Student Reflections on 360-Degree Video for Pseudo-Synchronous Collaborative Problem Solving in Online Mathematics Learning

Amie Albrecht, Lisa O'Keeffe, Bruce White
University of South Australia, Australia

Abstract
Online learning offers increased flexibility to students but also poses new complexities. For example, there are challenges in digitizing teaching approaches that rely on the co-construction of knowledge through social interaction and collaboration between learners. This study explores a novel pseudo-synchronous approach using 360-degree video to improve access to collaborative mathematical problem solving for online students. We trialed the use of 360-degree video extracts of authentic collaborative problem-solving situations to offer online learners the opportunity to engage with different approaches and methods in various mathematical problem-solving situations. Data were collected through online surveys and analyzed using descriptive statistics and thematic analysis to examine student experiences. The findings suggest students prefer face-to-face collaborative problem solving but see the value of having the 360-degree video as a support when face-to-face interaction is not available or for students choosing to engage in an online environment. The study demonstrates that pseudo-synchronous 360-degree video can provide meaningful collaborative learning experiences for asynchronous online learners.

Keywords: 360-degree video; Pseudo-synchronous learning; Online problem solving; Collaborative problem solving; Mathematics

Albrecht, A., O'Keeffe, L., & White, B. (2025) Student reflections on 360-degree video for pseudo-synchronous collaborative problem solving in online mathematics learning. *Online Learning, 29*(4), 341-366. https://doi.10.24059/olj.v29i4.4292

Introduction

In the current landscape of higher education, there is a growing demand for more online offerings. Online learning environments offer students increased access and flexibility, allowing them to pursue education while accommodating various constraints, such as work commitments, family responsibilities, geographical barriers, and more. However, from a teaching perspective, online learning introduces new challenges. One of the key complexities is ensuring that students receive equivalent learning outcomes and experiences, whether they are engaged in face-to-face or online modes of course delivery. This problem is particularly acute for teaching approaches that rely on social interaction among learners.

To address this challenge, we devised an approach we have termed *pseudo-synchronous* that bridges the gap between synchronous and asynchronous online learning. Unlike standard asynchronous learning, which typically presents static, predetermined video content, pseudo-synchronous learning uses immersive 360-degree video to emulate collaborative in-class experiences within an online problem-solving framework that students can engage with asynchronously. This pseudo-synchronous approach aligns with Picciano's (2017) argument that online education has evolved as a subset of learning in general rather than a subset of distance learning. Rather than simply digitizing traditional distance education methods, our 360-degree video framework draws upon established collaborative learning principles to create meaningful educational experiences. The goal is to preserve the essential social and cognitive dimensions of face-to-face problem solving while accommodating the flexibility required by online learners.

Social interactions in online learning can be either synchronous or asynchronous. In synchronous online collaboration, students come together in real time within virtual environments, such as virtual classrooms, video conferencing platforms, or live text-based chat rooms. While studies such as Choi and Walters (2018) found that students in fully online K-12 environments demonstrated an increase in their mathematical performance when engaged in synchronous environments, the real-time participation requirements inherently limit accessibility for students. Synchronous collaboration requires that all participants are available at the same time, which can be a barrier for some online learners and potentially contradicts the concept of flexible learning. An alternative is asynchronous collaboration, where students contribute at their own pace and on their own schedules, typically through mediums like online forums and discussion boards. However, due to their ordered and time-spaced nature, asynchronous interactions often miss the spontaneity of early idea generation and can become more focused on finished products and solutions rather than the dynamic, in-the-moment development and analysis of various approaches.

Group work, a particular type of social interaction, can be challenging for online learners and can lead to disengagement or even withdrawal from the course (Gillett-Swan, 2017). Researchers have found that asynchronous online communication does not always support cooperative learning processes, and that those who collaborate asynchronously have lower perceptions of belonging and higher negative affect (Peterson et al., 2009). Even for synchronous online learners, traditional approaches to group work can be inadvertently alienating as assumptions are often made that students inherently know how to effectively collaborate in groups and that they are fluent with the different technologies required for group work in online environments (Gillett-Swan, 2017). As such, facilitating and supporting social interaction and relationship development needs to be a priority in online learning (Gillett-Swan, 2017; Jaques & Salmon, 2007; Stoessel et al., 2015).

In relation to group work in online learning environments, Graham and Misanchuk (2004, p.184) distinguish between students functioning as “work groups” or as “learning groups.” In work groups, the collaboration is product-oriented with a focus on the outcome. Group members take on tasks that reflect their existing skills and strengths so as to maximize opportunities for successful completion of the task. In learning groups, the collaboration is learning-oriented with a focus on the process. Group members take on tasks to gain skills they have not already acquired so as to maximize opportunities for learning. The authors noted several challenges for instructors of online learning groups, including the design of learning activities and facilitation of group interactions.

This study was motivated by the prospect of having to transition a face-to-face mathematical problem-solving course into an online format that allowed students to engage asynchronously. Our primary objective was to ensure that online learners would not only achieve similar learning outcomes but would also be engaged in educational experiences that mirrored those offered in the face-to-face setting. In particular, we wanted to preserve the essence of collaborative mathematical problem-solving experiences that emphasized process over product.

The aim of this study is to examine how 360-degree video might support both the social and cognitive dimensions of collaborative problem solving for online learners, specifically addressing the research question:

> In what ways can 360-degree video be useful for emulating collaborative mathematical problem solving for asynchronous online learners?

In this paper we present our findings of the effectiveness of this approach.

360-Degree Video as a Tool for Learning

360-degree videos, also known as immersive videos, are a type of video recording that captures a view in every direction at the same time. The videos can be played back with different levels of immersion, from desktop to head-mounted displays. When playing back a 360-degree video, the viewer can control the perspective and interactively explore the entire scene, allowing them to feel present in the scene rather than merely observing it from a fixed point like in traditional video.

From a systematic review of the literature, Rosendahl and Wagner (2023) identified three main purposes for using 360-degree videos as a medium for teaching and learning: delivering educational content, creating immersive and interactive learning experiences, and facilitating reflection purposes (by both self and peers). The authors also highlighted the following potentials for using 360-degree videos in education: supporting multi-perspective observational and reflective learning, increasing motivation and interest amongst learners, creating authentic and realistic learning experiences, and fostering interactive and immersive learning processes. 360-degree video has been used across a range of disciplines, particularly those involving situated learning, such as supporting in-service and pre-service teachers of mathematics to develop and refine their practice (O'Keeffe et al, 2020; O'Keeffe & White, 2022; Balzaretti et al., 2019). Integrating video (of any form) in online teaching and learning platforms has shown to be effective in creating a sense of community (Borup et al., 2012).

Mathematical Problem Solving

Problem solving is a crucial skill in both modern work and everyday life (English & Gainsburg, 2015) and is a fundamental part of mathematics curricula around the world (Olivares et al., 2021). Research suggests that teaching mathematical content through problem solving is an effective practice for developing conceptual understanding and procedural skills, as well as positive beliefs about mathematics (Lester & Cai, 2016).

General frameworks for mathematical problem solving came to prominence with the work of Pólya (1945/2004), who described four stages: understanding the problem; devising a plan; carrying out the plan; looking back. Influenced by Pólya's work, Mason, Burton and Stacey (1982/2010) structured the process of tackling a problem into three phases: entry, attack, and review. Neither of these frameworks is intended to be linear as authentic problem-solving involves what NCTM describes as "engaging in a task for which the solution method is not known in advance" (NCTM, 2000, p. 52), and thus oscillates between getting to grips with the problem and pursuing lines of possible attack while constantly monitoring the degree to which these efforts are fruitful.

