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Introduction

Lesson study, a form of teacher professional development, has been used mostly in K-12 settings with teachers in the same physical location. Uchiyama and Radin (2009) discussed the benefits of participating in a lesson study, such as collaboration, collegiality and increased instructional motivation. These benefits are perhaps more imperative in a higher-education setting, where faculty members' expectations for tenure may not provide time and opportunities to collaboratively analyse student learning outcomes (Uchiyama & Radin 2009; Demir, Czerniak & Hart 2013; Chenault 2017). This is further compounded by the fact that at some locations, especially in higher education, there is seldom more than one content specialist. To overcome some of these barriers to collaboration, we, a group of five early-career higher-education faculty, specifically mathematics teacher educators (MTEs), chose to use lesson study for our professional development. As we were located in different states across the US, meeting physically was not possible. Hence technological tools helped to facilitate the lesson-study process. Technology allowed us to bridge our geographical distances to establish and maintain a collaborative network, which has continued beyond our lesson-study implementation. In this paper, we focus on how technology facilitated the lesson-study to support our professional development as early-career higher-education faculty.

Literature review

We first introduce the concept of communities of practice, with a focus on higher education and virtual communities of practice. We then review the literature on lesson study, with a focus on higher education, and provide an example of a virtual lesson study.

Communities of practice

In university settings, learning is often considered an individual endeavor. However, Lave and Wenger (1991) proposed that learning is situated within a community, and that it occurs when learners are deepening their participation in communities focused on a particular domain; this came to be known as a community of practice.

A community of practice (CoP) consists of a group of people who regularly convene to discuss topics of mutual interest, share information and practices and create new relationships of value (Wenger, McDermott & Snyder 2002). However, communities of practice differ from teams in that CoPs are not solely focused on accomplishing a task, but rather come together in partnership rooted in a domain of practice (Farnsworth, Kleanthous & Wenger-Trayner 2016). The domain of practice under focus in the current study is teaching future teachers of mathematics. Communities of practice have a rich and varied history in education. However, this paper focuses specifically on higher education-based CoPs and virtual communities of practice.

At the university level, CoPs have been used to support new instructors as well as deepen the practice of experienced faculty members (Williams, Ritter & Bullock 2012). Warhurst (2006) investigated a university-level program in the United Kingdom that organised all new lecturers into cohorts focused on supporting the development of "academic practice". Researchers found that new instructors felt less isolated, and that discussions between instructors within their CoPs were key to developing new pedagogical practices. Other higher-education faculty members have also found learning theory rooted in CoPs to be useful to their development. A study of Australian bioscience faculty members participating in a CoP found that participants felt that it created "a sense of belonging that counterpointed their feelings of academic isolation, and that provided them

with an avenue to engage in educational dialogue, share best practise [sic] in bioscience teaching and support one another in scholarship of teaching and learning" (Flecknoe et al. 2017, p. 13).

In *Digital Habitats,* Wenger, White and Smith (2009) examined how CoPs can develop with the emergence of new technologies. Writing over 10 years ago, they acknowledged that advancements will make online or virtual CoPs increasingly possible. This has indeed come to pass, even within higher education. In McDonald and Cater-Steel's (2017) edited volume on CoPs in higher education, over one-fourth of the chapters include examples of virtual CoPs. Many of the chapters cite the challenges faculty members faced developing teaching practices on their own as one of the reasons for forming CoPs. They found CoPs to be supportive and a source of learning and growth. For example, a study of CoPs that were designed for Australian chemistry instructors from institutes of higher education found that although the culture of chemistry tended to foster an "uncooperative" environment, using synchronous and asynchronous communication avenues (e.g. Skype and email) developed productive CoPs. They explained that "a geographically dispersed but disciplinarily close-knit community can function as a supportive, non-hierarchical CoP based around mentorship, and generate significant social capital" (Schultz & O'Brien 2017, p. 502).

The integration of technology can support CoPs. For example, Conole and Dyke (2004) discussed the benefits of information and communication technologies and asserted that "the communication and collaborative abilities of technology...[offer] the potential for learning enriched by engagement"; they also noted how well it aligns with Wenger's theory of learning with CoP (p. 117). Hoadley (2014) extended this through his investigation of how CoPs can be supported, and provided insight into research on virtual CoPs. He explained that "although one can conceive of technology supporting either the community, or the shared practice, or both, typically scholars have investigated technology's role in supporting the community (i.e. communication) rather than the practice itself" (p. 295). For this paper, we are interested in how the technology supported our professional development of our own teaching practice while we were engaged in the technology-facilitated lesson study.

Lesson study

Lesson study is a process of investigating teaching with the goal of instructional improvement; one of its main purposes is to help educators professionally develop through participating in a sustained professional community (Yoshida 2012) – in our case, a purposeful community of practice. The iterative lesson-study process is generally organised into a four-step cycle: (a) study the curriculum and formulate lesson goals, (b) plan a lesson, (c) conduct research lesson and (d) reflect (Lewis, Perry & Hurd 2009; Lewis & Hurd 2011). Since arriving to the US from Japan in the 1990s, lesson study has primarily been used to investigate instruction at the K-12 level, with teachers in a school or district designing and teaching a common lesson and studying the associated student learning. Although traditional lesson studies include participants gathered in the same room to witness the intricacies of the lesson, there have been attempts to broaden what it means to participate in a lesson study through the use of technology, such as video clubs and hybrid structures (e.g. Skultety, Gonzalez & Vargas 2017; Nickerson, Fredenberg & Druken 2014).

