot & Kettler, 2019). Alternatively, teachers who have less CK in science tend to rely more heavily on textbooks and more often deliver content using teacher-centered practices (Abell, 2008). For these reasons, educational researchers have stressed the importance of developing teachers' CK to improve teaching and learning in science (Kind et al., 2022). Importantly, bringing STEAM-based reforms to the classroom will require teachers to have a deep conceptual understanding of not only the science content students are learning, but also the art content that they can use to support students' engagement in meaningful integrated art and science learning.

A growing body of research has demonstrated that professional development can play a very supportive role in increasing teachers' CK (Kind et al., 2022), which in turn can better prepare them to teach science in integrated ways (Peters-Burton & Knight, 2022). Exploring how professional development can be used to help elementary science teachers grow their art and science CK is important for several reasons. First, at the elementary level, fewer teachers have a strong background in the sciences, let alone in the practices that support science learning (Davis et al., 2006). Moreover, novice teachers who have been in the teaching profession for less than five years are less developed in their CK compared to more expert or experienced teachers (Schoenfeld, 2006).

Teacher Learning Through Professional Development

This study and its design are grounded in a synthesis of cognitive and social constructivist perspectives. From the cognitive perspective, learning is viewed as occurring within the individual as they assimilate and accommodate new ideas into existing schemas over time (Piaget, 1971). Building on this perspective, social constructivism posits that social interactions between individuals in a community can lead to greater shifts in learning (Vygotsky, 1978). Taken together, and in line with the perspectives of other prominent scholars, this study approaches knowledge as personally constructed and socially mediated (Driver et al., 1994; Windschitl, 2002). This view offers three important implications for how teachers learn through professional development in both online and face-to-face contexts.

First, and consistent with research studying cognitive change, is the implication that teacher learning occurs over long periods of time (Gallagher & Reid, 2002). A growing body of research has demonstrated that the development of teachers' CK is a gradual and difficult process that begins even before teachers enter the classroom and continues throughout a teachers' career (Cochran et al., 1993; Kind, 2009). This has major implications for professional development aimed at increasing elementary science teachers' CK, particularly since elementary teachers tend to have a limited background in science content compared to secondary teachers or content specialists (Cantrell et al., 2003; Davis et al., 2006; Yilmaz-Tuzun, 2008). If the teachers are in their first five years of teaching (i.e., novice teachers), they may also have brief or infrequent exposure to science content through teaching or using rigorous science curriculum (Cantrell et al., 2003). Given that it can take years to fully develop stable conceptions of science content and how to effectively teach that content (Simmons et al., 1999), effective PD for increasing teachers' CK requires learning experiences that span an extended period (Goldenberg & Gallimore, 1991; Guskey, 2002; Supovitz & Turner, 2000) and may be particularly important for novice teachers.

Second, the learning activities included in a PD program should be designed in a way that promotes cognitive change related to individual teacher's understanding of science content. More specifically, teachers should be introduced to new ways of thinking about science content and provided with learning activities that facilitate their assimilation or accommodation of these new ideas (Ebert & Crippen, 2010). Thus, well-designed learning activities should provide both novice and experienced teachers with opportunities to reflect on, refine, and deepen their understanding of the content they teach. Finally, teachers will be more likely to increase their content knowledge if they are provided with ample time and opportunities to interact with and learn from one another (Driver et al., 1994; Windschitl, 2002). Novice teachers provided with ample opportunities to interact with experienced teachers may benefit from the opportunity to learn from their more experienced peers (Cobb, 1994; Vygotsky, 1978). Taken altogether, it is important to pay attention to not only the time allotted to professional development opportunities for developing teachers' CK, but also to the design of specific learning experiences that can affect cognitive change for novice and experienced teachers alike, and to the nature of the social interactions available to them that could mediate teacher learning.

KEY FEATURES OF PROFESSIONAL DEVELOPMENT FOR PROMOTING TEACHER LEARNING

Duration of PD

PD is more effective at promoting teacher learning if it is sufficient in duration, including the extent to which the PD is facilitated over time (i.e., days or semesters) in addition to the number of hours spent on learning activities (Goldenberg & Gallimore, 1991; Guskey, 2002; Supovitz & Turner, 2000). Boyle et al. (2005) found that teachers who participated in a long-term PD course reported higher levels of change in their teaching practice compared to those who did not. In another study, Boyle et al. (2005) found evidence that teachers who participated in longer-term PD activities reported a significant change to one or more aspects of their teaching practice as a result of their participation in the PD. Research into pedagogical content knowledge (PCK) development has shown that PD activities that engage teachers in learning over extended periods of time have been shown to be more effective in improving all aspects of a teachers' PCK and in shifting teacher practice (Cochran et al., 1993; Kind, 2009). While there is general agreement on the need for more time-intensive PD, there is not yet a consensus on an exact number of hours needed to optimize PD impacts. However, research "shows support for activities that are spread over a semester (or intense summer institutes with follow-up during the semester) and include 20 hours or more of contact time." (Desimone, 2009, p. 184).

Design Features of PD that Promote Teacher Learning

Four major categories of effective learning activities that promote teacher learning arise from a review of the literature. First, PD should include a focus on core science content and a model of teaching strategies for the content (Collinson et al., 2009; Jeanpierre et al., 2005). PD that provides explicit instruction in models of teaching grounded in the content can lead to an increase in both teacher and student learning (Penuel et al., 2011).

Second, PD should provide opportunities for teachers to actively learn new content and teaching strategies (Collinson et al., 2009) and to practice using integrated science practices and skills (Jeanpierre et al., 2005). Similarly, Darling-Hammond and McLaughlin (2011) posit that:

> *Teachers learn by doing, reading, and reflecting (just as students do); by collaborating with other teachers; by looking closely at students and their work; and by sharing what they see (p. 83).*

Thus, providing teachers with opportunities to experience multiple perspectives to reflect on science teaching, such as experiential exploration of the curriculum from the viewpoint of the student learner in addition to the teacher point of view, may aid teachers to learn new CK while developing pedagogical strategies that best support teaching that content.

