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Comparative Study of High-Quality Professional Development for High School Biology in a Face-to-Face versus Online Delivery Mode

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ABSTRACT: Online professional development (PD) can support broader accessibility than traditional face-to-face PD. However online delivery presents challenges for characteristics of high-quality PD, such as collaborative knowledge building and community development, that have proven positive outcomes in face-to-face modes. A few comparative studies have demonstrated equivalent outcomes when PD activities have been translated from a successful face-to-face implementation to an online format. This study investigates whether an online version of PD for high school biology teachers on using computer-supported complex systems curriculum and instruction can achieve the same high impact as the face-to-face version. We describe changes in design decisions to accommodate the online mode and measure impact on teachers' perceptions of their experiences and student outcomes. The results show positive teacher perceptions in both PD formats and roughly equal student outcomes. However, teachers articulated other benefits to online activities that indicate opportunities for improved access to high-quality PD.

Keywords: Online professional development, Complex systems, Comparative study

1. Introduction

Research has shown that high-quality PD can improve teachers' practice and have a positive impact on student outcomes (e.g., Desimone & Garet, 2015; Fischer et al., 2018). However, for many teachers who are geographically isolated, access to high-quality PD is a primary limiting factor in their professional growth and ability to address the changing landscape of science education (Peltola et al., 2017; Wei et al., 2009; Wilson, 2013). For these teachers, face-to-face PD is often not an option. As Hill (2015) and others have noted, traditional face-to-face PD is expensive and limited in its ability to scale. Offering PD online is a rapidly growing option that can support broader accessibility—anywhere, anytime—at lower costs (Dede et al., 2019; U.S. Department of Education, 2010). Yet, despite its promise, there are challenges in designing high-quality online PD that incorporates known best practices, such social learning and collaborative knowledge building, that have proven effective in face-to-face PD (Dede, 2009; Moon et al., 2014). A report by the U.S. Department of Education (2010) suggested that online PD can provide a more accessible option if it can be shown to be as effective as face-to-face PD. Some studies have demonstrated (e.g., Fishman et al., 2013) that PD offered online can be as successful as face-to-face modes in promoting improved teacher knowledge, classroom practice, and student outcomes. However, very few studies have directly compared effectiveness in both formats (Moon et al., 2014; U.S. Department of Education, 2010). Our study undertakes such a comparison.

From 2010 to 2014 we developed and delivered face-to-face PD to high school biology teachers using computer-supported complex systems curriculum and instruction. The PD was built on known characteristics of high-quality PD for science teachers (reviewed below). Findings from several studies of the PD (e.g., Yoon et al., 2017a; Yoon et al., 2016) show that teachers rated it highly, saw great curricular utility in supplementing and revising their practices, and demonstrated improved student participation and learning outcomes. The success of this project encouraged us to consider how to scale this work to reach more teachers. We consulted recent reports on the lack of high-quality teacher PD that implicated time and space as issues related to scale (Merritt, 2016). This led to a plan to move the PD entirely online. We chose edX as the platform, due to its mechanisms for reaching large numbers. In recreating the PD on edX, we attempted to stay true to the objectives and basic structure of the face-to-face PD while including adaptations in line with best practices for online learning (e.g., Booth 2012; Dede et al., 2019; Yuan & Kim, 2014). In the research reported here, we compare the results from the face-to-face PD to a pilot run of the online course.

2. Theoretical considerations

2.1. Designing high-quality PD

When determining what characteristics constitute high-quality PD for science teachers, some common practices emerge from the literature (e.g., Desimone, 2009; Gerard et al., 2011). These practices include a focus on relevant and useful content, eliciting and capitalizing on teachers' knowledge and skills, engaging teachers in active learning, allowing teachers time and space for reflection, and supporting collaboration. A review of studies focused on PD qualities that support technology-enhanced inquiry instruction in science by Gerard and colleagues (2011) also pointed out the importance of mentoring and access to expertise through facilitators and more senior teachers. The importance of building collaborative teacher communities as a way to provide ongoing PD has been written about for more than 2 decades (e.g., Cochran-Smith & Lytle, 1999; Lieberman, 1995). More recently, we have come to understand that providing opportunities for teachers to build social capital (i.e., the ability to acquire resources from others) is just as essential as supporting the development of teachers' human capital (i.e., skills and knowledge possessed by an individual), especially when resources and experience are limited (Yoon et al., 2017b). For online environments, scaffolded social forums where teachers can interact with one another and build on each other's knowledge and expertise are needed (Zeichner & Liston, 2014). Booth (2012) discussed the value of open exchanges of ideas, experiences, and resources in building trust in online professional learning communities. In setting a research agenda for more online teacher professional development research, Dede and colleagues (2009) outlined a number of additional benefits that include opportunities for reflection and greater participation by teachers who may normally remain silent in face-to-face modes. However, as that study suggested, more research is needed to determine whether and how online PD is a viable alternative to face-to-face PD (Dede, 2009; U.S. Department of Education, 2010).