Through engaging in video clubs in which high-school teachers videotaped their own lessons or created animated cartoons of lessons, Skultety et al. (2017) found that because videos captured activities in the moment, teacher participants could rewatch, analyse and discuss student learning and lesson modifications in greater detail, which might have been missed during live observations. During a hybrid lesson study with middle-grade teachers, Nickerson et al. (2014) created a website

that housed lesson-study documents (lesson plans, proposed modifications and lesson debriefs), videos of lessons, resources and discussion threads between team and non-team members. The website resulted in sustained teacher collaboration and communication throughout the lesson-study process, despite the geographical distances separating the teachers. Although these studies occurred with middle- and high-school teachers, they provide insight into the possibilities of extending the traditional lesson-study format to include ways for participants to engage in collaboration virtually. The videos allowed for the documentation and intense review of what occurred in the lesson, and the website encouraged communication and the sharing of resources across time and distance.

These examples were from K-12 education; few studies have examined how participants outside of K-12 have engaged in lesson study (e.g. Chappell 2003, cited in Kamen et al. 2011; Cooney, Darcy & Casey 2018), and even fewer (e.g. Cerbin 2011; Cooper et al. 2011; Kamen et al. 2011) have discussed how higher-education faculty members have participated in lesson study across institutions. Cerbin's (2011) book *Lesson study: Using classroom inquiry to improve teaching and learning in higher education* discussed three higher-education lesson studies conducted in the US. One was conducted in 2003 by instructors in four different departments (Biology, Economics, English and Psychology) at the University of Wisconsin-La Crosse. Teams of instructors developed learning goals and a research lesson, performed data analysis and refined their lessons for a second iteration the next semester. Their experiences led to a university-wide College Lesson Study Project. Two other American projects (at Colorado State University and Southwestern State University) also pursued lesson study in higher education (Kamen et al. 2011). Colorado State University completed a lesson study with a professional to develop goals for their calculus instructors to gain insight into their students' understanding of calculus concepts. Through the lesson study, they refined their lesson based on classroom observations and student achievements. Southwestern State University conducted a lesson study for teacher-education faculty members focused on assessment during hands-on science instruction and on supporting children's learning with invented mathematics problem-solving strategies. More recently, faculty at Maynooth University in Ireland completed a lesson study for a Critical Skills course module to support first-year students' writing (Cooney, Darcy & Casey 2018), and shared their students' learning as a result of the lesson study. In all of these examples, the lesson studies were completed with higher-education faculty members together in person.

Cooper et al. (2011) conducted a lesson study in higher education with mathematics teacher education (MTE) faculty members across universities within the same state (one researcher was on leave outside the US); thus, they were able to meet physically to plan their lesson, but could not meet physically during the semester while they taught the lesson. However, at least one group member was present during each lesson implementation; the lessons were videotaped for those not present. The team debriefed the lessons in person and via email. In this current study, using technological advances, we extend Cooper et al.'s (2011) work with virtual lesson study. Unlike Cooper et al., our lesson-study group was comprised of early-career MTEs who did not know each other prior to committing themselves to being a part of a CoP and eventually beginning the lesson study. Our different geographical locations meant that we could not meet physically; thus, all our communications took place through virtual exchanges.

Research question

Thus, our research question asks: how does technology-facilitated lesson study support the professional development of higher-education faculty?

Methods

Participants

Five early-career higher-education faculty, in tenure-track assistant professor MTE positions, came together as a CoP to support each other's professional development related to our teaching of elementary preservice teachers (PSTs). We originally met through the US Association of Mathematics Teacher Educators' Service, Teaching and Research (STaR) fellowship in the summer after our first year as tenure-track faculty members. During our initial two meetings in STaR, our discussions about our interests in teaching and research led us to form our group of five: two content MTEs who taught traditional college mathematics courses as well as combined mathematics content and methods courses for elementary and secondary PSTs, and three methods MTEs who solely taught elementary mathematics methods courses. In addition to the group members teaching different courses, their universities differed in size and focus. One MTE was from a small, private university in the northeast, while the rest were from public universities that ranged from 4,000 to over 30,000 students from the northeastern, midwestern, southern and western US. Our PST classes were mostly comprised of white females, with class sizes ranging from 11 to 30 students per class. Four of the MTEs had previously taught high-school mathematics; one taught middle school mathematics and two taught elementary school (some taught multiple spans). Although our different backgrounds and teaching responsibilities could be seen as an intellectual division (Crespo 2016), we saw our diverse backgrounds as one of the reasons our collaboration was compelling, and thus we committed ourselves to working together despite our physical distance.