While these frameworks describe the nature of problem solving, questions remain about how best to support students in developing these capabilities. There is some disagreement in the research literature as to whether mathematical problem-solving strategies can be taught. Schoenfeld's pioneering work (1985) on teaching problem-solving courses at the college level found that students became more effective problem solvers and could solve more challenging, unfamiliar problems, however teaching general problem-solving strategies (e.g. draw a diagram) proved less successful (Lesh & Zawojewski, 2007). Schoenfeld suggested a focus on teaching more specific tactics, a view also supported and elaborated by Foster (2023).

Facilitating problem-solving experiences can be challenging for teachers. In many mathematics classrooms and textbooks, problem solving is reduced to a checklist with general problem-solving skills being taught without students fully appreciating why, when and how to apply them to specific problems (Stacey, 2022; English & Gainsburg, 2015). Stacey (2022) argues that the need for strategies should arise from well-selected problems. Foster (2019) describes the challenge of deciding when and how to intervene as students face difficulties. He advocates scaffolding the problem-solving process rather than the specific problem itself, directing support and discussions towards more generic aspects of problem solving. To encourage reflection, he suggests asking questions to help students "reflect on what worked and what did not, and why, so that they talk not just about the mathematical content but about their approaches to solving the problem" (p. 9); this also helps activate students' metacognition.

Metacognition—thinking about one's own thinking—is crucial for successful problem solving. Schoenfeld (1992) revealed metacognitive differences in how novices and experts worked on unfamiliar problems. Novices often exhibited a lack of metacognitive awareness and persisted with ineffective approaches, while experts monitored their progress and made informed decisions about when to change strategy. Schoenfeld found that, with regular metacognitive coaching (i.e. asking questions designed to prompt student reflection), novices' problem-solving behavior became more expert-like.

Collaborative Mathematical Problem Solving

Recognizing that collaboration is a crucial skill in today's workplaces, in 2015 the Programme for International Student Assessment (PISA) introduced its first-ever assessment of collaborative problem solving to address the lack of internationally comparable data in the field. The results of PISA 2015 showed that competency in collaborative problem solving is associated with higher mathematics achievement. PISA 2015 defined collaborative problem-solving competency as "the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills and efforts to reach that solution" (OECD 2017, p. 47). Collaborative problem solving requires learners to jointly orchestrate their activities, mutually building upon each other's contributions (Hesse et al., 2015). They must also work together to negotiate and create shared group meaning (Stahl et al., 2014).

The framework for collaborative problem-solving skills, as presented by Hesse et al. (2015), has both social and cognitive dimensions. The social dimension is the *collaborative* part and relates to managing participants, including oneself. The cognitive dimension is the *problem solving* part and relates to managing the task at hand. In collaborative mathematical problem solving, the social dimension includes aspects like negotiating possible approaches, listening to and making sense of the ideas of others, responding to and building on contributions, and maintaining awareness of group dynamics, whereas the cognitive dimension is mainly individual mathematical problem solving as discussed earlier.

Ham and Hwang (2021) describe how new mathematical content can be learned through collaborative problem solving, emphasizing the importance of dialogical interactions in helping students to develop and refine their understanding of mathematical concepts. Participating in group discussions improves students' capacity to articulate and justify their thinking. Students gain insights from hearing and seeing the diverse range of approaches and strategies of their peers and, as a result, may access knowledge through peer support that would have been out of their reach had they been learning independently. Results from PISA 2015 showed that students who are regularly asked by teachers to discuss their work in class are likely to have more positive attitudes towards collaborating with others (OECD, 2017). Beyond its cognitive benefits, social interaction in mathematics also plays a motivational role, enhancing students' engagement and positive emotions toward mathematical learning (Schukajlow et al., 2023).

Bridging Theory to Practice: 360-Degree Video for Collaborative Mathematical Problem Solving

While the theoretical frameworks of collaborative problem solving and metacognition provide a strong foundation for mathematics education, their implementation in online learning environments presents unique challenges. As noted by Balzaretti et al. (2019), one of the fundamental challenges with standard video recording is that decisions need to be made about where to point the camera, creating researcher or teacher bias that predetermines what might be worth observing. When used for teaching purposes, this means students are limited to a single, predetermined perspective, potentially constraining the collaborative dimensions identified by Hesse et al. (2015). To address these limitations, this study examines how 360-degree video technology can create immersive learning environments that support both the social and cognitive dimensions of collaborative problem solving.

The design of this study operationalizes key theoretical frameworks within the 360-degree video experience. For instance, Pólya's four-stage problem-solving framework is supported through the environment's ability to allow students to observe multiple approaches to understanding problems, see various planning strategies from different group members' perspectives, follow the implementation of solutions from multiple viewpoints, and engage in comprehensive reflection by revisiting the entire collaborative process. Mason, Burton and Stacey's (2010) three phases were embedded in the design by structuring different experiences of initial problem engagement (entry), strategic development and testing (attack), and reflective evaluation of strategies (review).The theoretical foundation for this approach draws from socio-constructivist learning theory, where knowledge is constructed through social interaction and shared meaning-making (Stahl et al., 2014). The technology-enhanced approach in this study supports online independent learners to experience some form of collaborative (albeit mediated) problem solving. Within this framework, 360-degree video serves as a technological tool that facilitates collaborative learning by providing a shared, immersive reference point for mathematical problem-solving activities. This use of 360-degree video offers several advantages over traditional video for supporting collaborative problem solving in online environments. The immersive nature eliminates the camera bias inherent in conventional recording by providing comprehensive scene capture rather than predetermined focal points (Balzaretti et al., 2019). Additionally, the multi-perspective accessibility enables learners to explore different aspects of the mathematical problem space whilst maintaining shared context, supporting the metacognitive reflection processes identified by Schoenfeld (1992) and as recommended by Foster (2019).

Methodology

This study employs an exploratory survey design to investigate how 360-degree video can emulate collaborative mathematical problem solving for asynchronous online learners. The survey design incorporated both closed-ended questions (analyzed quantitatively using descriptive statistics) and open-ended questions (analyzed qualitatively through thematic analysis) to provide comprehensive insights into student experiences. The comparative element enables examination of differences between face-to-face and online problem-solving experiences within the same participant group, which is essential for understanding whether and how the 360-degree video intervention affected their experiences. We also explicitly categorized participants according to their past experiences learning mathematics in online mode, as this prior experience may influence their perceptions of and engagement with the pseudo-synchronous approach.

In this project we take a novel approach to designing learning experiences for asynchronous online learners by making use of 360-degree video recordings of on-campus students engaging in problem-solving tasks in mathematics. This approach is innovative in two key ways: (1) using authentic recordings of real peer collaboration rather than instructor-created content, and (2) enabling pseudo-synchronous engagement where asynchronous learners can virtually participate in genuine collaborative mathematical problem solving even though they are working at their own pace and location. To investigate this approach, the broader project used the online problem-solving framework in three different formats with three different cohorts of mathematics pre-service teachers. The first configuration explored collaborative mathematical problem solving, in both in-class and online learning environments, with students studying a mathematics course in face-to-face mode. The second configuration added an individual problem-solving activity in an online environment as part of a face-to-face course. The third configuration centered on problem-solving reflections in a mathematics course with students who either studied entirely online or entirely face-to-face. This paper reports on the first configuration, by introducing the online problem-solving framework and reporting on its use with one group of students to compare their problem-solving experiences in both online and face-to-face mode. This phase is guided by the research question:

> RQ: In what ways can 360-degree video be useful for emulating collaborative mathematical problem solving for asynchronous online learners?