Third, PD should include opportunities to consider students' ideas about content topics, which can be accomplished using various learning activities such as analyzing real student artifacts, classroom video of instruction, and prewritten teaching cases that pose problems of practice (Heller et al., 2012). These types of activities support teachers in noticing students' ideas and provide teachers with opportunities to form a deeper conceptual and ideological understanding of content topics (Darling-Hammond & McLaughlin, 2011; Heller et al., 2012).

Fourth, PD should provide activities that promote teacher reflection and metacognition. For example, Ebert and Crippen (2010) found that when the reform message of a PD was communicated in such a way as to initiate stress appraisal, conceptual change occurred, producing changes in classroom practice. In this case, stress appraisal forces teachers to confront their beliefs about science content and practices in light of the reform message and to reevaluate their existing schemas (Piaget, 1971) related to science teaching. This study also suggests the need for frequent opportunities for teacher metacognition and formative assessment of teachers' conceptions about the content and science practices through, for example, journaling, reflection essays, lesson plans, and observations, to encourage teacher learning (Ebert & Crippen, 2010).

Opportunities for Collaboration and Social Interactions with Peers

It is well documented that teaching is a highly social endeavor and that teachers' practices are heavily influenced by the context in which they teach, including the interactions they have with fellow teachers (Driver et al., 1994; Windschitl, 2002). However, teachers often experience a lack of opportunity to learn with and from one another (DeMonte, 2013). As such, PD programs are widely recommended to provide the chance for teachers to collaborate (Collinson et al., 2009; DeMonte, 2013; Luft & Hewson, 2014; Wilson, 2013). Many PD programs that do show improvements in teacher learning incorporate opportunities for collaboration among teachers (DeMonte, 2013). These opportunities for collaboration may be particularly important for novice teachers who have much to learn regarding both their CK, and PCK more broadly (Schoenfeld, 2010), and can benefit from the ideas of more experienced peers (Cobb, 1994). Teachers' interactions may take many forms, such as participating in small group and whole group discussions of new ideas, small group and whole group feedback sessions, collaborative video analysis of classroom teaching and students' ideas, or approximations of practice with peers (Russ et al., 2016).

Methods and Challenges of Delivering Time-Intensive PD

Longer duration, face-to-face PD tends to be spread throughout a semester or school year, and in a few cases these PD sessions are offered on weekends so as not to disrupt the classroom (Odden et al., 2002). However, in most cases, to participate in school or district sanctioned PD, in-service teachers must either leave the classroom to participate or wait until in-service days, which are infrequent and, in some cases, also underutilized (Borko et al., 2010). Other programs use a summer institute format that takes place over a week or more during the summer, when teachers are not in the classroom (Odden et al., 2002). The struggle to find more ideal schedules to meet the needs of teachers and PD facilitators indicates the many tradeoffs involved with face-to-face training. This has generated a growing interest in the potential of online courses to support teacher professional development (Wilson, 2013).

Potential of Online PD

Online PD courses may differ in their duration and more often resemble the long-term, face-to-face PD that spans weeks or semesters rather than PD that is condensed into a single week like in a summer institute. There is also some variability in the nature of the interactions available to participants. For example, some online PD programs are designed to incorporate both synchronous and asynchronous components (often referred to as hybrid learning), while others are designed to be fully asynchronous, with assignments completed by participants without live (or real-time) interaction. For this reason, the choices made in the design of a PD, such as its duration and modality, will have major implications for the nature of the activities and opportunities for interaction incorporated into it. This, in turn, may make these experiences vastly different from those offered in a face-to-face PD. Thus, it becomes essential that when evaluating the potential of using online PD for teacher learning, the nature of the experiences that are provided to teachers in the online space must be considered (Moon et al., 2014). In addition, it is equally important to explore the extent to which these differences impact teachers' learning outcomes (Borko et al., 2010), particularly for novice teachers who are in the earlier stages of their professional learning trajectories.

Need for More Research

While there are many studies that explore the efficacy of online PD programs, very few have compared the efficacy of online PD versus more traditional face-to-face modalities (Lay et al., 2020), particularly when the content is held constant between the modalities. One such comparison study of a curriculum-based program showed no significant difference in outcomes by program modality (Fishman et al., 2013). This could suggest that online PD may hold great promise for enhancing the sustainability and accessibility of intensive PD programs without sacrificing learning outcomes for teachers. However, this study does not describe the nature of the learning activities and types of social interactions available in each PD modality or the theoretical basis of their design, nor do they relate these differences to the outcomes observed in the results (see Moon et al., 2014). Moreover, Fishman et al. (2013) occurred at the secondary level, which includes specialized teachers who more often major in a science field and, therefore, have more science CK than found among most elementary teachers. No previously published, large-scale experimental study has rigorously examined the impact of the online versus face-to-face PD modality on teachers' science and art CK at the elementary level. Furthermore, there has yet to be a study that explores any potential differences in impacts for novice and experienced teachers who may enter PD programs with varying degrees of CK and therefore may require varying needs of support.

RESEARCH QUESTIONS

In the current study, we sought to explore the following research questions:

1. How does online PD compare to traditional, face-to-face PD for increasing teachers' Earth Science and Art CK?
2. Does the impact of PD modality (online or face-to-face) on teachers' CK learning outcomes differ for novice and experienced teachers?

METHODS

The PD in this study was designed to prepare upper elementary school teachers to implement an inquiry and arts-integrated earth science curriculum developed as part of a large-scale curriculum and professional development program. The training provided participating teachers with equally immersive PD in methods of visual and performing arts (VAPA) as well as inquiry-based approaches for teaching a novel elementary science curriculum that is grounded in earth science content. The goals of this PD required teachers to develop CK related to earth science in addition to the elements of art used to teach earth science content in the curriculum.

Design of Face-to-face and Online PD

Teachers participated in one of two versions of the same Earth Science PD, which we will refer to as either face-to-face or online PD modalities. The face-to-face version of the program ran in 2013–2017 in a large school district in Southern California. Each year, the program focused on and provided curriculum and PD on one disciplinary content area of science (Earth Science in 2014-2015, Life Science in 2015-2016, and Physical Science in 2016-2017). The online version was designed using the face-to-face version as a template and model. To make this possible, all PD sessions from the face-to-face PD implementation were captured on video and these videos were edited and incorporated into the online version. This training approach also assisted our efforts toward fidelity to ensure that PD content remained the same across both modalities. In the following sections we describe the duration of each PD version, the types of learning activities included in each modality of the PD, and the nature of the opportunities for social interactions between teachers. We will focus on any aspects of the design particular to each modality and to what extent the design differed in potential affordances for teachers.