2.2. What we know about the benefits of online PD

In this section, we provide more details about why online PD for teachers is beneficial. First, it allows for greater geographical diversity among participants and reduces transportation time and costs, as teachers can access online PD courses from anywhere (Bates et al., 2016). Specifically, asynchronous online PD provides learners with the ability to self-pace and access materials at flexible hours. Evidence shows this time flexibility is particularly appealing to PD participants, especially when teaching schedules do not allow for attendance in face-to-face programs (Parsons et al., 2019). Online PD also has the potential to reduce the overall cost of PD implementation when online resources are used repeatedly and participants are geographically dispersed (Fishman et al., 2013). Other researchers have hypothesized that online PD offers a natural avenue for developing and supporting online teacher communities in the longer term, which can help teachers continually reflect on and adapt their teaching practices (e.g., Frumin et al., 2018). Dede and colleagues (2019) and others have discussed the fact that online PD seems well-positioned to take advantage of many of the benefits brought about by learning engineering and other advancements in online educational platforms. Parsons and colleagues (2019) conducted a survey with 258 teachers across 41 U.S. states and found that the majority of respondents had participated in online PD opportunities.

Previous studies and the aforementioned potential notwithstanding, there still remains the issue of limited empirical research directly comparing the outcomes of online versus face-to-face PD in order to show that online PD can be as effective for teachers and ultimately for student learning. Fishman and colleagues (2013) used a randomized experiment to examine the differences in both secondary school teacher and student learning outcomes resulting from a PD delivered face-to-face and asynchronously online. Teachers from both PD groups exhibited similar increases in content knowledge and feelings of self-efficacy, with only minor differences in changes to classroom practices. Student performance also increased comparably across both groups. However, this study included an extensive 16-hour in-person orientation to situate teachers in the program. Given the geographically diverse nature of many online PD programs, we believe these results may not reflect a fully asynchronous PD delivery, especially when the PD content includes the introduction of novel technologies to teachers. Additionally, despite the promising results of Fishman et al. (2013), Moon and colleagues (2014) cautioned against overgeneralizing from this study and recommended additional research into the nuanced trade-offs between online and face-to-face PD. Other studies examining online versus face-to-face adult learning programs in professional and academic settings have suggested that outcomes from online PD could compare favorably with face-to-face PD, though these studies do not include practicing teachers and also lack the fully-asynchronous component (Kissau, 2015; Olivet et al., 2016). Further comparative research in explicitly online and asynchronous PD is needed. Our study asks the following research question: To what extent are asynchronous online PD experiences comparable to face-to-face experiences, in relation to teachers' perceptions and students' learning outcomes?

3. Methods

To address the research question, we used a comparative mixed methods design (Maxwell & Loomis, 2003). It is comparative in that we analyzed differences in teachers' perceptions of the PD delivery and subsequent student learning outcomes when teachers accessed the same curriculum through a face-to-face versus an online asynchronous PD platform. It is a mixed methods design in that we integrated quantitative and qualitative data analyses to reveal differences in patterns and outcomes with information that explains why or how those patterns and outcomes may exist in the data.

3.1. Context

This study is part of a long-standing program of research funded by the U.S. National Science Foundation that undertakes the design and dissemination of a curriculum to teach common topics in high school biology through complex systems modeling (Yoon et al., 2016; Yoon et al., 2017a; Yoon et al., 2018). The curriculum includes five units on the topics of Genetics, Evolution, Ecology, the Human Body, and Animal Systems. They entail working with an agent-based simulation tool and include experiences in core scientific practices as outlined in the *Next Generation Science Standards* (NGSS), such as analyzing and interpreting data, engaging in argument from evidence, and obtaining, evaluating, and communicating knowledge claims. Students normally work in groups of two to complete the units, each of which take 2 to 3 days to complete. The design of the curriculum was conducted alongside the PD activities, described in the following section.

3.1.1. The face-to-face PD

The face-to-face version of the PD ran for two iterations (1.1 and 1.2) between 2012 and 2014. We provide a brief summary here (for further details see Yoon et al., 2016; Yoon et al., 2017a). The participants attended 80 hours of programming over 2 consecutive years, with a 30-hour week-long summer workshop during August of each year and 10 additional hours in weekend workshops during the school year. The PD was designed to align with the following known characteristics of high-quality PD (Desimone, 2009): (a) *Addressing current content:* The biology topics selected for each unit constituted common topics that are mandated in the high school biology curriculum and local, state, and national standards. (b) *Active learning opportunities:* We focused especially on active learning as a way to support teachers in learning and implementing new technologies, a known challenge for teachers. During each summer of the PD, teachers completed the units from the curriculum in pairs to experience the curriculum as a learner and participated in additional activities that engaged them in reflecting on the experience and brainstorming how to support students in the future classroom implementation. Project facilitators were on hand to help teachers make sense of the simulations and activities, particularly when learning how to program. (c) *Coherence with professional demands:* We worked hard to scaffold experiences in several newer conceptions of scientific content outlined in the NGSS, such as integrating computer programming, scientific modeling and argumentation, and systems perspectives. This work included understanding individual teacher developmental trajectories in terms of their knowledge and experience with these different topics and taking into consideration the context within which they taught. We created adapted sessions to meet the teachers where they were in their development and needs to differentiate the curriculum for their student populations (e.g., one teacher taught in a school with a high English Language Learner population). (d) *Extended duration:* The PD took place both during the summer and school year to provide ongoing support and continuity as they implemented the project in their classrooms. Teachers also participated in a second year of PD. (e) *Collective participation:* We supported collaboration by working with specific content and age-level teachers in high school biology, several of whom were from the same schools, which allowed them opportunities to address coherence with professional demands. During each school year, participants conducted at least four of the curriculum units with their students.