Context

Developing Mathematical Thinking is a problem-solving course for mathematics pre-service teachers (PSTs). The course adopts a *learning group* philosophy (Graham & Misanchuk, 2004) with students engaging in sessions aimed at working together to tackle unfamiliar problems, chosen to illuminate a particular problem-solving strategy. Each activity is followed by a whole-class discussion to emphasize and draw out aspects of the problem-solving process. A primary objective of this pedagogical approach is for students to experience, appreciate and normalize the messy, non-linear nature of authentic problem solving. This includes recognizing that there are typically several different possible starting points, ways of organizing and representing work, and approaches to tackling the problem—some of which may prove less fruitful or lead to a dead end. The collaborative nature is pivotal, as it exposes students to more ways of thinking about a problem. The collaborative setting also encourages students to articulate and justify their thinking, actively listen to and interpret the ideas of others, and critically evaluate the merits of each approach while negotiating the path that will be taken by the group, that is, engaging in both the social and cognitive dimensions of collaborative problem solving (Hesse et al., 2015). The role of the teacher is to choose problems that reveal particular elements of problem solving, ask questions designed to help students internalize metacognitive skills, facilitate whole-class discussion to reflect on the learning experience, and ensure there is a shared understanding of the key outcomes from the activity.

Participants and Process

At the time of this study, there were 56 pre-service teachers enrolled in two separate classes, with 28 students in each class. The course was entirely conducted on campus in face-to-face mode and was of 13 weeks duration. In Week 5 of the course, each class was assigned and tackled a different group-based task. Class A tackled Problem A, referred to as the *3Ms problem*, inspired by M, M, and M from NRICH (n.d.), while Class B worked on Problem B, the *Cool Years problem* developed by the first author (see Figure 1). Both problems were chosen as they rely on the problem-solving strategy of *working systematically*, specifically, and listing solutions in an ordered way. Students collaborated in small groups of three or four, with

360-degree cameras recording the activities of groups who had agreed to participate in the study.

The 360-degree videos were then edited by the authors to create a series of excerpts to highlight aspects of the problem-solving process. Segments were chosen to highlight different problem-solving methods, show authentic student conversations about mathematics, and capture moments where students encountered difficulties, made errors, or achieved insights. These excerpts were subsequently used to create an online problem-solving framework for each problem, which will be detailed in a following section. In the closing stages of the course, during Week 12, students from each class individually engaged with the other problem outside of class time using an online framework, that is, Class A tackled Problem B and Class B tackled Problem A.

Ethical approval for this study was obtained from the University of South Australia Human Research Ethics Committee (Approval No. 203331). All participants provided informed consent prior to participation.

Data Collection

Students were asked to complete an online survey after each problem-solving experience (Weeks 5 and 12) as part of their regular coursework. The surveys included questions related to their previous choices about studying mathematics in face-to-face or online mode, their problem-solving approaches, the ways in which they used group members' ideas as well as the perceived difficulty of the task (rated on a scale of 1-10 where 1 represents *not difficult at all*, and 10 signifies *extremely difficult*). Additionally, students were asked to indicate their level of agreement with statements such as

- Hearing how other students approached the problem has improved your problem solving skills
- Working with a partner/group was useful to tackle the problem
- It was useful to communicate directly with your peers about challenges as you encountered them
- It was useful to be able to observe other groups' approaches to the problem as it helped you to get started or prompted ideas
- It was useful to be able to observe other groups' approaches to the problem as it helped you to refine your solution

Students were encouraged to provide open-ended responses to all scale-type survey questions, and all participants did so. In the final survey, students were also asked to express their preferred mode of learning for problem solving in mathematics, whether online or face-to-face.

All 56 students completed the group-based in-person task. For the online problem-solving task, 19 students from Class A completed Problem A and 12 students from Class B completed Problem B. This component was not mandatory, and some students opted not to participate. It should be noted here that seven of the 19 who completed Problem A in online mode, and four of the 12 who completed Problem B in online mode, had previously studied mathematics courses at the university in online mode. We recorded students' past experience with online learning modes, as this prior experience may have influenced their comfort level with the technology, their expectations for online support, and their engagement with the 360-degree video features, potentially making them more receptive to the pseudo-synchronous approach. All students were invited to take part in a focus group or interview, of which two students agreed to participate. However, the timing posed a challenge, with the course finishing just as students embarked on their teaching placements. Despite multiple efforts to reschedule, the interviews could not be completed.

Data Analysis

Given the exploratory nature of this study, a mixed-methods approach was used for data analysis. To gauge whether students thought the 360-degree videos were useful in emulating collaborative mathematical problem solving, ratings and closed questions from the online survey were subjected to quantitative analysis, with results reported using descriptive statistics (predominantly proportions and measures of central tendency and dispersion). Independent sample t-tests were also applied to compare mean responses between Problem A and Problem B across five Likert scale statements measuring student agreement with various aspects of the video experience.

Descriptive statistics were chosen as the primary quantitative approach due to the exploratory nature of this study and the small sample sizes. The quantitative analysis served to identify patterns in student responses that guided our qualitative investigation. For example, the high percentages of students finding videos useful for getting started (94% for Problem A, 83% for Problem B) directed our thematic analysis to explore how students used videos strategically. Similarly, the lower percentages for feeling less alone (47% for Problem A, 75% for Problem B) prompted deeper examination of social presence themes in the qualitative data. The non-significant differences found in the t-tests (p-values ranging from 0.25 to 0.80) suggested consistent experiences across problems, allowing thematic analysis across both conditions.

The thematic analysis employed an inductive approach, allowing themes to emerge from the data rather than analysing against predetermined categories. When coding discrepancies arose between researchers, these were resolved through discussion and consensus. This analytical approach directly addresses our research question by examining both the quantitative indicators of video usefulness and the qualitative insights into the specific ways students engaged with the pseudo-synchronous experience.

Design of the Online Problem-Solving Framework

The online problem-solving framework was created within a lesson activity module within the Moodle platform. The lesson activity allowed for a branching structure where students were directed to specific pages based on their responses. The online problem-solving framework designed for each problem followed the three phases of work detailed by Mason et al. (2010): entry, attack, and review. The workflow design reflects Picciano's (2017) principle that pedagogical objectives should drive technological approaches. By structuring the experience around Mason et al.'s entry-attack-review phases while embedding 360-degree video supports strategically rather than prescriptively, we aimed to address both the social and cognitive dimensions identified by Hesse et al. (2015).

For the purpose of describing the design of the online problem-solving framework, we refer to the Cool Years problem, as illustrated in Figure 1. The workflow is shown in Figure 2 and, in line with Foster (2019), is designed to scaffold the problem-solving process, not the problem itself. The entry phase starts with an introduction to the problem, which students are encouraged to independently tackle for five to ten minutes. Students are then prompted to write a text-based description of their approach. Next, they are directed to watch and reflect on short video clips showcasing various initial problem-solving approaches employed by other groups. Videos of key moments in the collaborative problem solving of other groups are also used during the attack and review phases. For the Cool Years problem, these six clips range from 12 seconds to 2.5 minutes, keeping segments brief to support sustained attention while capturing key collaborative moments. Questions designed to prompt reflection on the problem-solving process are embedded along the way and designed to replicate the types of questions that would be asked in class by the instructor to activate students' metacognition.

The inclusion of videos is intended to help address both the social and cognitive aspects of collaborative problem solving as outlined by Hesse et al. (2015). The videos guide students in refining their problem-solving processes in multiple ways: for example, assisting them when they get stuck, encouraging them to consider other approaches, prompting them to make sense of the ideas of others. Using 360-degree videos aims to help students feel part of the learning group, rather than participating as an external observer, thereby achieving the pseudo-synchronous experience that bridges the gap between asynchronous flexibility and synchronous collaborative engagement.