Duration and Modality of PD

The face-to-face PD was a week-long (40 hour) summer institute spread over one week, which was agreed upon by the facilitators as the most feasible face-to-face scheduling option with the fewest obstacles for the majority of participants involved. In this version of the program, teachers were brought to a central location where they participated in a combination of whole-group sessions and breakout sessions by grade level. The PD was led by a team made up of science trainers and teaching artists from the collaborating County Department of Education and the participating Performing Arts Center. By contrast, to address issues of accessibility and to fit teachers' busy schedules, the online course was designed to be completed by teachers asynchronously and at a flexible pace over a 12-week window of time. The decision to make the PD asynchronous was a design choice aimed toward providing as much flexibility to participating teachers as possible. This was also an important feature of the course since it took place during the fall, when teachers were working while they were enrolled in the course. The 12-week participation window was agreed upon in conjunction with district leaders, who were concerned that a shorter window of time would place undue stress on teachers who were also balancing a full teaching workload. Despite differences in the window of participation for each version, care was taken to ensure that the time-on-task duration of the PD was comparable across modalities. Both versions of the PD were designed to provide 40 hours of active professional development.

However, the nature of the online PD involved the potential for teachers to vary their time-on-task. For example, teachers who participated in the online PD could take more or less time to complete a given module depending on how quickly they were able to work through the content and participate in the activities. Those in the face-to-face version, however, were more strictly paced in the timing of individual sessions or planned activities within the face-to-face agendas. Teachers in the online PD could also choose to repeat content, rewatch videos, or pause and resume a particular section of the course to review particular ideas or to take notes on the ideas being presented. Though not strictly essential to online learning designs, this feature of the online PD was viewed as an affordance that would typically be desirable to most learners and curricular designers. In this way, the online modality could provide teachers with self-regulated and self-paced access to the ideas and activities designed for teacher learning over a longer period and in excess of 40 hours. Teachers in the face-to-face cohort were able to walk away from the PD with provided curricular materials and their own notes, but they did not have the opportunity to rewatch or repeat any of the activities that they engaged in during the synchronous, in person sessions.

Design Features, Collaboration, and Social Interactions in Each PD Modality

In line with current research on teacher learning, the focus of the learning activities built into both versions of the PD program was on the core science and art content and modeling of teaching strategies for the content (Collinson et al., 2009; Jeanpierre et al., 2005; Penuel et al., 2011). In the face-to-face PD, teachers were invited to participate from the perspective of students in the same STEAM lessons that were to be implemented in their classrooms during the academic year. Not only did this effectively model the science and art content and instructional strategies, but teachers also were able to actively engage in this content learning from the student perspective (Collinson et al., 2009; Darling-Hammond & McLaughlin, 2011; Jeanpierre et al., 2005; Penuel et al., 2011). This encouraged teachers to consider both their own current understandings of the science and art content in addition to how their students would experience the lessons, including any points of confusion or connection to students' prior knowledge.

In addition, these opportunities for active engagement provided spaces for teachers to collaborate with their peers by working together in small groups and whole groups in each learning activity. When designing the online version of the PD, we maximized the affordances of the online medium to provide teachers with opportunities to engage with the content in ways similar to the teachers in the face-to-face program. However, given the asynchronous nature of the online PD, all simulated lesson plans required teachers to participate individually rather than in small or whole group settings. Moments that required collaboration and peer-interaction were built into the simulated lessons to occur asynchronously. In both versions of the PD, care was also taken to consider students' ideas about content topics from the teacher perspective. This was accomplished by analyzing sample student artifacts created during each lesson and, in the case of the online PD, also included video clips of students producing those artifacts during classroom implementation of the lessons. The purpose of including these activities was to support teachers in noticing students' ideas and provide teachers with opportunities to form a deeper conceptual understanding of content topics (Darling-Hammond & McLaughlin, 2011; Heller et al., 2012).

Participants

The participants in this study included 205 upper elementary teachers from two large school districts in Southern California. Ninety-eight teachers participated in the face-to-face program during the 2014-2015 school year and 107 participated in the online program when it was first offered during the 2018-2019 school year. Teaching experience among the participating teachers ranged from one year to 33 years in the classroom, with an average of 14.83 years. The criteria for the teachers to be included in the selection pool was based primarily on whether they taught at an elementary school that was designated as receiving Title I funding. All teachers volunteered to participate in the PD with consent from their district and school principal. Teachers were compensated for their participation with a choice of stipend or course credits.

Data Sources

While multiple data sources were collected for participating teachers throughout the PD and subsequent curriculum implementation, the focus of this study was on the CK teachers gained as a result of their participation in the PD portion of the study. In order to measure changes in the participating teachers' earth science and art CK, we utilized researcher-designed assessments consisting of 27 multiple choice questions. The questions were designed to align with the earth science content standards addressed in the PD and corresponding lessons, including the specific vocabulary and any known scientific misconceptions for the earth science content, in addition to the arts-based CK required to teach science through the arts in the curriculum that corresponded with the PD.

Participating teachers from the face-to-face program completed paper-based tests prior to beginning the PD and after completing the 40-hour face-to-face PD program. Participating teachers from the online program completed the tests online via a Qualtrics survey prior to beginning the PD and after completing all 40 hours of the online program. In addition to assessing teachers' earth science CK, the assessment collected demographic data for each teacher, which included two of our independent variables of interest: teacher grade level and number of years of teaching experience.

Data Analysis

The dependent variables of interest from this measure were CK change scores, calculated by subtracting each participant's pretest score from their posttest score, which were used to discern any program-level impacts on teachers' CK. By using CK change scores, we were better able to reveal interactions between additional categorical independent variables necessary to explore the research questions of this study and also reduce the impacts of any differences in pretest score at baseline to instead look for overall growth.