The first year—2012–2013, which we refer to as Iteration 1.1—focused on the content and pedagogy of the curriculum, with participating teachers acting as co-designers in iteratively improving the simulations and supporting student and teacher materials. Based on feedback from teacher surveys and interviews, the second year—2013–2014, which we refer to as Iteration 1.2—included greater focus on increasing collaboration and relationship building among the teachers. (For more details about both years of PD activities, see Yoon et al., 2017a; Yoon, 2018.) Iterations 1.1 and 1.2 were used as comparison to the online implementation (Iteration 2.0) because they provided information about how to improve the curriculum materials and how to work with teachers as a community, which are both elements of high-quality PD.

3.1.2. The online PD

The online version of the PD (Iteration 2.0) ran July 2018 through June 2019. It was designed to create a space that, similar to the face-to-face PD, fostered social relationships as a way to engage in active sense making. Based on results and feedback from Iteration 1.0 (Yoon et al., 2017a), we found five categories of supports that the teachers indicated were most important for their learning from the PD. This included the following: (a) *supporting teacher beliefs*—teachers said that over the course of the PD, their confidence and beliefs about the utility of the curricular emphases (e.g., in modeling, argumentation, and systems) grew and was an important factor in encouraging shifts in their teaching practice; (b) *time and experience*—teachers believed that the 2-year PD afforded them more time to hone their expertise with the curriculum and more experience in the classroom in implementation; (c) *hands-on practice and training*—teachers found that the second year was particularly valuable in that they were able to garner more hands-on practice and training in learning how to use and teach with the computational models; (d) *just-in-time supports*—teachers believed that having the facilitation from project team members available to them while they were planning and implementing activities in the classroom was important; and (e) *interaction and building knowledge within the community*—teachers felt that the greater emphasis on sharing ideas and building relationships with other teachers in the PD provided them with more resources and partners to think through problems of practice.

The online PD was designed to provide these supports while offering a modified version of the in-person activities and discussions (including the known characteristics of high quality PD) for fully online delivery. Similar to the face-to-face iterations, the online PD was constructed to take 40 hours to complete and included the other known characteristics of high quality PD. To support teacher beliefs, we built dedicated modules on modeling, argumentation, and systems that provided readings, weblinks, and videos about the importance of each concept in scientific exploration. To provide the needed time and experience to become comfortable with project activities, teachers were able to move through the online PD modules at their own pace. We also believed that the archival nature of the online resources would allow teachers to access them anywhere, anytime, and as often as they needed. To provide hands-on practice and training, detailed walk-through videos with voice-over instruction were recorded to provide teachers with online support to practice the simulations on their own. Additionally, while teachers in the face-to-face PD presented problems of practice from their classroom implementation and had in-person discussions about strategies as a way to build knowledge and support teacher beliefs, participants in the online PD watched videos of teachers from Iteration 1.0 teaching the units in their classrooms and discussed strategies on a discussion forum that included the experienced teachers as active members. These videos and the presence of and access to experienced project teachers were also meant to function as just-in-time supports for teachers participating in the online PD. Finally, to support teacher interaction and community knowledge building, we created a curated online discussion forum with prompts that were used to seed discussion in the areas of teacher understanding of course content, classroom implementation, and collaboration or the sharing of resources and expertise.

The above modifications were made intentionally to maintain the objectives of the PD, the characteristics of high-quality PD, and the supports that were important to teachers in 1.0. To guide this transition and oversee consistency, three teachers from Iteration 1.0 acted as design collaborators for 2.0. They worked with the research and design team to provide insight on how well the online version compared to the face-to-face version of the PD. The online course consisted of seven modules and was designed to encompass 40 hours of instruction to be completed over a 6-week period. Additionally, three 2-hour synchronous online meet-ups were held during the school year. These meet-ups were designed to support participants in their implementation by providing space for sharing challenges and successes.

3.2. Population

The participants in each iteration of the study were recruited through the researchers' networks and were primarily a sample of convenience, though they represent many diverse classroom contexts.