Figure 1

Extract from the Cool Years Problem as Presented on the Moodle Platform

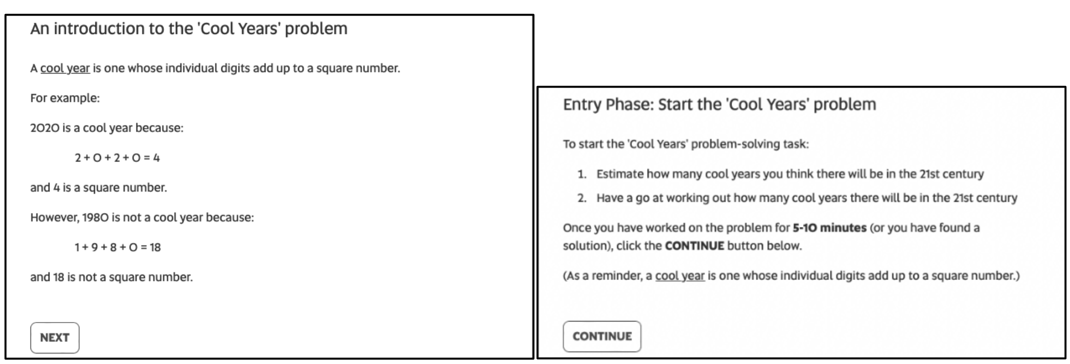
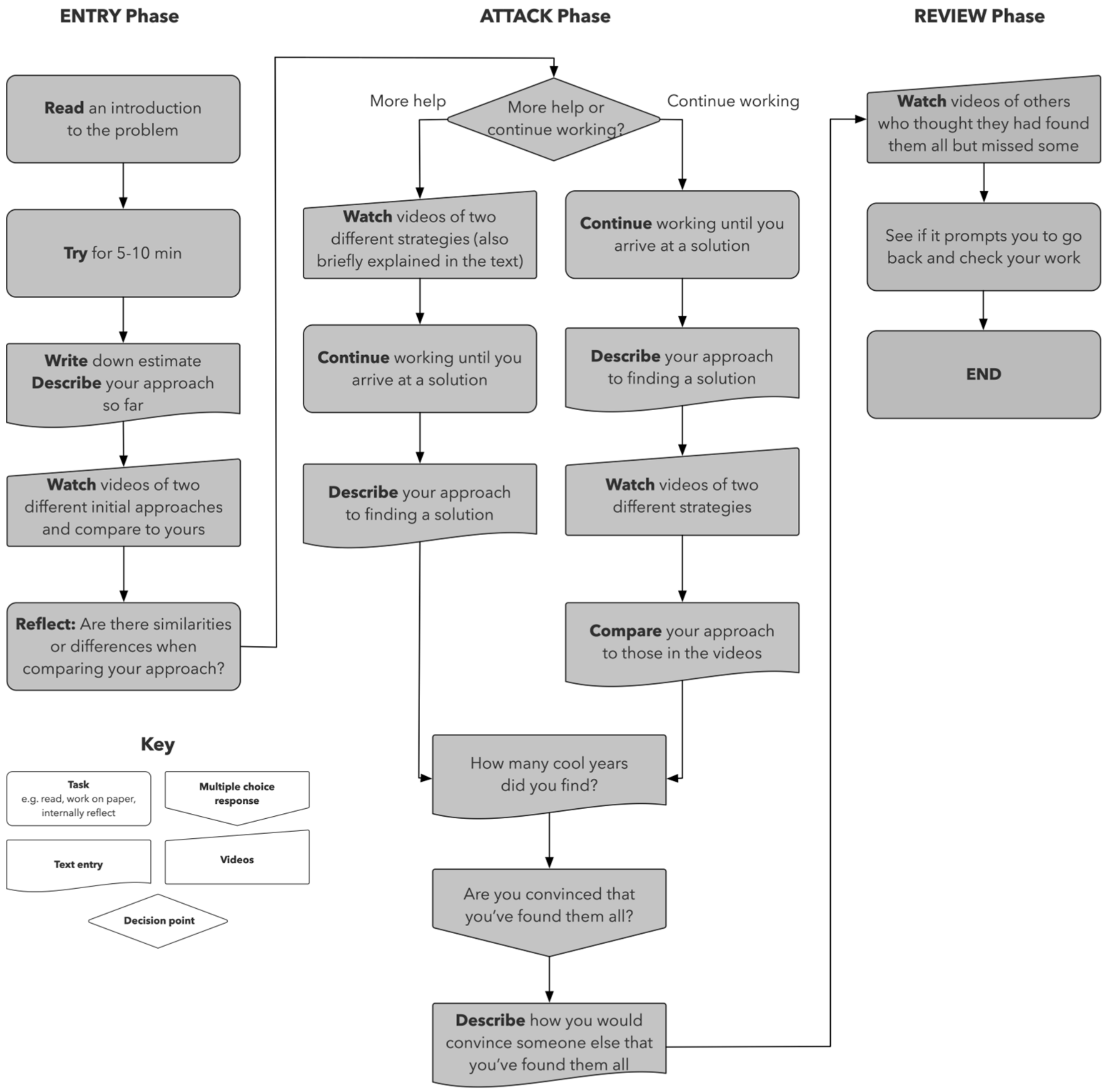


Figure 2

The Workflow for the Cool Years Problem



Findings

The quantitative data obtained after students completed problems in the face-to-face and online learning environments are presented in Table 1. This data shows the number of students (n) who completed each problem, the average perceived difficulty of the problem from 1 (*not difficult at all*) to 10 (e*xtremely difficult*) and the amount of time spent on each problem.

Table 1

Quantitative Data From Students' Problem-Solving Experiences

Problem	n	Learning environment	Difficulty rating (1-10)	Duration (min), [Median, Range]
Problem A (M)	24	in-class	4.50	~18 min
	19	online	4.34	86 min, [22.4, 195.0]
Problem B (C)	28	in-class	5.07	~28 min
	12	online	4.67	42.3 min, [19.5, 77.0]

It is important to note that in-class time was influenced by the duration of the workshop, while online time represents browser window activity duration which, as noted in the limitations, may overestimate actual engagement. Despite this, the longer time spent in online mode suggests students were investing significant effort in the pseudo-synchronous experience, potentially reflecting the self-paced nature of asynchronous learning. While the additional time could suggest videos made problems more challenging, the video content comprised only a small portion of the total online time (approximately 19 minutes of video within 86 minutes total for Problem A, and 9 minutes within 42 minutes for Problem B). This, combined with students' positive feedback, indicates the extended time reflects deeper engagement with both mathematical and collaborative learning components rather than confusion or inefficiency.

As evident from Table 1, both problems received a similar average difficulty rating, regardless of the learning environment. Students' open responses indicated that overall, they perceived the pitch of both problems to be suitable, regardless of the learning mode. They generally agreed that Problem A presented a manageable challenge, with one student noting the problem was "not difficult as such, finding the correct number of possibilities and justifying my answer effectively was where the activity became more difficult." On the other hand, responses regarding the difficulty of Problem B were more varied, with some finding it challenging and others deeming it relatively easy. For example, one student summarized the challenge of Problem B as "I did not find this task very difficult, as there was a clear pattern shown once you started the question. The hardest part was if you could see the pattern or not."

Students were also asked to indicate their level of agreement with five statements aimed at better understanding their difficulty ratings. The data is summarized in Table 2 below which presents the mean score response from a five-point Likert scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Independent samples t-tests show that there are no statistically significant differences in the mean responses with regard to problems A and B across any of the statements ($p = 0.25$, $p = 0.66$, $p = 0.80$, $p = 0.40$, $p = 0.80$), suggesting no variation due to differences in the tasks.

In general, students found it somewhat challenging not being able to communicate with peers and their lecturer (as evident the first three statements in Table 2). Students also found observing other groups' approaches via the 360-degree videos to be useful in getting started and in refining their solutions.