This study focused on two independent variables: version of PD (online or face-to-face) and number of years of teaching experience. The first independent variable, PD modality, indicates which version of the program that the teacher participated in (online or face-to-face). As the two PD programs were offered in different years, teachers did not have a choice in the PD modality. Overall, we had 98 teachers participate in the face-to-face version and 107 teachers participate in the online version of the PD. Of these, 98 teachers from the face-to-face PD and 82 teachers from the online PD completed both the pre- and posttest and therefore were included in the analyses. Finally, the second independent variable was the number of years of teaching experience for each teacher. This is a continuous variable that was collected using demographic questions included at the beginning of each pretest and posttest. This measure was recoded to group the teachers into two categories: novice or experienced teachers. In accordance with the research literature on teaching experience (e.g., Davis et al., 2006), those teachers with 0–5 years of experience were recategorized as novice teachers and those with 6 or more years of experience were categorized as experienced teachers. Based on this recoded variable, there were a total of 28 novice and 177 experienced teachers who participated in the program. Of these, 26 novice and 154 experienced teachers completed the pre- and posttests and were therefore included in the analyses. As with any large-scale PD program, we did experience some teacher attrition, which led to missing posttest scores for 25 of the 205 participating teachers. To manage missing data, pairwise deletion was employed where teachers with missing posttest scores were excluded from the analyses.

To explore both research questions, we conducted a two-way ANOVA in which the dependent variable was the earth science and art CK change score, pooled for all grade levels, and the independent variables were teaching experience (novice or experienced) and PD modality (online or face-to-face). Next, to explore any significant interactions further, we conducted post hoc testing where we split the data file by teaching experience and performed two one-way ANOVAs to look at any differences in CK change scores by PD modality for novice vs. experienced teachers. Finally, we calculated the effect size of any significant interactions to determine the extent to which any variance in the dependent variables was explained by the independent variables.

RESULTS

Table 1 contains the descriptive results for the pretest, posttest, and calculated CK change scores. Two hundred five teachers participated in the pretest of CK. The average pretest score was *M* = 21.93, with SD = 2.35. One hundred eighty teachers completed the posttest of CK, with an average score of M = 23.71 and SD = 1.68. Using the pre- and posttest scores, we calculated CK change scores for the 180 teachers who completed both the pre- and posttest. For these teachers, we saw a mean CK change score of *M* = 1.81, *SD* = 2.18.

Table 1.
CK Test Score Descriptive Statistics

CK Measure	*N*	Minimum	Maximum	*M*	*SD*
Pretest Score Total	205	13	26	21.93	2.353
Posttest Score Total	180	18	26	23.71	1.676
CK Change Score (Posttest-Pretest)	180	-3.00	9.00	1.8111	2.17859
Valid N (listwise)	180				

To explore both research questions, we conducted a two-way ANOVA in which the dependent variable was the earth science and art CK change score, pooled for all grade levels, and the independent variables were teaching experience (novice or experienced) and PD modality (online or face-to-face). Table 2 summarizes the descriptive statistics for this analysis and Table 3 presents the results for the two-way ANOVA.

Table 2.
Descriptive Statistics for Two-Way ANOVA

Teacher Category	Modality of PD	*M*	*SD*	*N*
Novice Teachers	Face-to-face	.9286	1.59153	14
	Online	3.6667	2.83912	12
	Total	2.1923	2.60798	26
Experienced Teachers	Face-to-face	1.7500	1.95661	84
	Online	1.7429	2.27581	70
	Total	1.7468	2.10061	154
Total	Face-to-face	1.6327	1.92320	98
	Online	2.0244	2.44432	82
	Total	1.8111	2.17859	180

Table 3.
Two-Way ANOVA Exploring Change Score by PD Modality and Teaching Experience

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	52.861[a]	3	17.620	3.892	.010	.062
Intercept	361.517	1	361.517	79.861	.000	.312
teachexp	6.716	1	6.716	1.484	.225	.008
pdmodality	41.216	1	41.216	9.105	.003	.049
teachexp * pdmodality	41.648	1	41.648	9.200	.003	.050
Error	796.717	176	4.527			
Total	1440.000	180				
Corrected Total	849.578	179				

[a] R Squared = .062 (Adjusted R Squared = .046)

RQ1: How does online PD compare to traditional, face-to-face PD for increasing teachers' Earth Science and Art CK?

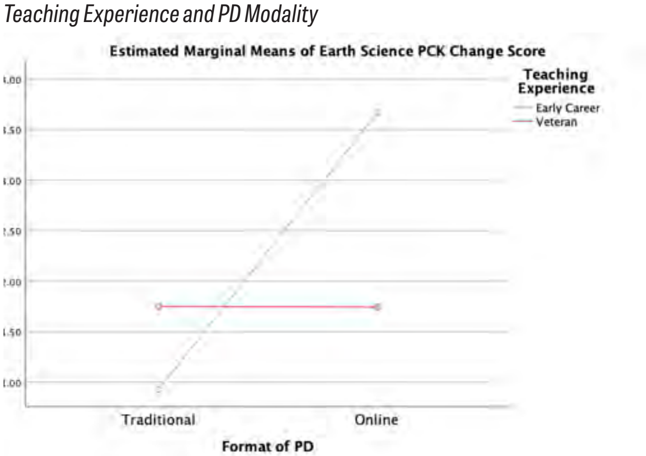
When we compared outcomes by modality, the online group had greater mean CK change scores

(M = 2.02, SD = 2.44) than the face-to-face group (M = 1.63, SD = 1.92). The results for the main effect of the PD version on the CK change scores revealed that this was a significant difference, where $F(1, 176) = 9.105$), $p = .003$, with the online program leading to higher CK change scores. However, the calculated effect size, eta-squared, was small ($\eta^2 = .049$) and indicated that only 4.9% of variance in CK change scores was explained by the PD modality.

RQ2: Does the impact of PD modality (online or face-to-face) on teachers' CK learning outcomes differ for novice and experienced teachers?