Context-lesson study process

Study the curriculum and formulate goals. As a group, we identified a common teaching interest: how to support our elementary PSTs as they make instructional decisions based on children's mathematical thinking. We chose to focus on the professional noticing construct (Jacobs, Lamb & Philipp 2010) due to its emphasis on how teachers attend to students' problem-solving strategies, interpret their mathematical thinking and decide on next instructional steps to support or push students' thinking forward. From our knowledge of our own and others' work with professional noticing, we knew that the final instructional decision piece is the most difficult for PSTs because of their lack of experience with actual students' thinking (see Jacobs & Spangler 2017 for a review of the literature on teacher noticing). To address this need to support our PSTs, we created an activity in which they would analyse a set of elementary students' written work samples that could be considered as representative of a whole class, then decide on the next steps in instruction, for both the individual students and the class as a whole.

We chose to focus on the mathematical concept of multiplication, as it is cited as one of the foundational concepts that PSTs worldwide struggle to teach from a conceptual viewpoint; this struggle is shown in research from Australia (e.g. Chinnappan 2005) to South Africa (e.g. Jita & Vandeyar 2006) to the US (e.g. Ambrose, Baek & Carpenter 2003). Often teachers are unsure on how to approach the ideas of multiplication with students apart from memorising multiplication tables (Trivett 1980). Fully understanding the concept of multiplication requires teachers to know more than how to solve problems involving elementary multiplication (Ball & Bass 2003). For example, teachers must know different interpretations of multiplication, understand how multiplication is interpreted within different story contexts and possess knowledge of different strategies children use when solving multiplication problems. Wallace and Gurganus (2005) assert that "teaching for mastery of multiplication facts no longer means rote memorization of basic

facts. Making the connection between conceptual understanding and computational fluency is important for all students" (p. 33). Carpenter, Fennema, Franke, Levi and Empson (2015) further cite the difficulty in understanding multiplication, as some problems are non-symmetric in nature (unchangeable referents), while others are systemic, with factors not attached to a specific referent. The current paper's authors (in press) cite the need for knowledge not only about the concept of multiplication but also about how students think about and learn multiplication. Our decision to situate the lesson within the concept of multiplication led to our common lesson goal: to support PSTs in understanding student written work and making sound next-step instructional decisions based on children's mathematical thinking using the mathematical concept of multiplication.

We began our search for sample sets of students' multiplication work (i.e. multiple students' written work on the same multiplication story problem) that would help our PSTs delve into students' early understandings of the concept of multiplication. We chose to use "The Case of Mr. Harris and the Band Concert", a written classroom scenario from a third-grade classroom, with associated multiplication work found in the US National Council of Teachers of Mathematics' (NCTM) *Taking Action: Implementing Effective Mathematics Teaching Practices in K-Grade 5* (Huinker & Bill 2017). We chose the Mr. Harris work samples due to the variety of students' solution strategies that were presented, which provided a contextual scenario.

Plan: pilot study. We began our virtual community of practice with regular, weekly meetings via Google Hangouts, a free virtual meeting/teleconference software, to plan the specifics of our lesson and develop professional noticing assignments for our PSTs. The process of studying the curriculum and planning the lesson took about three months, as we needed to ensure that our lesson met the needs of each of our different student populations.

That autumn, our initial plan was for four MTEs (one was on a semester-long leave but participated in the other aspects of the project) to teach the lesson during the same week and then meet to debrief about our results. However, this was not logistically possible. We each taught the lesson at different times throughout the semester, and when we met to debrief, we shared the struggles and concerns we had experienced with the lesson as we had taught it, and made minor modifications to the lesson. After the first two MTEs taught the lesson, we came to the realisation that through our virtual discussions we were growing professionally and engaging in aspects of a lesson study. The other two MTEs taught the lesson that semester without many changes, and we considered our autumn teaching of the lesson a pilot study (Gupta et al. 2018). The following semester, when all five MTEs taught the lesson, we formalised our process and conducted a formal lesson study.

Plan: lesson study and technology. We connected and planned the lesson primarily using tools provided by Google: Google Drive to share ideas and compile all documents for access either synchronously or asynchronously, Google Hangouts for virtual meetings, Google Docs to plan, reflect on and refine the lesson by creating documents and Google Slides to design the lesson plan. Because these documents were accessible to all, we did not worry about working on different versions or losing information, as the work was automatically saved and past changes could be viewed. During our initial planning meeting, we created a Google Doc that became our main organising document. In it, we kept running notes for each meeting, maintained a "to-do" list and documented our lesson changes and research plans.

Throughout the lesson study, we continued our weekly virtual meetings using Google Hangouts, which allowed us to view each other and share our screens, thus creating an environment that felt as if we were in the same room. Additionally, we audio-recorded each meeting. After each

meeting, each of us created an individual online journal with Google Docs to document our individual professional development as supported by our own reflections.

The pilot lesson was modified over two months of planning discussions, and we decided on the lesson components and structure shown in Figure 1.