Table 2

Number and Percentage of Students Who Agreed with the Following Statements

Statement	Problem A (n=19)	Problem B (n=12)
1. Not being able to hear, in real time, how other students approached the problem limited how much I learned from the problem.	5 (26%)	6 (50%)
2. It was difficult not being able to communicate directly with my peers about challenges as I encountered them.	12 (63%)	8 (66%)
3. It was difficult not being able to communicate directly with my lecturer about challenges as I encountered them.	10 (52%)	7 (58%)
4. It was useful to be able to observe other groups' approaches to the problem as it helped me to get started or prompted ideas.	18 (94%)	9 (75%)
5. It was useful to be able to observe other groups' approaches to the problem as it helped me to refine my solution.	17 (89%)	10 (83%)

Students were also invited to reflect on their problem-solving experiences in the two different learning environments. However, given that the focus of this paper is to better understand the potential of the framework to support students studying in online mode, the remainder of this section focuses on students' perceptions from experiences working online: the usefulness of the videos, their preferred learning mode, and their recommendations about potential video enhancements.

How did you use the videos?

Analysis of student responses across both problems revealed three distinct patterns of video usage:

- Group 1 (Did not/would not use) comprised students who either could not access the videos due to technical issues, or chose not to use them because they solved the problem without assistance and saw no value in viewing them.
- Group 2 (Did not use but could see the potential) comprised students who solved the problem without using the videos but recognized their potential value for situations where additional support might be needed.
- Group 3 (Found them helpful) comprised students who actively used the videos and found them beneficial for their problem-solving process, whether for confirmation, clarification, or gaining new approaches.

Seventeen of the 19 students who completed Problem A in online mode (and completed all elements of the post-project reflection) watched the videos. The two who did not reported technical issues, indicating they could not get the videos to load. These students fall into Group 1 (technical barriers rather than choice). No students fell into Group 2 for Problem A. The remaining 17 students all belong to Group 3, as they indicated they found the videos helpful. Individual student responses include:

- "I used the videos initially to make comparisons with my answers, then I used them for gaining ideas and clarification of problems."
- "Help[ed] with my thinking and to ensure I was on the right track and thinking the same as others."
- "Once I knew I was doing it correctly, I skipped along. The videos were more of a clarification rather than feeling like I was involved in a classroom environment."
- "At first I didn't use much of the videos, it wasn't until later where they asked deeper questions which prompted me to think of other ways of thinking."
- "I watched each of the videos at least once, I found attempting the problem, watching the video and their approaches and then re-attempting the problem effective. Watching others not only solve it but make mistakes are good because it makes you consider why their approach is not correct."
- "I used the videos to watch how my peers approached the problem after I had reached my solution. It was a bit frustrating knowing certain aspects of the problem that I could say to help them but not being able to."
- "Watching others not only solve it but make mistakes are good because it makes you consider why their approach is not correct."

These responses demonstrate that students used the videos for multiple purposes: comparison and verification (quotes 1 and 2), selective engagement based on their confidence level (e.g. quote 3), adaptive use responding to prompts and evolving needs (quote 4), iterative learning cycles of attempt-watch-reattempt (quote 5), and post-solution analysis for deeper understanding (quotes 6 and 7). Rather than passive consumption, students exercised metacognitive autonomy over their learning, choosing when to skip content, when to engage deeply, and how to integrate video observations with their own problem-solving approaches.

The twelve students who completed Problem B in online mode (and completed all elements of the post-project reflection) were distributed across all three groups. Two students fell into Group 1, indicating they thought the problem was 6 to 7 out of 10 in terms of difficulty but solved it without issue and didn't need to use the videos. One of these students did watch the videos but felt their approach was so different from hers that it confused her. Five students belonged to Group 2, solving the problem without using the videos. However, they did watch them and indicated they could see the potential of the videos if they had needed additional support. Student comments include

> I think if I had gotten stuck the videos would have been helpful"; I used the videos to see how others solved it which was interesting to see that one group did it similar to me….I believe they would of been helpful it I did get stuck.

The remaining five students comprised Group 3, all indicating they found the videos very helpful in completing Problem B. The responses and usage patterns are varied, ranging from just using the first video to help them get started to “I was fascinated by other approaches and wondered if they would have helped me solve this more quickly,” and “I was on the wrong path and the videos helped.”

Overall, the 360-degree videos offered students unique affordances compared to conventional videos, including the ability to control their viewing perspective and explore different aspects of the collaborative problem-solving environment. This created a more immersive experience that allowed them to feel present in the learning group rather than simply observing from a fixed viewpoint.

Getting Stuck

Students undertaking both problem-solving tasks were asked to indicate if the videos were helpful, or could be helpful, if they got stuck. Twelve of the students doing Problem A indicated that they did get stuck, and all found the videos helpful, adding comments such as “I only used the videos when I got stuck or was unsure. Which helped me to come up with ideas or to reaffirm my pattern of thinking,” “I feel like initially I didn't get stuck, but after the final video it made me realize I may have the wrong answer after all but it was still helpful to have to realize where I went wrong,” and “The videos did help. I saw a few things that I forgot to think about when attempting the problem.” Five of the students completing Problem B indicated they got stuck and they too all found the videos useful.

Using Videos in Online Problem Solving

We were interested in students’ perceptions as to whether having access to videos, such as the 360-degree videos provided in this project, would be useful if they were required to complete a problem-solving course in external/online mode. The student perception data, in response to these five statements, is provided in Table 3, with students organized according to the problem they had completed in an online learning environment. Students were asked to indicate whether they agreed that the videos were helpful in relation to a number of statements.

Table 3

Number and Percentage of Students Who Agreed That Videos Were Helpful in Relation to Each of the Following Statements

Statement	Problem A (n=19)	Problem B (n=12)
1. Getting a feel for what was happening in the internal version of the class.	16 (84%)	9 (75%)
2. Providing guidance/support if it was difficult to get started with a problem.	18 (95%)	10 (83%)

3. Providing guidance/clarity around how to approach a problem.	17 (89%)	9 (75%)
4. Providing guidance/clarity around solutions.	13 (68%)	7 (58%)
5. Making them to feel less alone as an external student.	9 (47%)	9 (75%)

Which Mode Did You Prefer?

From their experiences of working on two problems, students were asked to reflect on their preferred mode for problem solving: online or in-class. As a reminder, seven of the 19 students who completed Problem A and four of the 12 students who completed Problem B in online mode have previously studied mathematics courses at the university in external/online mode.

Problem A

Of the 18 students, 14 (of which seven had previously studied mathematics in an online mode) who responded to this question indicated a preference for problem solving in face-to-face mode. Responses include:

> I much prefer working in a face-to-face group in comparison to online. Problem solving was quite similar, except that not all ideas can be extracted from video, in comparison to in-person. With face-to-face, you are also able to obtain visual representation of problem solving, whether it is gaining assistance or giving in.

> I prefer face to face for the reason that you can all write things down together and discuss in real time, however if I had to do this online, this way of doing things would be more than ok to complete these sort of workshops.

Of the remaining four, three indicated that working with the videos in external mode was a similar problem-solving experience for them. One of these students had previously studied in online mode and they added, “however you somehow feel isolated as you can’t share your ideas with your peers and bounce off of their ideas in a way that makes problem solving seem fun.” The other student noted a preference for working independently, so they don’t have a preference for either online or face to face, adding that working in online mode can be “quicker to get through the content because I was not getting distracted by others, however, it would be more difficult if I was to get stuck and needed assistance.” This student had not studied mathematics in online mode before.