When we compared outcomes by teaching experience, we saw that novice teachers earned higher CK change scores (M = 2.19, SD = 2.61) than experienced teachers (M = 1.74, SD = 2.10). However, the results for the main effect of teaching experience on CK change scores revealed no significant difference, where $F(1, 176) = 1.484$, p =.225. Next, looking at the interaction between teaching experience and PD version, the results revealed a significant interaction, where $F(1, 176) = 9.200$, $p = .003$. The calculated effect size, eta-squared, was small ($\eta^2 = .050$) and indicated that 5% of variance in CK change scores was explained by the interaction between PD version and teaching experience. Figure 1 shows a plot of the estimated marginal means of the CK change score by teaching experience and by PD version.

Figure 1.
Estimated Marginal Means Change Score by Teaching Experience and PD Modality



To explore the significant interaction further, we conducted post hoc testing where we split the data file by teaching experience and performed a one-way ANOVA to look at any differences in CK change scores by PD modality for novice versus experienced teachers. The results for both one-way ANOVA analyses are presented in Tables 4 and 5. For experienced teachers, the results shown in Figure 1 and Table 2 appear to reveal little difference in CK change scores across the two PD modalities. Experienced teachers in the online group had a mean CK change score of M = 1.74, SD = 2.28 while those in the face-to-face group had a mean CK change score of M = 1.75, SD = 1.96. As shown in Table 4, for experienced teachers, this difference in CK change scores across the two PD modalities was not significant, with $F(1, 152) = .000$, $p = .983$.

Table 4.
One-Way ANOVA Exploring Change Score by PD Modality for Experienced Teachers

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.002	1	.002	.000	.983
Within Groups	675.121	152	4.442		
Total	675.123	153			

As shown in Figure 1 and Table 2, the novice teachers appeared to benefit more from the online program with a mean CK change score of M = 3.67, SD = 2.84 versus the face-to-face program which had a mean CK change score of M = .93, SD = 1.59. Results from the post hoc testing revealed that this was a significant difference, with $F(1, 24) = 9.562$, $p = .005$, with novice teachers in the online course showing significantly higher CK change scores (Table 5). The calculated effect size, eta-squared, ($\eta^2 = .2849$) was large and indicated that 28.49% of the variance in the dependent measure was explained by the independent variable.

Table 5.
One-Way ANOVA Exploring Change Score by PD Modality for Early Career Teachers

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	48.443	1	48.443	9.562	.005
Within Groups	121.595	24	5.066		
Total	170.038	25			

DISCUSSION

As research continues to highlight the importance of content knowledge, teacher professional development has become an area of intensive focus. Given that CK develops over long periods of time (Gallagher & Reid, 2002) and requires more intensive forms of professional learning (Cochran et al., 1993; Kind, 2009), the research community has become increasingly interested in the potential of online learning and its applications to professional development (e.g., Butler & Leahy, 2010). Online learning may provide a more sustainable, affordable, and accessible platform for supporting teachers' continued growth (Alqarni, 2015; Marrongelle et al., 2013). However, there is currently limited research exploring how online learning compares to more traditional face-to-face PD for developing elements of teachers' PCK.

The results of this study comparing the effect of face-to-face and online versions of the program on teachers' CK development were promising. While both the online and face-to-face programs led to overall gains in teachers' CK, teachers who participated in the online PD did experience significantly higher gains in their CK scores. However, it is important to note that the effect size of the gain in the scores was very small (Cohen, 1988). These results suggest that online PD can be used to effectively increase the CK for upper elementary teachers, and more importantly, that it will not reduce learning gains compared to face-to-face models, which are widely used. Furthermore, these results are consistent with a similar study that found that online PD can be an effective alternative to a face-to-face PD for teacher learning (Fishman et al., 2013). However, while Fishmen et al. (2013) kept content constant across modalities, they did not address the theoretical design used in developing the online or face-to-face versions compared in their study (Moon et al., 2014). We sought to build on this very important work by specifically focusing on the opportunities for learning and social interaction afforded by each design modality and incorporating these opportunities in the design of both versions of the program, where possible.

The results of comparing the impact of PD modality for novice and experienced teachers highlight other potential affordances of online PD for novice teachers. In particular, we see that novice teachers who participated in the online PD had significantly higher gain in CK scores compared to novice teachers who participated in the face-to-face PD. The effect sizes we calculated using eta squared were large (Cohen, 1988), suggesting that the difference in modality (face-to-face or online) accounted for a large percentage of the variation seen in the results between teachers in each group. Importantly, there was no significant difference in gain for the scores of the experienced teachers between the two versions of the program, and experienced teachers in both cohorts exhibited significant gains in their CK. In addition, when we compared teachers' CK learning scores independent of PD modality, there was no significant difference between the learning gains experienced by early career and experienced teachers. Thus, the online version differentially supported novice teachers' CK development, while simultaneously benefiting experienced teachers in significantly raising their CK. This is particularly important when we consider that novice teachers have been shown to enter the classroom with significantly lower levels of PCK (Davis et al., 2006; Schoenfeld, 2010), and, therefore, are considered to have a high need for intensive professional learning experiences aimed at developing both their content and pedagogical knowledge (Boyle et al., 2005; Goldenberg & Gallimore, 1991; Guskey, 2002). In the following discussion, we will highlight a few major differences between the two PD modalities for some insight that might further illuminate the results of this study.

During the design of both versions of the PD program in this study, many aspects were intentionally held constant. First, the content covered in the online PD version was identical to the content used in the face-to-face PD because we incorporated video from the original face-to-face PD in the online design. This ensured that the facilitators and nuances of content delivery during PD implementation were held constant. Additionally, similar numbers of opportunities for interaction with other teachers were maintained by adding pause points for peer interaction in the virtual space, which provided teachers with opportunities to engage with the content in similar ways to those who participated in the face-to-face PD. Finally, we designed both PD programs to require 40 hours of engagement with the content and corresponding learning activities.

