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Coordinating scaffolds for collaborative inquiry in a game-based learning environment

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Abstract

Collaborative inquiry learning affords educators a context within which to support understanding of scientific practices, disciplinary core ideas, and crosscutting concepts. One approach to supporting collaborative science inquiry is through problem-based learning (PBL). However, there are two key challenges in scaffolding collaborative inquiry learning in technology rich environments. First, it is unclear how we might understand the impact of scaffolds that address multiple functions (e.g., to support inquiry and argumentation). Second, scaffolds take different forms, further complicating how to coordinate the forms and functions of scaffolds to support effective collaborative inquiry. To address these issues, we identify two functions that needed to be scaffolded, the PBL inquiry cycle and accountable talk. We then designed predefined hard scaffolds and just-in-time soft scaffolds that target the regulation of collaborative inquiry processes and accountable talk. Drawing on a mixed method approach, we examine how middle school students from a rural school engaged with Crystal Island: EcoJourneys for two weeks (N=45). Findings indicate that hard scaffolds targeting the PBL inquiry process and soft scaffolds that targeted accountable talk fostered engagement in these processes. Although the one-to-one mapping between form and function generated positive results, additional soft scaffolds were also needed for effective engagement in collaborative inquiry and that these soft scaffolds were often contingent on hard scaffolds. Our findings have implications for how we might design the form of scaffolds across multiple functions in game-based learning environments.

KEYWORDS

collaborative inquiry learning, problem-based learning, scaffolds, game-based learning environments

Collaboration is a valuable skill in many contexts because so much work today is interdisciplinary and global in nature. In the context of science education, collaborative inquiry can be defined as collaboratively planning and carrying out scientific investigations as well as engineering designs (Appendix F, NGSS Lead States, 2013). Collaborative inquiry learning can take multiple forms because of how inquiry can be defined and the plethora of computer-supported tools that are available to scaffold inquiry (Bell, Urhahne, Schanze, & Ploetzner, 2010). One approach to supporting collaborative science inquiry is through problem-based learning (Hmelo-Silver, Kapur, & Hamstra, 2018). Problem-based learning (PBL) is a pedagogical approach to collaborative learning that is driven by complex, ill-defined problems. PBL can be integrated into digital game-based learning environments that provide rich, dynamic problem contexts for science learning (Rowe, Shores, Mott, & Lester, 2011). Coupled with the ability to capture student interactions, game-based learning environments introduce the opportunity to better understand students' collaborative inquiry (Plass, Homer, & Kinzer, 2015).

An underlying assumption of PBL is that effective learning is influenced by productive discussions and interactions with others as students engage in the inquiry process. A PBL approach to collaborative inquiry includes two critical dimensions, the collaborative inquiry process and accountable talk. The PBL inquiry process is fundamentally collaborative and includes sharing information, considering evidence, evaluating ideas, and constructing explanations (Hmelo-Silver & Barrows, 2008). Accountable talk, on the other hand, refers to holding students accountable for the use of evidence in their explanations, and to engage with the learning community by building on each other's ideas and listening to their peers (Michaels, O'Connor, Hall, & Resnick, 2010). A key element in promoting successful PBL is the role of scaffolds that allow learners to engage in effective collaborative inquiry processes that may be challenging for students in the absence of these supports (Ertmer & Glazweski, 2015).

However, integrating game-based learning environments with PBL to scaffold collaborative inquiry poses two core challenges. First, scaffolds in PBL are often categorized based on their specific functions, such as supporting conceptual or content understanding, procedural or strategic knowledge, metacognitive, and motivational understanding (Kim, Belland, & Walker, 2018; Su & Klein, 2010). Given that scaffolds can support multiple processes, how might we understand the interaction among scaffolds that address various practices? Can one scaffold intended for a specific function be used for another? This is critical when designing scaffolds for collaborative inquiry, which include the inquiry process and accountable talk, two interdependent but different processes.