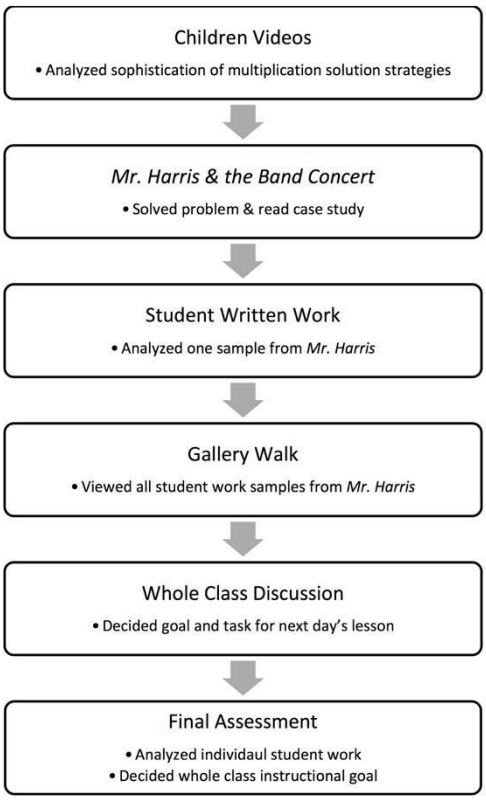

Figure 1. Components and structure for the common lesson

Conducting research lesson and reflecting. For this phase, we each videotaped our lessons, audio recorded our PSTs' group-based conversations and photographed our students' in-class work. We then transferred these files to a secure, shared, cloud-based drive for easy access. Individually, we watched each other's lesson videos, keeping running notes housed on Google Drive. We noted aspects of the instruction that stood out to us, such as missed opportunities to develop our PSTs' thinking or instances where we felt the MTE did a particularly stellar job. Additionally, as we reflected on our colleagues' teaching, we found ourselves reflecting back on our own teaching. Often, we noticed things we had not seen when we ourselves were teaching in the moment. When we convened for our virtual meetings, we used our running notes to guide our discussions. During the discussions, we critiqued our teaching, provided suggestions on ways to improve, asked for advice and sought out resources that would allow us to continue refining all aspects of the lesson. Throughout this cycle, we continued to meet virtually using Google Hangouts, often multiple times each week, and continued with our running notes, "to-do" list and online journal reflections on Google Docs.

Design and data analysis

The study adopted a qualitative research methodology to examine the ways a technology-facilitated lesson-study process provided professional development for the MTEs. According to Creswell (2007, p. 40), qualitative methodology is used when "complex detailed understanding of the issue" is needed; hence this methodology best suited this research design. Data were collected in numerous forms, including our individual online journals, transcriptions of the virtual planning meetings, "real-time" observation notes housed on Google Drive and various emails and phone texts sent during the lesson-study process. These multiple sources were used to provide triangulation (Simons 2009) to the data analysis. Two researchers first undertook individual open coding of the compiled data set, and found instances where our conversations focused on technology. This included both instances in which technology was explicitly discussed and those when conversations or ideas were clearly based directly on the use of the technologies. The two researchers independently categorised the coded instances of technology-specific conversations to develop themes related to our learning based on the principle that evidence of MTE learning must be present for the data to receive a code. The two researchers verified the initial codes and examples of evidence through discussions. Inter-coder agreement and member-checking by team members not participating in the coding process were used to verify emerging themes and enhance reliability. Once potential themes were determined, they were brought to the full research team for discussion and review.

Findings

Supporting MTEs' professional development through technology-facilitated lesson study

The goal of this investigation was to determine how technology-facilitated lesson study supported the professional development of MTEs. Through data analysis, we found three themes: engaging in the lesson study process provided the opportunity for professional development across geographical distances by 1) transforming the lesson planning process, 2) opening a window into one another's classroom to reflect and grow 3) and building professional relationships to solidify our community of practice.

Transforming the lesson-planning process

Using Google Drive helped us organise our documents and work together synchronously, which transformed our planning and allowed us to focus on pedagogical development. The excerpt below from the transcribed planning meeting of February 3, 2016 illustrates how technology facilitated our collaboration, and shows how this transformation served our professional growth. The example highlights how the use of Google Docs and Google Slides allowed us to create, share and work on documents together, and in turn led to our individual as well as collective professional development.

> MTE-5: Okay, I can pull from the Google Doc that we have the section called, "plan for implementation" which has our step-by-steps. But, I don't know if we want to refine our steps or create a PowerPoint from scratch or….
>
> MTE-3: It almost sounds like we should be looking at all of these PowerPoints [referring to the individual PowerPoint slides created during the pilot study] and then having everyone discuss what went well, what didn't and meshing, making a new lesson from everybody else's?

…

MTE-3: What do you think about if we each print off everybody's PowerPoint and we each spend time individually looking at them? Or having each person individually talk through what they remember about the lesson, what went well and what didn't, and we could take notes on that?

MTE-1: So, I put my PowerPoint into a Word Document so we could put it as a new document in the Google Drive, within the PowerPoint folder and we can take notes on it.

MTE-4: That sounds good. Like a starting point.

MTE-1: Let me copy and paste it.

MTE-3: I just did, "Open with Google Docs" and it opened.

MTE-1: I know, the question is, can you take notes on it? I don't think you can.

MTE-3: Yeah, I can type on it.

MTE-5: We have a Google Doc version of it now.

MTE-3: MTE 5's there now.

MTE-4: What happens is, when somebody turns it into a Google Doc, then we can work on that one.

MTE-3: So just open the Google Doc since I turned it into a Google Doc.