3.2.1. Face-to-face teacher participants

Iteration 1.0 of the PD included 10 teachers, seven women and three men, from a metropolitan area in the northeastern United States. The years of experience for the teachers ranged from 3.5 to 19 years, with an average of 8 years. The schools they taught at were all public schools but ranged in demographics, with the student body at one school almost entirely White (3% minority) and another 71% ethnic minority. The socioeconomic demographics were also wide ranging, with school measurements of low-income students ranging from 14% to 59%. Across the 10 participating teachers' classrooms, more than 300 students were reached each year, with 354 participating in research in Iteration 1.1 and 361 participating in Iteration 1.2. See previous results for more detailed demographic information on teachers (Yoon et al., 2017a; Yoon, 2018) and schools and students (Yoon et al., 2016; Yoon et al., 2017a) for 1.0.

3.2.2. Online teacher participants

For the online PD, six teachers from five different schools in three metropolitan areas in the northeastern United States participated in the course. The teachers had a range of 3 to 19 years of teaching experience with an average of 8.5 years. The teachers were employed mainly in public schools with the exception of one independent school. Two of the teachers taught at the same school, and the other four were each at one of the other schools. The demographics of these schools also demonstrated diversity. The most diverse school had 82% ethnic minority, while the least diverse had 19%. The percentage of low-income students ranged from 62% to less than 5%. Five of the participating teachers agreed to collect data on their students and, with some attrition, resulted in data from 88 participating students for the 2.0 dataset. See Table 1 for further details.

Table 1. Demographics of teachers and schools

Teacher	Years of experience	Number of students	School level characteristics sample		
			% Low income	% Minority	% Minority
1-1	3.5	45	59.0%	71.7%	79.7%
1-2	14	12	59.0%	71.7%	79.7%
1-3	8	22	27.7%	38.9%	43.4%
1-4	12	16	36.0%	NA	31.6%
1-5	5	46	59.0%	71.7%	79.7%
1-6	8	23	NA	NA	NA
1-7	5	48	27.7%	38.9%	43.4%
1-8	6	63	14.8%	29.9%	42.2%
1-9	19	21	14.2%	3.2%	20.0%
1-10	5	65	18.0%	36.7%	38.2%
Average	8.6	36.1	35.6%	42.7%	40.4%
Total		361			
2-1	3	29	NA	19%	10.3%
2-2	11	16	4.7%	24%	50.0%
2-3	19	14	30.4%	41%	42.9%
2-4	7	14	63.0%	82%	92.8%
2-5	4	NA	NA	NA	NA
2-6	7	15	4.7%	24%	57.1%
Average	8.5	24.8	25.7%	38%	50.6%
Total		88			

3.2.3. Student participants

Student populations were similar across the three iterations, with more female than male participants, and with a skew towards lower grades. See Table 2 for further details.

Table 2. Demographics of students

Student characteristics	Iteration 1.1 (2012-2013)	1.2 (2013-2014	2.1 (2018-2019)
Number of students (n)	363	361	88
Gender			
Male	160 (44.1%)	157 (43.4%)	34 (38.6%)
Female	177 (48.7%)	198 (54.9%)	50 (56.8%)
Grade			
9th	137 (37.7%)	170 (47.1%)	36 (40.9%)
10th	71 (19.6%)	75 (20.8%)	30 (34.1%)
11th	61 (16.8%)	92 (25.5%)	15 (17.0%)
12th	5 (1.4%)	14 (3.9%)	6 (6.8%)

3.3. Data sources

To investigate our research question, data from four sources were collected from each of the three iterations of the PD: teacher post-course satisfaction surveys, teacher post-course and post-implementation interviews, student pre- and post-implementation content knowledge surveys, and student pre- and post-implementation classroom experience surveys. In this paper, we present data on the teacher post-course satisfaction surveys and student content knowledge and experience surveys from both the face-to-face and online PD versions. We present teacher-interview data only from the most recent online PD version, which was used to elaborate on outcomes from teacher- and student-survey data.

Upon completing the PD summer course, teachers were administered a PD satisfaction survey to measure their perceptions of the PD. This comprised 18 five-point Likert-scale questions (1 = strongly disagree to 5 = strongly agree) that probed their experiences with the course resources in the areas of overall course satisfaction (e.g., "The course covered topics that are relevant to the grade(s) I teach"); module construction and delivery (e.g., "The modules actively engaged those in attendance"); and usability of materials in specific teaching activities (e.g., "The student worksheets given out during the course will be useful in my teaching"). This survey has been used in previously published studies (e.g., Yoon et al., 2015) to ascertain teachers' opinions on the extent to which the PD was enjoyable and had utility in their instruction. Studies have also shown that teachers perceptions of the effectiveness of participation in online teacher professional learning communities is strongly mediated by their sense of learning satisfaction (e.g., Tsai, 2012).