Problem B

Of the 12 students, nine (of which four had previously studied mathematics in an online mode) indicated a preference for problem solving in face-to-face mode. Responses include “I prefer face to face as I like to also have the social aspect of class but with the maths I found it to be 50/50 I liked hearing other people’s point of view and help me start the problem”; “I think face to face is much better. I believe you learn more working in groups and ways to solve a problem that you wouldn't necessarily think of" and

> I found working face to face easier as I can find help to the specific question that arise from me. I had questions about the groups I was viewing and it was frustrating no being able to interact with the people in the video for explanations or clarifications. The problem-solving process took longer and was less fun than working with others. However, the video was more beneficial than working completely alone.

Of the remaining three students (none of whom had previously studied mathematics in online mode), one student indicated that the mode didn't really matter to him, noting that "both required independence and problem-solving skills. Face to face just allows for further communication if needed." Another indicated they prefer working independently, so online is their preferred option, adding "It was definitely a different kind of experience [using the videos] but was easy enough to overcome. Maybe if the problem was more difficult, I would have benefited from face-to-face discussion." Similarly, the third student said

> It was a different problem-solving experience, I did like this way however as I was able to use the videos to help understand the question. I would struggle however if the video did not explain the problem very well and then I wouldn't be able to work with others to discover how to attempt the problem.

In summary, of the 31 students, 23 expressed a preference for face-to-face problem solving. Sixteen of these 23 students highlighted that real-time or synchronous communication with peers and instructors influenced their choice. These students liked that they could talk to someone else to guide their thinking, for example, "The online support [the 360-degree videos] was useful for tackling the problem independently, however I am not able to ask questions and have meaningful conversations." Additionally, seven of these 23 students noted that face-to-face problem solving allowed them to see others' work, and that they preferred having this visual component to problem solving. While they preferred face-to-face problem solving, six students commented that, if they had to study online, the problem-solving framework and the videos would help them to succeed. Only three of the 31 students preferred online mode for problem solving, citing its efficiency and lack of distractions. However, the students also noted that if the problem had been more difficult, they might have preferred a face-to-face discussion.

Are There Modifications or Changes That Would Make the Videos More Useful?

Students were asked to reflect on what would make the 360-degree video snippets more useful. The most common suggestion (n=9) raised by students was to include a greater emphasis on student written work, for example, "greater emphasis on what students are writing … recorded working out as well as discussions. Listening to their reasoning was good but I couldn't visualise what they meant sometimes." Only one other suggestion was made by more than one student, and that was to confirm some more specific detail about the problem such as explaining the intent/purpose as well as clarifying if the group in the video is working on the most efficient approach. This comment suggests that the student was focused more on solving the problem, rather than learning about the problem-solving process, as detail about the latter is provided alongside each video in the online framework. One student suggested more videos would be helpful adding “the more opinions and ideas, the better” and another suggested more students from other groups interjecting and challenging ideas of the group within a video would be helpful.

Some students also made note of the quality of the audio being inconsistent, particularly in relation to hearing the lecturer address the whole class. Another student suggested adding subtitles to help with audio issues. A technical issue was raised about playing the videos on particular types of phones or tablets. Both of these comments are worth consideration as they raise questions about access to the knowledge and information being disseminated in online form.

Discussion

The initial findings suggest that the majority of students prefer a face-to-face learning environment. They feel secure having others with whom to discuss and ask questions. In-the-moment availability of a teacher or peers also emerged as a key factor. The perceived importance of having peers or an educator at hand is not surprising, particularly in the context of the students’ previous learning experiences in this course, which was very collaborative in nature. The premise is also well aligned with the view of Borko et al. (2008) and Ham and Hwang (2021) that knowledge and meaning can be co-constructed or refined through the social practices of discussion and peer-to-peer explanation. The preference for immediate social interaction parallels the findings of Choi and Walters (2018), who found that while synchronous discourse sessions improved mathematical performance in online environments, students still required real-time coordination for meaningful collaboration.

Collectively, these findings underscore the rationale for developing pseudo-synchronous learning approaches that bridge the gap between the flexibility of asynchronous learning and the immediate social support valued in synchronous environments. Our 360-degree video approach appears to occupy a middle ground, providing access to collaborative processes when face-to-face interaction is unavailable while acknowledging that technological solutions may serve best as supplements to, rather than replacements for, the immediacy of in-person collaboration. Such an approach supports Picciano's (2017) argument that effective online education requires thoughtful integration of multiple modalities rather than simple translation of face-to-face methods.

As discussed earlier, group work in asynchronous learning is complex with studies (e.g. Peterson et al., 2009) highlighting how poor or limited communication contributes to disengagement, lower perceptions of belonging, and higher negative affect. The insights provided by students clearly demonstrate that the social components of learning remain critical in online learning environments, regardless of student’s stated preference for face-to-face or online learning modes. Thus, the findings in this pilot align with the arguments presented by Gillett-Swan (2017) and Stoessel et al. (2015) regarding the importance of prioritizing social interaction and relationship development in online learning environments. Regardless of the chosen learning mode, students need to feel connected to their learning, peers, and educators. The pseudo-synchronous approach trialed in this study is one attempt to foster a sense of connection among online learners.

While the data indicates that the majority of students felt the use of 360-degree video excerpts would not sway them to choose an online mode over face-to-face mode, they did indicate that, if compelled to study online, these videos would have helped them have a sense of how other students might be thinking and working. This finding aligns with social presence theory, which emphasizes how learners' sense of connection and awareness of others can enhance learning engagement (Garrison et al., 2000). The 360-degree videos appear to facilitate vicarious learning, allowing students to observe and learn from peer strategies and approaches even in the absence of direct interaction. Additionally, they felt the videos would help alleviate feelings of isolation, especially in the context of challenging problem-solving tasks. Students recognized the value of having pre-planned 360-degree video snippets as a tool, particularly when they needed guidance on getting started or if they got stuck. This observation echoes the findings of Barfield (2016) and O'Leary and Wood (2019), suggesting that the collaborative component adds an extra layer of feedback on one's own approaches (informally from group members) and creates more opportunities to see other approaches and ways of thinking.

Importantly, students demonstrated metacognitive autonomy in their engagement with the videos, using them strategically rather than passively. Rather than watching all content sequentially, some students made deliberate decisions about which parts of videos to engage with based on their own requirements, such as using them for comparison after reaching solutions, for clarification when stuck, or skipping ahead when confident in their approach. This strategic engagement reflects both the social and cognitive dimensions of collaborative problem solving (Hesse et al., 2015), where students gain insights from peer approaches whilst engaging in individual reflection and self-regulated learning.

The findings also demonstrate how these videos can support the social dimension of collaborative problem solving (Hesse et al., 2015), even in asynchronous contexts. When students encountered difficulties and turned to the videos for support, they were effectively accessing peer perspectives and collaborative strategies, extending the benefits of group problem solving beyond traditional synchronous settings. However, while the 360-degree videos supported many aspects of collaborative learning, there were (surprisingly) some limitations in relation to the social dimension of collaborative problem solving. Although Hesse et al. (2015) emphasize the importance of real-time negotiation and dynamic interaction, the videos could only provide one-way observation (leading to some frustration at being unable to interact with people) rather than the reciprocal exchange required for true collaboration. The students who preferred online problem solving did so primarily because they perceived it to be more efficient, suggesting they were primarily focused on completing the task (the *work group* mentality) rather than learning about other ways of solving problems (the *learning group* mentality). This focus underscores the challenge of fostering genuine collaborative learning in online environments, where the social dimension of problem solving can easily be overshadowed by task completion. The findings also highlight the importance, in a collaborative learning environment context, of choosing tasks that are at the level of challenge that require students to *need* to work with others—that is, moving students out of *work group* mode and into *learning group* mode (Graham & Misanchuk, 2004). Thus, the level of challenge presented by the problem should contribute to a learning-group oriented focus, shifting emphasis from end-product to process. Reflecting on the student data makes it clear that specific design choices within the online framework are crucial in supporting this shift in thinking from *work group* to *learning group*. Key design elements that appeared to drive this shift included the strategic positioning of videos at decision points rather than as passive content, embedded reflective questions that prompted metacognitive thinking, and the optional nature of video supports that required students to make deliberate choices about their engagement. Over-scaffolding can reduce or eliminate the problem-solving aspect of the task. Therefore, a key insight of this project from an educator perspective is that the level of scaffolding or structure provided must be carefully tailored, with its pitch being just as significant as the difficulty level of the problem itself.