Although we had used Google Docs during the previous summer and autumn to create documents directly online, we had not realised that we could upload documents created in other programs onto our shared files and edit them synchronously. Our need to find an efficient way to compare our presentations created during the pilot study caused us to discover a new use of the technology. As we began reviewing MTE-1's presentation, we noticed that the first slide contained her written essential questions for the lesson. After looking through the document, our conversation shifted towards a more pedagogical focus (see dialogue below from the same planning meeting).

MTE-3: I was saying I like the first slide. I always put objectives as the first slide, and that's what you did.

MTE-1: I like this. If I'm really good I sometimes get to the essential questions, always at the end again, so I can say, "What did we learn?" I have to tell you, I come back to my essential question for the day, about 10% of the time.

MTE-3: I never go back to my objectives, that's a very interesting point.

MTE-5: I had an observation where the professor had talked to me about that. Have a good closure.

MTE-3: I'm terrible at closure.

MTE-1: Me, too!

MTE-3: Because I'm always rushing to finish.

Part of the professional learning that occurred for us was learning more about the functionality of Google Drive and figuring out how it could help us as we went through the lesson-study process; in this case, how we could easily plan collaboratively. As we worked on the presentation at the same time, we were able to collaborate through the slides and video-conference tools in real time as effectively as if we were in a face-to-face meeting. Instead of reviewing separate sheets of paper and spending time ensuring we were looking at the same paper, our collaboration was made easier and more efficient. This supported the development of our teaching practice by allowing us to focus on the actual planning of the lesson, despite the fact we were separated by large geographical distances.

During this planning meeting, the whole group went on to have an in-depth discussion about how to set and share lesson objectives with our PSTs, instead of the logistics of how to share documents and develop slides. As a result of our discussion, we developed a set of essential questions and created a Google Slide to be used as a part of the lesson. This was highlighted by MTE-3 and MTE-5's reflections; the functionality of Google docs was beneficial, but more importantly, we were thinking and learning about our own teaching.

> In this meeting, we began planning our common lesson. We utilized the collaborative [feature] of Google Docs. We used MTE-1's PowerPoint and converted it to a lesson outline. The online collaboration [feature] of Google Hangouts for the lesson and Google Docs for the video chat was extremely helpful in discussing and noting down our thoughts…. One major change to my pedagogy is to turn my lesson objectives into questions. I feel now that it is extremely helpful to have my objectives as guiding questions. I am working on having a great opening and closing (and a good middle, too). I think that the essential questions can be asked in the beginning, but more especially at the end to have a great closing so the students can understand what they were supposed to and have satisfaction with their learning (MTE-5, Online Journal, 2/3/2016).

> In terms of my own teaching, I really like MTE-1's essential questions. I think they are similar to objectives which I've always done, but since I know I have issues with lesson closure, perhaps starting and ending my lessons with the same essential questions will keep both me and my students on the same page. This is something I want to try out immediately (MTE-3, Online Journal, 2/3/2016).

The ability to develop the lesson in real time together using collaborative tools supported us to discuss our teaching decisions as we created the lesson together, which led to us learning more about teaching. Each person contributed and questioned decisions, and each person was able to change the official lesson plan in a way we could all witness and discuss as it was happening. It was active, participatory professional development with built-in accountability: we were all going to be teaching this lesson. As the following quote demonstrates, we were learning and appreciating how technology supported our development: "I LOVE Google Docs and the fact that we are all working on the document together. We are able to talk about it, think out loud, ask each other questions and make progress" (MTE-3, Online Journal, 3/28/2016). Technology made communication easy for us to focus on the actual lesson study, and thus, grow professionally.

A window into one another's classrooms

One of the most powerful experiences of engaging in this technology-facilitated lesson study was that it provided us with a window into one another's classrooms to reflect and grow despite the geographical distance. This occurred in two ways: the use of video with Google Drive upload and playback capabilities, and the use of Google Hangout to watch a lesson in real time.

Videotaped lessons. As we were unable to physically observe lessons in person, the videotaped lessons allowed us to observe one another's instruction to see the different strategies we each used to engage our PSTs, give each other feedback for improvement and reflect on our own teaching. These videotaped lessons were artifacts that we could pause, rewind, review and use to focus on specific aspects of our teaching.

Throughout our early discussions when we viewed our teaching, we realised that we were not pressing our PSTs enough for justification on their instructional decisions nor on how those

decisions would develop the children's mathematical understanding of multiplication. Analysis of data highlighted the lesson study's impact on our own growth in being aware of our PSTs' thinking. Teuscher, Switzer and Morewood (2016) call for MTEs to conceptualise the subtleties and complexities of teaching practices prior to teaching to support PSTs' development of understanding. Our data analysis revealed that due to the involvement in lesson study, we grew in our ability to question PSTs, and to recognise and use "teachable moments" to stimulate our PSTs' learning.

Throughout the lesson-study process, we had rich discussions about what it meant to push our PSTs. An example of this is shown in MTE-1's reflective journal entry in which she contemplated her own questioning: "when we want to push students there are so many ways to push them – you can push on strategies (i.e. making 10s), number choices, problem types, or…" (MTE-1 journal, 3/4/2016). Early on, we struggled to ask questions and push our PSTs on their "next-step" decisions. In the example below, MTE-3 began the concluding discussion by asking a group to share their next steps and the reasoning behind them.