While many aspects of the PD design were held constant, the duration of the PD over time differed significantly between the online and face-to-face cohorts. In particular, the face-to-face cohort met over the course of one week, whereas members of the online cohort were able to maintain sustained collaboration through the course activities over 12 weeks. PCK and its components can take a long time to develop, particularly for novice teachers (Simmons et al., 1999). It is possible that this extended access to peers and resources in the online modality provided novice teachers with a greater degree of support throughout the year as well as the time needed for these new concepts to take root in their science CK and practice. This aligns with research conducted on the supportive conditions necessary for novice teachers, which indicates that novice teachers value working with more experienced peers and sharing in resources but often do not have these opportunities (Burke et al., 2015).

In addition, the nature of the virtual learning space allowed teachers to participate at their own pace, including choice of when and from where teachers participate and choice in learner navigability, including the ability for teachers to replay, fast forward, or even repeat material as needed. These affordances were unique to the online PD, since teachers participating in the face-to-face PD did not have the option to access learning experiences at different times or speeds or to repeat any activities. In a survey of teachers who had participated in online PD, Parsons et al. (2019) found that teachers "perceived the ability to access materials anytime as the most important benefit of online PD" (p. 37). Thus, it is reasonable to assume that this major difference between the online and face-to-face versions of the PD could account for some of the differential impacts of teacher learning observed in the current study. However, the Learning Management System used to deliver the online PD in this study was not capable of tracking any differences in how novice or experienced teachers made use of these affordances. Therefore, future studies should explore the extent to which such features are valued and utilized by different populations of teachers.

One limitation of this study is the nature of the program timeline, which required the face-to-face version of the course to run first so that it could be video recorded and the online version following behind after all three years of the face-to-face program were implemented. As a multiyear study, this means that there are inherent differences in the status of the Next Generation Science Standards roll out in the state of California, which could have led to differences in teachers' initial CK for the online and face-to-face cohorts. However, this limitation was partially remedied by using CK change scores, which better captures gains in CK related to the program and works to blind the data to differences in pretest scores. In addition, as previously mentioned, the two PD versions spanned a different number of weeks even though the content covered was the same.

Future studies could also explore the types of identity-based roles taken up by teachers in online versus face-to-face PD and any inherent influences on learner behaviors and intellectual risk-taking. Social factors in any group setting can have significant impacts on the way teachers, particularly new teachers, engage in the social interactions designed for teacher learning. While we expect that the online PD spaces will alter the social dynamics between novice and experienced teachers that might exist with face-to-face spaces, the Learning Management System used in the design of this study did not provide the nuanced data required to adequately explore these lines of investigation. Further research into the potential of online PD, particularly for novice teachers, should explore the affective experiences of participating teachers and any differences in these experiences across PD modalities. Within the field of online learning, the availability of assessment tools based on user-experience has recently grown as a useful resource to explore the nuances of how online learning design can impact teacher learning.

CONCLUSIONS

Throughout the course of this study, we saw evidence of many of these affordances of online learning as a result of transitioning our PD and curriculum program to a fully online modality. For example, the online version of the program made it possible for the participating district to provide in-depth learning experiences to teachers that were both convenient and human-centered in their design and implementation. Such online training is typically more affordable and sustainable both economically and for the personnel involved. In addition, the online modality allowed us to maintain the fidelity of content from instance to instance of the PD course and eliminated any differences in content or experience based on differences in PD facilitators or even changes in PD staff over time, as would be more common in a traditional face-to-face PD program.

The findings from this study add to an existing body of knowledge exploring the potential of online PD and suggest that online PD can be an effective tool for increasing all teachers' CK, with the potential to differentially benefit novice teachers. Exploring how online PD can be used to help elementary science teachers, particularly novice teachers, in growing their CK is important since fewer teachers at the elementary level have a strong background in the sciences, let alone in the practices that support science learning (Davis et al., 2006). This issue is compounded for novice teachers in elementary spaces because they are less likely to have had significant exposure to science content through teaching or use of rigorous science curriculum (Cantrell et al., 2003). This study sheds light on the ways in which online PD could prove instrumental for teacher learning while also addressing other issues of access to high quality, time-intensive PD while paying attention to the types of learning and social experiences necessary for teacher learning.

Funding: This study was part of the Equitable Science Curriculum for integrating arts in Public Education (ESCAPE) funded by the National Science Foundation [grant number NSF DRL-1321343, 2013-2020].

References

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? International Journal of Science Education, 30(10), 1405–1416. https://doi.org/10.1080/09500690802187041

Alqarni, A. S. (2015). The effectiveness of online professional development for teachers. In Proceedings of E-Learn: World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education (pp. 1384–1390). Association for the Advancement of Computing in Education. https://www.learntechlib.org/primary/p/152259/

Borko, H., Jacobs, J., & Koellner, K. (2010). Contemporary approaches to teacher professional development. In P. Peterson, E. Baker, & B. McGaw (Eds.), International encyclopedia of education (3rd ed., pp. 548–556). Elsevier. https://doi.org/10.1016/B978-0-08-044894-7.00654-0

Boyle, B., Lamprianou, I., & Boyle, T. (2005). A longitudinal study of teacher change: What makes professional development effective? Report of the second year of the study. School Effectiveness and School Improvement, 16(1), 1–27. https://doi.org/10.1080/09243450500114819

Bube, A. (2021). Educational potentials of embodied art reflection. Phenomenology and the Cognitive Sciences, 20(3), 423–441. https://doi.org/10.1007/s11097-020-09685-z

Burke, P. F., Aubusson, P. J., Schuck, S. R., Buchanan, J. D., & Prescott, A. E. (2015). How do early career teachers value different types of support? A scale-adjusted latent class choice model. Teaching and Teacher Education, 47, 241–253. https://doi.org/10.1016/j.tate.2015.01.005

Butler, D., & Leahy, M. (2010). Moving towards innovation: The development of a sustainable framework for teacher professional development. In D. Gibson & B. Dodge (Eds.), Proceedings of SITE 2010—Society for Information Technology & Teacher Education International Conference (pp. 3985–3992). Association for the Advancement of Computing in Education. https://www.learntechlib.org/primary/p/34003/

Cantrell, P., Young, S., & Moore, A. (2003). Factors affecting science teaching efficacy of preservice elementary teachers. Journal of Science Teacher Education, 14(3), 177–192. https://doi.org/10.1023/A:1025974417256