On average, students spent more time engaging in online problem solving than their in-class peers. We see three potential reasons for this that need further investigation: (1) the in-class time allocated to the problem is directed by the teacher/educator and there may have been individuals who would have liked more time to work on the problem; (2) the online collaborative problem-solving environment included more in-built reflection and required more processing time (Balzaretti et al., 2019; Rich & Hannafin, 2009) and hence students needed more time to work through the problem; (3) the mechanics of working through an online platform to submit and move through the stages of the learning framework may have added more time. These findings suggest several design recommendations for future online delivery, including developing more intuitive navigation systems to reduce time spent on platform mechanics, creating faster transitions between framework stages, and providing scaffolding feedback that helps students gauge appropriate time investment for different phases of problem solving. Additionally, incorporating timing guidance or optional pacing suggestions could help students manage their engagement more effectively while preserving the flexibility that asynchronous learning offers.

Studies such as Ham and Hwang (2021) point to the limitations of focusing on the end-product in collaborative mathematical problem solving. In this study, the videos served as optional supports during each phase of problem solving. For instance, during the entry phase, students who were unsure of how to get started had the option of hearing and seeing the initial discussions from one of the in-class groups, thereby redirecting the focus from worked solutions to idea generation. Similarly, during the attack phase, students could review alternative approaches through the 360-degree video prompts without being exposed to the answer or solution. This is particularly important in the context of mathematical problem solving, where a key part of the learning is in knowing what to do when you don't know what to do. Over-scaffolding by providing solutions too early removes opportunities to challenge and extend students' thinking. This approach contrasts with the worked-example effect (Sweller et al., 1998), which emphasizes the benefits of showing complete solutions to reduce cognitive load for novice learners. While worked examples can be effective for skill acquisition, our design deliberately withholds full solutions to maintain the productive struggle essential for developing problem-solving competence. This creates a tension between providing sufficient guidance to support learning and preserving the exploratory nature that fosters deeper mathematical thinking and metacognitive development.

Additionally, the design of these video supports aligns with Foster's (2019) principles of scaffolding the problem-solving process rather than the specific problem itself, providing guidance on approach rather than solutions. Students, particularly those in Problem A, highlighted that the videos helped them make comparisons between their work and that of others, clarify their own thinking processes, and think of other ways of approaching the problem. The students' ability to reflect on and evaluate their own thinking processes echoes the metacognitive awareness that Schoenfeld (1992) identified as crucial for effective problem solving.

The student comments highlighted that 360-video excerpts provided authentic experiences (Rosendahl & Wagner, 2023). Rather than polished examples, they featured actual students working through the various stages of solving a problem. This was an intentional decision by the teaching team to underscore a focus on the process, rather than a solution or end-product. Emphasizing that authentic problem solving is inherently messy and non-linear was also important, as being good at problem solving is not necessarily about finding a straightforward path to the solution — a point that can get lost when studying in isolation without exposure to the difficulties that others may be encountering. In some ways this is a pseudo-synchronous interpretation of Ham and Hwang's ideas (2021) of learning through dialogical interactions and the importance of developing and refining understanding of mathematical concepts. Our intention was that students might gain insights from hearing and seeing the diverse range of approaches and strategies of their peers. The findings indicate that seeing the "forwards and backwards" of group discussion, including mistakes, helped reassure some students working in online mode. However, it appears that the success of this approach is problem-dependent, as students who perceived the problem as too easy tended to skip over the details presented in the 360-degree videos. This highlights some limitations of the 360-degree video approach. The risk of passive viewing emerged when students found problems insufficiently challenging, suggesting that the immersive format alone cannot guarantee active engagement. Additionally, some students may have experienced cognitive overload from processing both the mathematical content and the 360-degree video simultaneously, a challenge for immersive learning environments as discussed by Mayer (2020). This warrants further investigation. Future research should systematically examine how problem characteristics—such as complexity level, solution pathways, and cognitive demand—affect student engagement with 360-degree video supports to improve pseudo-synchronous collaborative learning experiences.

While the 360-degree videos showed promise in supporting both social and cognitive dimensions of collaborative problem solving, our findings reveal both the potential and complexity of translating face-to-face collaborative benefits to online environments. The technology appears most effective when thoughtfully integrated with appropriately challenging tasks and careful scaffolding design, suggesting that pseudo-synchronous approaches can serve as valuable supplements to, rather than replacements for, traditional collaborative learning experiences.

Limitations

This study has limitations that should be considered when interpreting the findings. The survey response rate for the online problem solving was 68% for Problem A and 43% for Problem B. Non-response bias may limit the generalizability of results. Some students chose not to respond to the survey and hence are not represented in our understanding of the overall student experience. The voluntary nature of participation also introduces self-selection bias, as students who chose to engage with the online problem-solving framework may have been more motivated, technologically comfortable, or generally more engaged with the course content, limiting generalizability to the broader population of mathematics pre-service teachers.

Technical and measurement issues also posed limitations. While we noted that two students experienced issues with the 360-degree videos, other students may have had similar problems that influenced their decision not to participate or respond to surveys. Such technical barriers could impact both the quality of the learning experience and students' willingness to engage fully with the online components, potentially affecting our assessment of the pedagogical approach's effectiveness. Our measurement of online engagement time was based on browser window activity rather than actual problem-solving time. Students may have left windows open while attending to other tasks, meaning that our time data may overestimate actual engagement and limit our understanding of the relationship between time investment and learning outcomes.

The qualitative analysis process, while following established procedures, has methodological constraints. The coding process was conducted primarily by two researchers, and inter-rater reliability was not formally assessed, which may affect the consistency and credibility of the thematic analysis. Additionally, the study relied solely on survey data and did not include follow-up interviews with participants, which significantly limited data triangulation and our ability to explore student experiences and perspectives in greater depth or to clarify ambiguous survey responses. Finally, our statistical analysis methods, while appropriate for the data collected, were limited to descriptive statistics due to the small sample size precluding more sophisticated analyses.

These limitations suggest that future research should employ larger, more representative samples with mandatory participation, systematic documentation of technical issues, and more rigorous qualitative analysis procedures including inter-rater reliability assessments and interview data.

Conclusion

The importance of collaborative learning opportunities is well-established in educational contexts, with benefits including communication, interpersonal skills, metacognitive thinking, and problem solving. This study confirms that these skills are equally important for students who opt for or need to learn via online learning environments, despite the challenges of prioritizing collaboration in asynchronous modes.

Our findings directly address the research question (*In what ways can 360-degree video be useful for emulating collaborative mathematical problem solving for asynchronous online learners?*) by demonstrating that the pseudo-synchronous experiences facilitated by 360-degree video and piloted in this study were deemed by students as useful and worthwhile, and could enhance their sense of connection to their coursework, their educators, and their peers. Students referred to the opportunities created to "check in" on processes and progress via the videos, which served as viable alternatives to checking in with peers or teachers. While acknowledging that the pseudo-synchronous experiences are not identical to face-to-face or synchronous interactions, students found value in using the videos as they allowed them to validate their own approach and observe their peers' work (albeit not necessarily the finished product)—tasks typically confined to face-to-face or synchronous modes of learning.