> PST-1: ...because it didn't seem that a lot of the kids actually used multiplication, we want[ed] to see if they understand. We saw that they understand the process of grouping in a certain amount, but we want to see if they are actually able to multiply those groups together, so we said we would do smaller numbers like 5 times 10, which are also more rounded off, to see if they are able to add additional groups to that and then connect that to multiplying.
> MTE-3: So what would your goal for the lesson be?
> PST-1: To see if they are able to not rely on addition and actually multiply.
> PST-4: And understand the relationship between addition and multiplication.
> MTE-3: Okay, so what would you hope you would see in terms of – you said if you did 5 times 10, what types of strategies would you hope to see? I know I'm pushing you. Like when you say you hope to see them do multiplication, what would you hope to see?
> PST-2: I think less of a reliance on the counting by ones, less of Molly and Tyrell's method and more of, it might still be okay for them to do 5, 10 15, 20, but because they understand that they are equal groups, rather than just thinking of it as adding.

MTE-3 then moved on to a different group to discuss their next steps. Although she said she was pushing them, she struggled with pushing PSTs' thinking, partially due to time constraints but mostly because of our groups' lack of anticipating our PSTs' responses. This is further exemplified through MTE-3's reflection after teaching the second part of the lesson.

> I felt like it all went wonderfully until I was rushed at the end. They had very short discussions about what task they would pose to the whole class and I didn't go a good job responding. I tried to push one group, but didn't have time to do more.... Two of the groups wanted to return to an easier problem and have the students actually multiply. They really want to see a[n] "x" symbol. The other group wanted to focus on arrays, but were not specific as to how they would do so. I wished that as a group we had not only talked about our own next step, but also how to respond to our students' and push them further (MTE-3 journal, 3/7/2016).

Further analysis shows that we became better able to anticipate our PSTs' responses through our iterative discussions and reflections. For example, MTE-4's PSTs indicated that they wanted a

student shown in a video (Carpenter et al. 2015) to move from direct modeling (a solution strategy where a student physically represents the groups and items in a group with blocks or in a drawing and counts the total number of objects) to a skip-counting strategy (counting by the number of items in the group). Because, based on student responses from previous iterations in the lesson study, we had anticipated the PSTs' responses would lack specificity, MTE-4 pushed her PSTs to provide justifications for their responses. This led to PSTs referencing children's ability to subitise (in other words, the degree to which children find it "easy to visualise" and recognise small quantities of objects) and the standards ("they learn to skip-count by ten" in kindergarten) when rationalising their explanations. The transcript of MTE-4's discussion for video 4.1 (Carpenter et al. 2015) provides evidence of this:

> MTE-4: If we were to think of a next step, what would we do, what problem would we pose, what question would we ask?
> PST-1: Try to move her on to skip-counting. So that she is counting each one, try to get her to counting by twos, instead of one at a time.
> MTE-4: Are there any other ways to try to get her to skip-count?
> PST-2: I don't know if it would be skip-counting but at least have her realise that she had six in the first group and then just going, 6, 7, 8, 9…at least not having her count the whole first group.
> MTE-4: At least just remembering that first group. So how would we get her to do that, to not count that first group?
> PST-3: Just ask her, how many are in that pile? In the first one?
> MTE-4: So asking her how many are in that pile or how many are in each pile.
> PST-1: You could start with smaller numbers so it is easier for her to visualise the smaller number, rather than there being so much on each plate.
> MTE-4: Okay, so what number choices would you pick?
> PST-1: Something small, like 5 or under. Closer to 2 or 3.
> MTE-4: Any particular reason for 2 or 3?
> PST-1: It's just really easy to visualise. It's larger than one, so you are not counting by ones, but it is still small enough, and 5 is kind of what you could do with one hand.
> PST-4: Tens would work really well, because she would know that it is three groups of 10. So that would be really easy to show, if you have three tens, it's 30. I think, right? Because they learn to skip counting by 10, in the second grade – you said earlier?
> MTE-4: In kindergarten.
> PST-4: So they should know that already. So that would be a good introduction to use skip-counting to solve multiplication.

After teaching this lesson, MTE-4 reflected in her journal:

> Really ensuring that we are pushing for the hows and whys are so important. I think also, reflecting back to our lessons in the fall, I think that one reason we did not get the results we wanted was because we did not focus on these questions, but also, I think we were unsure as to really what we wanted students to say or get out of the lesson. Yes, we did say we want them to decide next steps, but I think through this process we too have become more specific and asked how and why questions to ourselves, which have in turn caused us to be more specific and have clearer expectations of the lesson and our students (MTE-4 journal, 3/5/2016).

This process of critiquing our teaching as MTEs illustrated the growth in our teaching practice as we pushed our students for justifications. The following excerpts also highlight how watching one another's videotaped lessons caused us to reflect on our own teaching and grow as professionals.

> It seems like the major thing for us to do as instructors is to ask "why" and to push them [PSTs] to be more specific! I did enjoy watching MTE-2 as she taught. It was so good to see her in a different light: we see each other every week for our meetings and Google Hangouts but it was nice to see her engaging in her practice, in front of a class and asking questions. She asked a lot of good questions (MTE-4, Online Journal, 3/2/2016).