Cobb, P. (1994). Where is the mind? Constructivist and sociocultural perspectives on mathematical development. Educational Researcher, 23(7), 13–20. https://doi.org/10.3102/0013189X023007013

Cochran, K. F., DeRuiter, J. A., & King, R. A. (1993). Pedagogical content knowing: An integrative model for teacher preparation. Journal of Teacher Education, 44(4), 263–272. https://doi.org/10.1177/0022487193044004004

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Collinson, V., Kozina, E., Kate Lin, Y.-H., Ling, L., Matheson, I., Newcombe, L., & Zogla, I. (2009). Professional development for teachers: A world of change. European Journal of Teacher Education, 32(1), 3–19. https://doi.org/10.1080/02619760802553022

Corrigan, M., Grove, D., Wong, J., Andersen, S., Hughes, B. (2022). Finding Nothing is Something: Shrinking the Gap between Emerging Bilingual Learners and English Fluent Students (Case in Point). *International Journal of Educational Methodology, 8*(1), 11-28. https://doi.org/10.12973/ijem8.1.11

Darling-Hammond, L., & McLaughlin, M. (2011). Policies that support professional development in an era of reform. Phi Delta Kappan, 92(6), 81–92. https://doi.org/10.1177/003172171109200622

Daugherty, M. K. (2013). The prospect of an “A” in STEM education. Journal of STEM Education: Innovations and Research, 14(2), 2. https://www.jstem.org/jstem/index.php/JSTEM/article/view/1744

Davis, E. A., Petish, D., & Smithey, J. (2006). Challenges new science teachers face. Review of Educational Research, 76(4), 607–651. https://doi.org/10.3102/00346543076004607

Davis, E. A., & Stephens, A. (Eds.). (2022). Science and engineering in preschool through elementary grades: The brilliance of children and the strengths of educators. National Academies Press. https://doi.org/10.17226/26215

DeMonte, J. (2013). High-quality professional development for teachers: Supporting teacher training to improve student learning. Center for American Progress. https://www.americanprogress.org/article/high-quality-professional-development-for-teachers/

Desimone, L. M. (2009). Improving impact studies of teachers’ professional development: Toward better conceptualizations and measures. Educational Researcher, 38(3), 181–199. https://doi.org/10.3102/0013189X08331140

Driver, R., Asoko, H., Leach, J., Scott, P., & Mortimer, E. (1994). Constructing scientific knowledge in the classroom. Educational Researcher, 23(7), 5–12. https://doi.org/10.3102/0013189X023007005

Ebert, E. K., & Crippen, K. J. (2010). Applying a cognitive-affective model of conceptual change to professional development. Journal of Science Teacher Education, 21(3), 371–388. https://doi.org/10.1007/s10972-009-9183-2

Fishman, B., Konstantopoulos, S., Kubitskey, B. W., Vath, R., Park, G., Johnson, H., & Edelson, D. C. (2013). Comparing the impact of online and face-to-face professional development in the context of curriculum implementation. Journal of Teacher Education, 64(5), 426–438. https://doi.org/10.1177/0022487113494413

Gallagher, J. M., & Reid, D. K. (2002). The learning theory of Piaget and Inhelder. iUniverse.

Gess-Newsome, J., Taylor, J. A., Carlson, J., Gardner, A. L., Wilson, C. D., & Stuhlsatz, M. A. M. (2019). Teacher pedagogical content knowledge, practice, and student achievement. International Journal of Science Education, 41(7), 944–963. https://doi.org/10.1080/09500693.2016.1265158

Goldenberg, C., & Gallimore, R. (1991). Changing teaching takes more than a one-shot workshop. Educational Leadership, 49(3), 69–72.

Grapin, S. (2019). Multimodality in the new content standards era: Implications for English Learners. TESOL Quarterly, 53(1), 30–55. https://doi.org/10.1002/tesq.443

Guskey, T. R. (2002). Professional development and teacher change. Teachers and Teaching, 8(3), 381–391. https://doi.org/10.1080/135406002100000512

Hadzigeorgiou, Y. (2016). 'Artistic' science education. In Y. Hadzigeorgiou (Ed.), Imaginative science education: The central role of imagination in science education (pp. 185–215). Springer International Publishing. https://doi.org/10.1007/978-3-319-29526-8_7

Hardiman, M., Rinne, L., & Yarmolinskaya, J. (2014). The effects of arts integration on long-term retention of academic content. Mind, Brain, and Education, 8(3), 144–148. https://doi.org/10.1111/mbe.12053

Heller, J. I., Daehler, K. R., Wong, N., Shinohara, M., & Miratrix, L. W. (2012). Differential effects of three professional development models on teacher knowledge and student achievement in elementary science. Journal of Research in Science Teaching, 49(3), 333–362. https://doi.org/10.1002/tea.21004

Higgins, J., & Bonne, L. (2011). The challenge of sustaining and scaling up teacher professional learning and development in mathematics [Editorial]. Mathematics Teacher Education and Development, 13(1), 1–5. https://mted.merga.net.au/index.php/mted/article/view/43

Hughes, B. S., Corrigan, M. W., Grove, D., Andersen, S., & Wong, J. T. (2022). Integrating arts with STEM and leading with STEAM to increase science learning with equity for emerging bilingual learners in the United States. *International Journal of STEM Education*, 9(1), 1-19. https://doi.org/10.1186/s40594-022-00375-7

Jeanpierre, B., Oberhauser, K., & Freeman, C. (2005). Characteristics of professional development that effect change in secondary science teachers' classroom practices. Journal of Research in Science Teaching, 42(6), 668–690. https://doi.org/10.1002/tea.20069

Kind, V. (2009). Pedagogical content knowledge in science education: Perspectives and potential for progress. *Studies in Science Education*, *45*(2), 169–204. https://doi.org/10.1080/03057260903142285

Kind, V., Park, S., & Ho Chan, K. K. (2022). Science teacher professional knowledge and its relationship to high-quality science instruction. In J. A. Luft & M. G. Jones (Eds.), Handbook of research on science teacher education (pp. 329–339). Routledge. https://doi.org/10.4324/9781003098478-29