Individual interviews for the online PD participants were conducted with teachers at the end of the summer course and again at the end of the school year. Post-course surveys used semi-structured questions to gather information about teachers' experience in the course in terms of the online format (e.g., "Were there specific topics you felt were better delivered in an online format and others face-to-face?"), social interactions with peers (e.g., "To what extent did you find the discussion aspect important to your learning?"), and support from the project team (e.g., "Do you feel you received adequate support from the team and the prior project teachers?"). Post-implementation interviews were conducted with teachers to gather information about how they implemented the curriculum in their classrooms and how participation in the course prepared them to do so (e.g., "What aspect of the online course did you feel best prepared you for teaching?"). Additionally, they were asked about the usefulness of the online meet-ups (e.g., "What was the most helpful aspect of the online video meetups?") and the support from the project team that continued into the school year (e.g., "Do you feel you received adequate support from the project team during the school year?"). To understand teachers' perceptions about benefits to student learning, we also asked the following question: "Discuss some of the benefits for your students you saw with particular modules." Individual interview lengths ranged from 22 to 42 minutes, and the audio-recorded interviews were transcribed.

Students in both the face-to-face and online versions of the PD course completed two surveys pre-implementation and two surveys post-implementation. Though the surveys contained the same questions, they were administered 9 months apart, to mitigate the effects of item exposure. The first survey testing content knowledge consisted of 14 multiple choice questions about biology content (e.g., "There are many different enzymes located in the cytoplasm of a single cell. How is a specific enzyme able to catalyze a specific reaction?") and one open-ended question about complex systems (e.g., "Imagine a flock of geese arriving in a park in Philadelphia, where geese have not lived before. Describe how the addition of these geese to the park may affect the ecosystem over time. Consider both the living and nonliving parts of the ecosystem."). A classroom experience survey was also administered that consisted of 44 five-point Likert-scale questions (1 =

strongly disagree to 5 = strongly agree) that probed students' experiences with instructional strategies in the classroom that were targeted for improvement in the PD (e.g., "I often work together with other students to learn about science; I use computer technologies to share information about science").

3.4. Data analysis

We identified overarching trends and triangulated findings between the four data sources. For the satisfaction surveys, average Likert-scale responses were calculated for all 18 items and then aggregated in the three areas of overall course satisfaction, module construction and delivery, and usability of materials in specific teaching activities. The averages for all three iterations of the PD were compared for equivalence in the three areas across the 3 years. The teacher interview transcriptions were qualitatively mined for comments and insights that offered support for the findings from the surveys as well as insights into how well we were able to meet the needs of teachers in the five categories of PD support that Iteration 1.0 teachers believed were the most important to address (i.e., supporting teacher beliefs, time and experience, hands-on practice and training, just-in-time supports, and interaction and building knowledge within the community).

Scores of the student multiple choice content questions were compared from pre- to post-implementation for each year using a paired *t*-test to see if the average scores changed from the beginning to the end of the curriculum implementation. To understand the amount of impact, we calculated the effect size (Cohen's *d*). Responses to the open-ended complex systems question were scored on a scale of 1 (not complex) to 3 (completely complex) for each of four different dimensions of complex systems understanding, which are listed in Table 3. The pre- and post-responses were combined and two researchers on the project each coded 40 (23%) responses, achieving a Cohen's Kappa interrater reliability score of 0.87. The remaining responses were coded by one of the researchers. These components were derived from earlier research (Yoon, 2008; Yoon, 2011; Jacobson et al., 2011; Pavard & Dugdale, 2000). Aggregate scores on this assessment ranged from 4 to 12.

Table 3. Categories of complex systems components

Complex systems components	Descriptions
Predictability	The emphasis is on the predictability of the effects caused by the agent in question. In a complex framework, it is impossible to anticipate precisely the behavior of the system. This is because the actions of agents cannot be predicted (as random forces or chance factors can affect an agent's actions) even if we know the rules or characteristics of the agent.
Processes	Processes refer to the dynamism of the mechanisms that underlie the phenomena (i.e., how the system works or is thought to work). In a complex systems framework, there is no definite beginning and end to the activity. System processes are ongoing and dynamic.
Order	The focus is the organization of the system or phenomenon as centralized or decentralized. In a complex systems framework, control is decentralized and distributed to multiple parts or agents. Order in the system is self-organized or "bottom-up" and emerges spontaneously.
Emergence and scale	Emergence refers to the phenomenon where the complex entity manifests properties that exceed the summed traits and capacities of individual components. In other words, these complex patterns simply emerge from the simpler, interdependent interactions among the components. In a complex system, because parts or agents are interdependent in multiple ways, an action (small or large) that is imposed on the system may have large and far-reaching consequences on the numerous parts and agents of the system. This may in turn result in large-scale change and evolution.

For more information about the data and reliability analyses on the complex systems coding for Iteration 1.0, see Yoon et al., 2017a. The 2.0 data was coded by two researchers who were trained on the coding manual by a researcher who conducted the analysis of the 1.0 data. The two researchers then coded 23% of the responses (30 out of 132 pre- and post-responses) independently. An interrater reliability of .88 was achieved. One of the researchers then coded the remainder of the responses. The results of this coding were then compared using a paired *t*-test of total scores.