The wider project in which this paper is situated explores strategies to support students in online learning environments to engage in collaborative mathematical problem solving, which poses a significant pedagogical challenge. However, refining our online pedagogical skillset is becoming increasingly important, not only because more students seek to flexibly engage in higher education but also to enable teachers and educators across all sectors to be ready to respond to shifting learning activities online as and when needed.

References

Balzaretti, N., Ciani, A., Cutting, C., O'Keeffe, L., & White, B. (2019). Unpacking the Potential of 360degree Video to Support Pre-Service Teacher *Development. Research on Education and Media*, 11(1), 63–69. https://doi.org/10.2478/rem-2019-0009

Barfield, A. (2016). Collaboration. *ELT Journal*, *70*(2), 222–224. https://doi.org/10.1093/elt/ccv074

Borko, H., Jacobs, J., Eiteljorg, E., & Pittman, M. E. (2008). Video as a tool for fostering productive discussions in mathematics professional development. *Teaching and Teacher Education*, *24*(2), 417–436. https://doi.org/10.1016/j.tate.2006.11.012

Borup, J., West, R. E., & Graham, C. R. (2012). Improving online social presence through asynchronous video. *The Internet and Higher Education*, *15*(3), 195–203. https://doi.org/10.1016/j.iheduc.2011.11.001

Choi, J., & Walters, A. (2018). Exploring the impact of small-group synchronous discourse sessions in online math learning. *Online Learning*, *22*(4), 47-64. https://doi.org/10.24059/olj.v22i4.1511

English, L., & Gainsburg, J. (2015). Problem solving in a 21st-century mathematics curriculum. In *Handbook of International Research in Mathematics Education* (3rd ed.). Routledge.

Foster, C. (2019). The fundamental problem with teaching problem solving. *Mathematics Teaching*, *265*, 8–10.

Foster, C. (2023). Problem solving in the mathematics curriculum: From domain-general strategies to domain-specific tactics. *The Curriculum Journal*. https://doi.org/10.1002/curj.213

Gillett-Swan, J. (2017). The challenges of online learning: Supporting and engaging the isolated learner. *Journal of Learning Design*, *10*(1), 20–30.

Graham, C. R., & Misanchuk, M. (2004). Computer-mediated learning groups: Benefits and challenges to using groupwork in online learning environments. In T. S. Roberts (Ed.), *Online collaborative learning: Theory and practice* (pp. 181–202). Idea Group.

Ham, Y., & Hwang, J. (2021). Mathematical literacy and collaborative problem-solving: comparison between Korean and U.S. *Journal of Educational Research in Mathematics*, *31*(3), 299–320. https://doi.org/10.29275/jerm.2021.31.3.299

Hesse, F., Care, E., Buder, J., Sassenberg, K., & Griffin, P. (2015). A framework for teachable collaborative problem solving skills. In P. Griffin & E. Care (Eds.), *Assessment and teaching of 21st century skills: Methods and approach* (pp. 37–56). Springer.

Jaques, D., & Salmon, G. (2007). *Learning in groups: A handbook for face-to-face and online environments*. Routledge.

Lesh, R., & Zawojewski, J. (2007). Problem solving and modeling. *Second handbook of research on teaching and learning*, *2*, 763-804.

Lester, F. K., & Cai, J. (2016). Can mathematical problem solving be taught? Preliminary answers from 30 years of research. In P. Felmer, E. Pehkonen, & J. Kilpatrick (Eds.), *Posing and solving mathematical problems: advances and new perspectives* (pp. 117–135). Springer International Publishing. https://doi.org/10.1007/978-3-319-28023-3_8

Mason, J., Burton, L., & Stacey, K. (2010). *Thinking mathematically* (2nd ed.) Prentice Hall. (Original work published 1982)

Mayer, R. E. (2020). *Multimedia learning (3rd ed.)*. Cambridge University Press. https://doi.org/10.1017/9781316941355

National Council of Teachers of Mathematics [NCTM] (2000). *Principles and standards for school mathematics*. NCTM

NRICH. (n.d.). *M, M and M*. https://nrich.maths.org/problems/m-m-and-m

OECD (2017). *PISA 2015 assessment and analytical framework: Science, reading, mathematic, financial literacy and collaborative problem solving.* OECD Publishing.

Olivares, D., Lupiáñez, J. L., & Segovia, I. (2021). Roles and characteristics of problem solving in the mathematics curriculum: A review. *International Journal of Mathematical Education in Science and Technology*, *52*(7), 1079–1096. https://doi.org/10.1080/0020739X.2020.1738579

O'Keeffe, L., Alessandra, R. Vannini, I., & White, B. (2020). Promote informal formative assessment practices in Higher Education: The potential of video analysis as a training tool. *Form@ re: Open Journal per la formazione in rete, 20*(1), 43-61.

O'Keeffe, L., & White, B. (2022). Supporting mathematics pre-service teacher reflection with 360degree video and the knowledge quartet. *Australian Journal of Teacher Education.* 47(3).

O'Leary, M., & Wood, P. (2019). Reimagining teaching excellence: Why collaboration, rather than competition, holds the key to improving teaching and learning in higher education. *Educational Review*, *71*(1), 122–139.

Peterson, A. T., Beymer, P. N., & Putnam, R. T. (2019). Synchronous and asynchronous discussions: Effects on cooperation, belonging, and affect. *Online Learning*, *22*(4), 7-25. https://doi.org/10.24059/olj.v22i4.1517

Picciano, A. G. (2017). Theories and frameworks for online education: Seeking an integrated model. *Online Learning*, *21*(3), 166-190. https://doi.org/10.24059/olj.v21i3.1225

Pólya, G. (2004). *How to solve it: A new aspect of mathematical method* (Vol. 85). Princeton University Press. (Original work published 1945)

Rich, P. J., & Hannafin, M. (2009). Video annotation tools: Technologies to scaffold, structure, and transform teacher reflection. *Journal of Teacher Education*, *60*(1), 52–67. https://doi.org/10.1177/0022487108328486

Rosendahl, P., & Wagner, I. (2023). 360° videos in education – A systematic literature review on application areas and future potentials. *Education and Information Technologies*. https://doi.org/10.1007/s10639-022-11549-9

Schoenfeld, A. H. (1985). *Mathematical problem solving*. Academic Press.

Schoenfeld, A. H. (1992). Learning to think mathematically: Problem solving, metacognition, and sense-making in mathematics. In D. Grouws (Ed.), *Handbook for research on mathematics teaching and learning* (pp. 334-370). New York: MacMillan.

Schoenfeld, A. H. (2016). Learning to think mathematically: problem solving, metacognition, and sense making in mathematics (Reprint). *Journal of Education*, *196*(2), 1–38. https://doi.org/10.1177/002205741619600202

Schukajlow, S., Rakoczy, K., & Pekrun, R. (2023). Emotions and motivation in mathematics education: Where we are today and where we need to go. *ZDM-Mathematics Education*, *55*(2), 249–267. https://doi.org/10.1007/s11858-022-01463-2

Stacey, K. (2022). Looking back on Pólya's teaching of problem solving. *Teaching Mathematics and Computer Science*, *20*(2), 207–217.

Stahl, G., Koschmann, T., & Suthers, D. (2014). Computer-supported collaborative learning. In R. K. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (2nd ed., pp. 479–500). Cambridge University Press. https://doi.org/10.1017/CBO9781139519526.029

Stoessel, K., Ihme, T. A., Barbarino, M-L., Fisseler, B., & Sturmer, S. (2015). Sociodemographic diversity and distance education: Who drops out from academic programs and why? *Research in Higher Education, 56*, 228–246.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, *10*, 251–296.