Lay, C. D., Allman, B., Cutri, R. M., & Kimmons, R. (2020). Examining a decade of research in online teacher professional development. Frontiers in Education, 5, 573129. https://doi.org/10.3389/feduc.2020.573129

Loewenberg Ball, D., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? Journal of Teacher Education, 59(5), 389–407. https://doi.org/10.1177/0022487108324554

Luft, J. A., & Hewson, P. W. (2014). Research on teacher professional development programs in science. In N. G. Lederman & S. K. Abell (Eds.), Handbook of research on science education (vol. 2, pp. 889–909). Routledge. https://doi.org/10.4324/9780203097267

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. International Journal of STEM Education, 6, 2. https://doi.org/10.1186/s40594-018-0151-2

Marrongelle, K., Sztajn, P., & Smith, M. (2013). Scaling up professional development in an era of common state standards. Journal of Teacher Education, 64(3), 202–211. https://doi.org/10.1177/0022487112473838

Moon, J., Passmore, C., Reiser, B. J., & Michaels, S. (2014). Beyond comparisons of online versus face-to-face PD: Commentary in response to Fishman et al., "Comparing the impact of online and face-to-face professional development in the context of curriculum implementation." Journal of Teacher Education, 65(2), 172–176. https://doi.org/10.1177/0022487113511497

NGSS Lead States. (2013). Next generation science standards: For states, by states. The National Academies Press. https://www.nextgenscience.org/

Odden, A., Archibald, S., Fermanich, M., & Gallagher, H. A. (2002). A cost framework for professional development. Journal of Education Finance, 28(1), 51–74. https://www.jstor.org/stable/40704157

Parsons, S. A., Hutchison, A. C., Hall, L. A., Parsons, A. W., Ives, S. T., & Leggett, A. B. (2019). U.S. teachers' perceptions of online professional development. Teaching and Teacher Education, 82, 33–42. https://doi.org/10.1016/j.tate.2019.03.006

Penuel, W. R., Gallagher, L. P., & Moorthy, S. (2011). Preparing teachers to design sequences of instruction in earth systems science: A comparison of three professional development programs. American Educational Research Journal, 48(4), 996–1025. https://doi.org/10.3102/0002831211410864

Peters-Burton, E. E., & Knight, K. L. (2022). Integrated STEM teacher education: An opportunity for promoting equity. In J. A. Luft & M. G. Jones (Eds.), Handbook of research on science teacher education (pp. 465–476). Routledge. https://doi.org/10.4324/9781003098478-41

Piaget, J. (1971). Biology and knowledge: An essay on the relations between organic regulations and cognitive processes. University of Chicago Press.

Roth, K. J., Garnier, H. E., Chen, C., Lemmens, M., Schwille, K., & Wickler, N. I. Z. (2011). Videobased lesson analysis: Effective science PD for teacher and student learning. Journal of Research in Science Teaching, 48(2), 117–148. https://doi.org/10.1002/tea.20408

Russ, R. S., Sherin, B. L., & Sherin, M. G. (2016). What constitutes teacher learning? In D. H. Gitomer & C. A. Bell (Eds.), Handbook of research on teaching (5th ed., pp. 391–438). AERA. https://doi.org/10.3102/978-0-935302-48-6_6

Sanders, L. R., Borko, H., & Lockard, J. D. (1993). Secondary science teachers' knowledge base when teaching science courses in and out of their area of certification. Journal of Research in Science Teaching, 30(7), 723–736. https://doi.org/10.1002/tea.3660300710

Schoenfeld, A. H. (2006). What Doesn't Work: The Challenge and Failure of the What Works Clearinghouse to Conduct Meaningful Reviews of Studies of Mathematics Curricula. *Educational Researcher*, *35*(2), 13–21. https://doi.org/10.3102/0013189X035002013

Shulman, L. (1987). Knowledge and teaching: Foundations of the new reform. Harvard Educational Review, 57(1), 1–23. https://doi.org/10.17763/haer.57.1.j463w79r56455411

Simmons, P. E., Emory, A., Carter, T., Coker, T., Finnegan, B., Crockett, D., Richardson, L., Yager, R., Craven, J., Tillotson, J., Brunkhorst, H., Twiest, M., Hossain, K., Gallagher, J., Duggan‐Haas, D., Parker, J., Cajas, F., Alshannag, Q., McGlamery, S., … Labuda, K. (1999). Beginning teachers: Beliefs and classroom actions. Journal of Research in Science Teaching, 36(8), 930–954. https://doi.org/10.1002/(SICI)1098-2736(199910)36:8<930::AID-TEA3>3.0.CO;2-N

Supovitz, J. A., & Turner, H. M. (2000). The effects of professional development on science teaching practices and classroom culture. Journal of Research in Science Teaching, 37(9), 963–980. https://doi.org/10.1002/1098-2736(200011)37:9<963::AID-TEA6>3.0.CO;2-0

Vrasidas, C., & Zembylas, M. (2004). Online professional development: Lessons from the field. Education + Training, 46(6/7), 326–334. https://doi.org/10.1108/00400910410555231

Vygotsky, L. S. (1978). Mind in society: The development of higher psychological processes. Harvard University Press. https://doi.org/10.2307/j.ctvjf9vz4

Wilson, S. M. (2013). Professional development for science teachers. Science, 340(6130), 310–313. https://doi.org/10.1126/science.1230725

Windschitl, M. (2002). Framing constructivism in practice as the negotiation of dilemmas: An analysis of the conceptual, pedagogical, cultural, and political challenges facing teachers. Review of Educational Research, 72(2), 131–175. https://doi.org/10.3102/00346543072002131

Yilmaz-Tuzun, O. (2008). Preservice elementary teachers' beliefs about science teaching. Journal of Science Teacher Education, 19(2), 183–204. https://doi.org/10.1007/s10972-007-9084-1

Zhang, T., McConnell, T. J., Lundeberg, M. A., Koehler, M. J., Stanaway, J., Zhang, M., Urban-Lurain, M., Eberhardt, J., & Parker, J. (2008, January 10). If you build it, why will they come back?—Motivation of teachers to reenroll in a professional development project [Paper presentation]. International Conference of the Association of Science Teacher Educators, Saint Louis, MO, United States.