For the classroom experience survey, averages of Likert-scale responses on the pre- and post-surveys and analyzed using paired *t*-tests to determine whether average scores changed.

4. Findings

Findings from the online course for both teacher perceptions and student outcomes showed similar positive increases in usability, interest, and growth to the face-to-face versions of the PD. We provide more details of these findings below.

4.1. Teacher perceptions of online delivery indicate opportunity for accessible PD

Both the satisfaction surveys and the interviews highlighted positive perceptions that teachers had of the online course. The satisfaction surveys showed comparable results to the face-to-face course and the interviews provided reinforcement for the focus on the five areas of support.

4.1.1. Positive satisfaction survey results

Findings from the satisfaction survey showed that teachers in the online PD had a very positive experience, rating all 18 Likert-scale items on average between 4.5 and 5. Aggregate averages in the areas of overall course satisfaction, module construction and delivery, and usability of materials were 4.60, 4.69, and 4.70, respectively. These findings were roughly comparable to those found in Iteration 1.1 of the face-to-face PD (4.73, 4.78, 4.66) but slightly less than Iteration 1.2 (4.95, 4.98, 4.84). In the category of usability of materials, the online teachers (Iteration 2.0) rated items as higher than the teachers in the first year of face-to-face PD (4.70 for online, compared to 4.66 for Iteration 1.1 of face-to-face), which is significant because those items asked whether the specific teacher resources (learned about and acquired online) would be used and/or helpful to their instruction. Teacher interviews also signaled the same positive feelings about the usability of the online PD resources. For example, multiple teachers in the online PD said that the curriculum fit well into their existing Biology course. One teacher, Amber, said:

> I already do these topics. So, on a day where I might have done a different activity, I can just do this instead. So, I love that part of it. I feel like this is actually doable.

While commenting on the computer programming aspect of the curriculum, another teacher, Fran, mirrored Amber's enthusiasm, saying that the new curriculum might facilitate learning better than her old way of teaching:

> This is like just stuff that fits exactly into my curriculum . . . I'm getting pretty excited about kind of changing my curriculum in a way that hopefully facilitates the learning a little better but also kind of filling that need for computer science.

4.1.2. Success of teacher supports

In all five of the categories of PD supports that we intentionally attended to in the design of the online course, we also saw overwhelmingly positive responses. In the category of *supporting teacher beliefs*, there was near unanimity in their interests and beliefs about the utility of modeling, argumentation, and systems in the science classroom based on their experience with the course. For example, Fran said the following about the importance of systems understanding:

> It was a valuable experience for the kids to get their hands on systems modeling. Because that's like I see a lot of . . . I just feel that that makes people wiser to understand systems. And I also think it's important for job prospects later. I think even if kids don't go into science, knowing that like the world functions as like interconnected systems is just like a valuable way of seeing things. So, I thought that was huge.

Teachers also felt that their confidence and skills in delivering these curricular concepts improved, and this was particularly important for teachers whose schools had a similar instructional focus. For example, Amber said:

> Yes, especially argumentation. We as a department have actually been focusing on that a lot in the past month or so, and it's actually a goal in the department to flip our curriculum into more claim, evidence, reasoning, and inquiry. So . . . we did our ecology unit this year using inquiry and argumentation, and [this project] helped me to be more comfortable with that, because it's not easy when you're used to teaching something a

certain way, and then you do it a different way. You let the kids come up with it, and let the kids figure it out through their evidence and reasoning. So, because I did [this project], I was much more comfortable with that switch and doing it. I feel like it really helped prep me, and it will continue to help prep me because we're going to do this with all of our units.

The video footage of 1.0 teachers implementing project activities proved to be the most valuable resource in addressing the category of *time and experience* for the online teachers who felt that being able to visualize events in the classroom was an enormous help in anticipating student learning challenges. Being able to witness real classrooms and teachers using the activities also provided insights into teaching experiences that boosted their confidence. These thoughts are encapsulated in the following comment from Melanie:

> Not only was I learning something but I also liked the videos, and even though we only had to watch snippets of the teachers implementing the modules in the classroom, just seeing someone else all doing it, was like so helpful to me to figure out how I was going to implement it. Because, if I just had the modules and I just had the materials like, there's a big leap between just having a worksheet and knowing how to guide the students through and having the videos where the teachers were reflecting on what went well or what went better, I think. I felt way more confident than just like getting the material that I could actually implement it in my classroom, so I thought that was really helpful. I like the way it's built into like, giving background information and then the challenge like you trying to like model yourself and getting frustrated and trying again like putting yourself in the mind of the student before jumping into, okay, this is how teachers implement it in their classrooms. So, it kind of brought you through the student experience and then the teacher experience. I thought that was great.

For the category of *hands-on practice and training*, teachers appreciated the self-paced nature that the online PD afforded. Amber commented:

> Cause they said go in this as a student, which I felt was really important to see what they would see, and I honestly don't know if I would have time to do that during the school year.