> I loved watching MTE-1's video and taking notes. It was great to see all of our hard work in action. As I watched, I was constantly thinking about how this would work in my class; how do I anticipate it being similar or different. What would I like to change…how will I CUT TIME because I have less time to spend than she did. I loved when MTE-1 would say or do something that I wouldn't have naturally done (MTE-3, Online Journal, 3/2/2016).

As seen through the excerpts above, MTE-4 and -3 reflected on their own teaching while watching videos of their peers. They were self-analysing their own teaching, specifically considering how to incorporate more questioning to elicit student responses and reflecting on adapting strategies into their classrooms.

Real-time classroom observation. In addition to our observations of one another's teaching through videotaped lessons, the technology also opened a window into the classroom though providing a means for a group observation of a real-time lesson. Using Google Hangout, we virtually joined MTE-2's class and watched as she presented the planned lesson to her PSTs. As MTE-2 taught the lesson, the other four MTEs observed, analysed and took real-time observation notes on a Google Doc. We kept a running dialogue between each other focused on strategies and teaching that worked well or needed to be addressed in the lesson. The following excerpt shows a dialogue between MTE-3 and MTE-4 on the Google Doc during the lesson.

> MTE-3: I think what is missing is more discussion of mathematically why this was a sophisticated method. What it shows about the student's number sense and her understanding of A groups of B...am I correct that they still haven't used A groups of B phrasing?
> MTE-4: Yes, I have not heard that phrasing yet (Real-Time Observation Notes, 6/3/2016).

It was through this discussion that the MTEs identified a portion of the lesson that MTE-2 skipped. While MTE-2's class was on break or working on independent small-group activities, text messaging provided a convenient way to communicate strategies and suggestions to adjust teaching and observation of the lesson in real time. Figure 2 illustrates some of the conversation that occurred over text messaging during the break.

Figure 2. Text messages shared between MTEs at the beginning of the lesson

The exchanges were quick and to the point, as MTE-2 was in the middle of teaching her lesson and only had a moment to converse. In Figure 2, MTE-3, a content MTE, addressed the need to focus on the meaning of multiplication as *A groups of B*, while MTE-4, a methods MTE, mentioned the missed opportunity to address the content standards. This collaboration between content and methods MTEs allowed for us to ensure that both areas (mathematics content and pedagogy) were addressed in the lesson. After MTE-2 viewed the messages, she began the next part of the lesson by drawing students' attention to the concerns highlighted by the other MTEs. Technology thus facilitated our real-time observation of MTE-2's classroom, provided a learning opportunity across geographical distances and served as a rewarding and powerful means of professional reflection for everyone, as highlighted through the excerpt below:

> MTE-4: I would even love it if we could somehow team teach this lesson, I would love to have you all cut in and add questions or push my students' thinking in-the-moment!
>
> MTE-1: I agree. I need to get better at pushing my students' thinking and having you all around to help push would be interesting (Real-Time Observation Notes, 6/3/2016).

As we watched and discussed missed opportunities, we recognised the power in seeing others modeling practices such as how to press students for justifications and how to critique our teaching practices. These conversations and the opportunity to view one another in the classroom provided a window for us to reflect on and develop our own teaching practice.

Building professional relationships and solidifying our community of practice

As we continued our collaboration throughout the lesson study, our discussions broadened to include conversations about common struggles, interests and teaching- or research-related resources we encountered. In a sense, our virtual community of practice evolved to include issues of importance to us in our tenure-track positions, rather than just focusing on the specific lesson we were researching. Through the use of technology, we discussed, shared, and analysed teaching and learning processes, and supported each other in our professional growth. This was particularly evident in our online journals.

> I love these discussions because normally I do this on my own and have to make decisions without discussion. This lesson is going to keep getting better and honestly, my confidence in my own ideas is getting better (MTE-1, Online Journal, 2/3/2016).

> One final note on what I gained about the sense of community. I feel more comfortable and excited about being a professor now that I have this group to talk with and work with. There are many demands on providing excellent teaching and publications. I know that my promotion and tenure file is better because of it. These are great people (MTE-5, Online Journal, 2/3/2016).

Being early-career MTEs, and often the only MTEs at our institutions, we found that engaging in a virtual community of practice opened different paths that had initially been obstacles to our growth. We were able to observe a peer colleague through Google Hangout, provide real-time feedback and have discussions, learn from each other and often push back on ideas to solidify our own understanding.

This pushing back and the MTEs' sense of comfort was evident during a planning conversation in which we discussed ways to assist our students in deciding on the next instructional decision for the whole class, which we noticed our students still struggled to accomplish after multiple revisions to our common lesson. Most MTEs in the group wanted to provide the PSTs with Mr. Harris's instructional goal for his next lesson. Instead, MTE-2 wanted the PSTs to determine the goal for themselves, rather than its being provided.

> Yeah, I'm still not – I'm going to be frank – I'm still not completely sold on the idea of giving them the goal before. Like, I was listening to your conversation and everything, and I completely understand what you guys are saying that it's like we're scaffolding a little bit and all those things. But what I'm feeling is, I hope it doesn't boil down to just the fact that they have to write a problem for the goal rather than connect it to – how it is the next steps (MTE-2, Planning Meeting, 3/17/16)?