Similarly, Melanie discussed the utility of having time to reflect on her practice after she was able to work at her own pace:

> I would go through the module myself, do the whole worksheet myself that took, you know, maybe like an hour and then an hour or two just thinking about like what did I want to directly introduce. Did I want to make like a slide to show them? Did I want to like, you know, put a little bit of the simulation up on the board just to kind of direct them?

In the category of *just-in-time supports*, all teachers commented positively on being able to access the course resources just before they taught the unit in their classroom, as evidenced in these comments by Elizabeth and Amber:

> Well, before I taught the module, each module I went back and looked at the online aspect of the course that is about that module and seeing the different teachers teach it, which is really helpful.

> I went back . . . because I wanted to refresh myself on a couple of things . . . So, I went back again and re-looked at some of that stuff to kind of remind myself of what I did when I went through it. To be honest with you, I probably should've spent a little more time. I did a quick review, like, "Oh, yeah. I remember doing this. Yep. Yep."

Regarding the category of *interaction and building knowledge within the community*, teachers were again positive about our efforts to scaffold opportunities for sharing. Here is what Fran said about the school-year synchronous online meet-ups:

> It was helpful to hear about the different challenges that people had with implementation so that I could like think about how I might solve those. It just, it's always a good learning opportunity for me to hear about other teacher's experiences, because it helps me reflect on my own practice and when I get to like share ideas, even if I don't share an idea out loud, if I'm able to generate an idea of like, how might I have solved that problem? It is a good practice for me as a teacher to be improving my skills.

Elizabeth similarly commented about the necessity to join the meet-ups to hear about implementation issues that she would not otherwise have known about given that she was the only person implementing the project in her school:

> He could offer adjustments based on solutions you've found or just make a mental note like, "Okay, this is challenging. So, I have to think about this beforehand even if I'm not doing the unit for like two months." I'm just using each other as resources because nobody else at my school obviously is doing it. So, it was really helpful to be like, "Oh yeah, this works really well. I'm going to ask this particular question," or "When the groups were grouped in this particular way that was helpful." So, all those kinds of tools of practice are really good.

4.2. Similar student outcomes for face-to-face and online PD delivery modes

Student outcomes were measured in three areas through two survey tools. The results from Iteration 2.0 are compared here to the results from the first two iterations, which can also be found in more detail in Yoon et al. (2017a). Students' content knowledge in biology improved significantly for all three iterations of the PD (Table 4) with medium effect sizes for the two iterations of the face-to-face PD (d = 0.56 and 0.67) and a small to medium effect size (d = 0.36) for the online PD. Students' understanding of complex systems also improved significantly for all three iterations of the PD (Table 5). Here, the online PD showed a greater effect size (d = 0.38) than the first year of the face-to-face PD, which had only a small effect (d = 0.19).

With respect to the student classroom experience survey measuring students' perceptions of their learning, there was a significant positive increase in all three iterations of the PD (Table 6) with the online PD showing a greater effect size than Iteration 1.1 of the face-to-face PD but not as high as Iteration 1.2. Of note, the data shows similar pre-test averages and standard deviations for all three measures across the Iterations 1.1, 1.2, and 2.0, which suggests some level of equivalence for the populations being measured. These results show that online delivery of PD can have comparable student outcomes to PD delivered face-to-face.

Table 4. Student biology content knowledge results across three project iterations

Iteration	Pre-test Avg* (*SD*)	Post-test Avg* (*SD*)	Difference	*t* value	*df*	*p* value	Cohen's *d*
1.1	6.71 (2.31)	8.13 (2.78)	1.42	10.73	362	< .001	0.56
1.2	7.67 (2.36)	9.43 (2.47)	1.76	12.50	345	< .001	0.67
2.0	7.63 (2.46)	8.50 (2.42)	0.87	3.69	87	< .001	0.36

Note. *Scores are out of 14.

Table 5. Student complex system content knowledge results across three iterations

Iteration	Pre-test Avg* (*SD*)	Post-test Avg* (*SD*)	Difference	*t* value	*df*	*p* value	Cohen's *d*
1.1	6.18 (1.48)	6.51 (1.49)	0.33	3.51	353	< .001	0.19
1.2	5.80 (1.23)	6.79 (1.29)	0.99	12.26	360	< .001	0.65
2.0	5.95 (1.25)	6.51 (1.51)	0.56	2.62	63	< .05	0.38

Note. *Scores are out of 12.

Table 6. Student classroom experience survey results across three iterations

Iteration	Pre-test Avg* (*SD*)	Post-test Avg* (*SD*)	Difference	*t* value	*df*	*p* value	Cohen's *d*
1.1	3.44 (0.48)	3.63 (0.56)	0.19	6.86	320	< .001	0.36
1.2	3.51 (0.44)	3.80 (0.45)	0.29	11.54	309	< .001	0.67
2.0	3.77 (0.41)	3.94 (0.42)	0.17	3.35	80	< .01	0.41

Note. *Scores are out of 5.

The results from the surveys that show significant increases in both student content knowledge and perceptions of science are supported by data from the teacher post-implementation surveys. A common theme across comments from the online PD teachers (Iteration 2.0) was the way that students understood key concepts about of complex systems. Amber commented on how seeing random variation occurring in the simulations provided a different perspective for students, which allowed for deeper understanding of the content:

> They seemed to really grasp the fact of how random some of these events are, even though they do not seem random, in terms of the genes turning on and off. And tying in the complex systems, that's a topic that we go quickly over, and they just say, "Oh, they go on and off," but they do not really know it happens or why it happens. So, this [simulation] actually showed them how and why that happens.

Another theme among teacher comments about student learning was the value of scientific argumentation. Sandy discussed how her experience with the online module on argumentation permeated all aspects of her teaching, which in turn shifted student behavior toward the scientific practice of identifying and using evidence, as the following comment illustrates:

> Every single time, even for a small thing that's going on, we just point out, okay use your evidence and by now students really welcome it. They use it automatically. This is what's happening, this is my reasoning, and this is my evidence.

5. Discussion

The goal of this project was to examine the viability of scaling access to high-quality PD at low to no cost by adapting a successful face-to-face PD initiative to an online delivery mode. Some of the strongest barriers to teachers' professional growth are access to expertise and resources and time constraints (Merrit, 2016; Peltola et al., 2017). By moving PD online, scaling costs can be cut while access for those with time and geographic constraints can be increased. Though some studies (e.g., Fishman et al., 2013; Kissau, 2015) have suggested that online PD can be just as effective as face-to-face PD, more direct comparison research is needed to support these findings (Moon et al., 2014). This study adds to this research with additional evidence that online PD can be as effective as face-to-face PD. Previous research has shown that more time and training with a curriculum lead to stronger and more sustained change and that the ideal duration of PD is 2 years (Gerard et al., 2011; Yoon et al., 2017a). This can potentially explain the higher outcomes from Iteration 1.2 of the face-to-face PD. The outcomes from the online delivery were comparable to, and in some cases even better than, the outcomes from Iteration 1.1 of the face-to-face PD. This suggests that though extended time is beneficial to teachers, similar results can be achieved in the same amount of time whether the PD is delivered online or face-to-face.

The question then becomes how online PD can be designed as a viable alternative to face-to-face PD (Dede, 2009; U.S. Department of Education, 2010). In this study, we have detailed a number of design decisions that we believe supported the comparable satisfaction results from teachers and the learning and experience results from students in both PD modalities. First, our data showed that attending to teacher beliefs that were aligned with what Desimone (2009) described as coherence with professional demands was important to the usability of PD activities and resources. For example, two teachers in our study (Amber and Sandy) reported that in their schools developing student skills in scientific argumentation was a major focus (as we found in several of our 1.0 and 2.0 schools). This state of affairs greatly encouraged teachers' shifts in pedagogical approaches. Next, our data was replete with comments about the overall success of the videos of 1.0 teachers' implementations. We believe that being able to visualize real classrooms and hear from real teachers who also provided metalevel information about pedagogical choices sped up the time that it would have normally taken teachers to feel comfortable teaching with the project resources. This, coupled with the ability for teachers to work at their own pace trying out the activities that they were going to ask their students to complete, enabled time for authentic reflection. We discussed research about these design features in the introduction and theoretical considerations (e.g., access to expert teachers; Gerard et al., 2011); affording time for teachers to reflect on their teaching practices (Frumin et al., 2018); and we offer this insight not so much as something new to consider for the delivery of online PD but as part of a combination of design choices that we believe led to our successful project outcomes. Lastly, we hypothesized that the online nature of PD, with the anywhere, anytime accessibility, would be a component in the ability to deliver just-in-time supports and opportunities for teacher interaction and building knowledge within the community. Our data suggest that this was a good hypothesis given that all teachers mentioned that they returned to the online course to refresh their understanding before teaching with the project activities and all teachers who attended the synchronous online meet-ups found high utility in participation. It is important to note that these teachers were geographically dispersed in different parts of the country, which was a central consideration in undertaking this research with the eventual goal of providing access to high-quality PD for teachers who don't normally have access (Peltola et al., 2017). In other forthcoming research, we discuss the success of additional design efforts that we made in encouraging collaborative discourse in the discussion forum.

A limitation of this study is the relatively small sample size of students from classes of teachers who participated in the online PD. It could be that the sample was biased in some way. However, one of the primary benefits of an online delivery mode is its ability to reach a larger number of teachers. In the summer of 2019, the course was launched on edX, enrolling 260 teachers in 20 countries and 17 U.S. states, with a 16% completion rate (41 teachers). Additional data is being collected on a subset of these teachers and their students in order to provide a more robust data set for comparison with the face-to-face data.

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