After MTE-2 shared her concerns, we discussed this issue, and MTE-3 provided suggestions to move forward. MTE-2 later reflected on the discussion and wrote, "when MTE-3 said that students need to anticipate what the children would do with the next step task – it was like 'Aha!' for me. 'Yes!!!! That is it!'" (MTE-2, Online Journal, 3/17/16). This shows our group's level of comfort and our ability to have a discussion and decide about how to move forward with the lesson. Throughout our time studying the curriculum and setting goals, planning, conducting the research and reflecting on the lesson study, we developed relationships and grew to trust each other. This can be seen in MTE-2's dialogue and reflection, as she was comfortable in challenging suggestions to push our thinking. However, she was also open to hearing ideas and changing her mind to support students. Meeting virtually and engaging in these conversations allowed us the space to solidify our community of practice to largely focus on developing our pedagogical skills and continue building our professional relationships and agency as we grew into our roles as early-career MTEs.

Technology challenges and limitations

Engaging in this lesson-study process across five different states and accomplishing the teaching of our common lesson would not have been possible without technology; however, we were limited by technical issues. There were times when our technology did not work due to insufficient memory storage, placement of the recorder or human error in starting or stopping the recording

(Figure 3), and times when our videos did not capture students' conversations or actions. We were only able to interpret and discuss things captured on video or audio recordings, which may have omitted other important aspects of the lesson or teaching.

Figure 3. Text message highlighting technology challenge

Conclusions

Through the process of technology-facilitated lesson study, we grew into a virtual community of practice focused on our teaching and instruction. We reflected on our teaching practice, gained understanding of our PSTs' thinking, learned strategies to develop our PSTs' thinking and grew as early-career higher-education faculty members. Perhaps one of the biggest impacts has been the degree to which many of the effects of the study have lasted. We continue to hold weekly virtual meetings during which we share teaching resources, contact one another when we have questions about teaching different topics and share classroom successes and challenges with one another. We continue to engage in multiple research activities together, such as presenting at conferences, publishing papers and brainstorming ideas for other individual research projects. Participating in the technology-facilitated lesson study provided us with learning opportunities to grow as professionals and supported us to create meaningful learning experiences for our PSTs. The sections below outline the future research directions stemming from this paper and discuss implications for higher education.

Future work

The development of a lesson to study led not only to our development as classroom instructors, but to our becoming part of a virtual community of practice. Traditionally lesson study focuses on the

increased learning of the students; however, we extended the lesson-study methodology to investigate how engaging in this technology-facilitated lesson study supported our learning. In Xu and Pedder's (2014) review of the research on lesson study from 2002-2017 that spanned the globe and pre-K-16 education, they found that only 7% of the research articles focused on teacher learning through lesson study. Future work could investigate this process of learning through lesson study. As Xu and Pedder (2014) state, "There remains a great deal of further research and conceptual work to do before [there is] a well-developed explanatory theory of teachers' and students' learning in [lesson study] contexts" (p. 46). Our next step with this research is to contribute towards a theory of our learning through lesson study. Having formed a community of practice through our technology-facilitated lesson-study process, we could use Wenger's (1998) social theory of learning to investigate our learning along the Wenger's four dimensions: community (learning as belonging), meaning (learning as experience), practice (learning as doing) and identity (learning as becoming) (p. 5).

Implications

Although we met through the STaR program, we believe there are ways for other higher-education faculty members to engage in similar professional-development opportunities and create virtual communities of practices. One suggestion is to reach out to other faculty either at their own university or through professional organisations. While the following observation from Yoshida (2012, p.149) was specifically for K-12 teachers, we believe it applies directly to our work as MTEs:

> To build a community of professional learning or lesson study where teachers can learn from each other, we need to break the barrier of isolation. Isolation is an enemy of lesson study and precludes the improvement of experience and knowledge in teaching and learning by teachers. We need to think about how we can share our experiences and knowledge gained from lesson study within and across schools to support student learning and understanding.

Thus, we call on higher-education organisations around the world to provide structure and space for virtual communities of practice at the university level to develop and participate in lesson studies, and we call on national and international associations to do the same at conferences. Perhaps through initial face-to-face meetings at conferences, higher-education faculty members at different institutions can discuss mutual interests and develop into virtual communities of practice that can choose a topic for completing a lesson study.

We also call on higher-education institutions to ensure that faculty have access to up-to-date technology that supports collaboration. Since the time that we conducted our lesson study, the advances and availability of technology have changed. For one, we have now switched to Zoom for our teleconferencing meetings, which allows us to record our conversations within the program and text in real time, and has been more stable than Google Hangouts. Some of us work at institutions that have professional accounts with Zoom, and we are allowed to take full advantage of the program's capabilities. Finally, we call on members of the administration to encourage and support new tenure-track faculty members' collaboration rather than pushing for sole authorships and research. As Crespo (2016, p. 12) writes, "Educational problems are much too big for any one of us to take on and solve by ourselves, and...it will take...a whole village of committed mathematics educators to make the kinds of changes we are all striving to make."

With the advances in technology, these villages can now cross geographical locations and assist higher-education faculty members as they continue their professional development through participating in technology-facilitated lesson studies.

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