Second, in the context of PBL, scaffolds can be delivered in two forms, either as predefined hard scaffolds or just-in time, discursive soft scaffolds (Saye & Brush, 2017). Scaffolding the PBL inquiry cycle is well-suited for game-based learning environments because the inquiry process itself can be embedded as hard scaffolds, either as part of the game play or visual representations (Belland, Walker, Kim, & Lefler, 2017). On the other hand, soft scaffolds such as questions and prompts can also be effective in helping students understand the inquiry process and engage in accountable talk. However, soft scaffolds present significant challenges in that scaffolds such as questions, are often just-in time and responsive to student actions. Although conversational agents have demonstrated some success in using soft scaffolds to support accountable talk (Dyke, Howley, Adamson, Kumar, & Rosé, 2013), it remains unclear how we might coordinate hard scaffolds focusing on the inquiry process with soft scaffolds that support engagement in accountable talk. This is especially crucial in the context of game-based inquiry learning, where discussions are often initiated because of the actions undertaken in the inquiry phases such as gathering and analyzing data (Pedaste et al., 2015). These two challenges highlight how designing scaffolds for collaborative inquiry must attend to the co-occurrence and interplay between the form of scaffolds across its different functions of supporting engagement in the inquiry process and accountable talk.

To address this challenge, we conducted a study to examine how hard scaffolds supporting the inquiry process coordinated with soft scaffolds that encouraged accountable talk. The study was conducted with groups of rural sixth-grade students who engaged in a game-based learning environment, Crystal Island: EcoJourneys, over 2 weeks. In the game-based learning environment, groups of students engaged in several cycles of inquiry consisting of investigation and brainstorming phases (Saleh et al., 2019). Students individually met in-game characters and interacted with objects during the investigation phase and used a virtual collaborative whiteboard in the brainstorming phase. The virtual whiteboard was embedded with hard scaffolds, such as representations or organizational structures that guided students' inquiry processes. As groups interacted with the virtual whiteboard, soft scaffolds such as prompts delivered by facilitators supported how students discussed their ideas. Collectively, the hard and soft scaffolds coordinated to support students' inquiry process and accountable talk.

Drawing on a mixed methods approach that utilized interaction and verbal data analysis (Chi, 1997; Hall & Stevens, 2015), we examined how hard and soft scaffolds supported students' collaborative inquiry in our game-based learning environment. We considered the roles of hard and soft scaffolds whose function were to support engagement in the inquiry process and accountable talk in our investigation of the following research questions:

1. How do hard scaffolds provided in the game-based learning environment contribute to students' engagement in inquiry?
2. How do soft scaffolds provided by facilitators contribute to students' engagement in accountable talk?
3. How does the coordination of hard and soft scaffolds support engagement in inquiry and accountable talk?

Addressing these questions will provide insight into how to identify group actions that can be used to trigger scaffolds at the right time in technology-rich PBL and to advance our understanding of how the combinations of scaffolds can better support collaborative inquiry processes. In the remainder of the article, we first provide a brief overview of the dimensions of collaborative inquiry. Second, we define and highlight the need to coordinate hard and soft scaffolds to support the PBL inquiry process and accountable talk, and elaborate how the scaffolds are instantiated in Crystal Island: EcoJourneys. Finally, we present our analysis and discussion about how hard and soft scaffolds supported inquiry and accountable talk.

1 | A PROBLEM-BASED LEARNING APPROACH TO COLLABORATIVE INQUIRY

Collaborative inquiry rests on the fundamental assumption that engaging in scientific practices is best fostered through social interactions with others. Given that there are multiple frameworks for both collaborative learning and inquiry learning (Dillenbourg, 1999; Pedaste et al., 2015), we utilized problem-based learning (PBL), a form of inquiry learning that leverages social interactions to support students in learning through complex problem solving (Hmelo-Silver, 2004). From a sociocultural perspective, PBL posits that learning is best achieved through social interaction by providing cognitive challenges that motivate students to resolve them (Savery, 2019). There are several defining characteristics of PBL: students (a) solve complex inquiry problems based on real life issues as part of their learning experience, (b) work in small groups, (c) have ownership over the learning process, and (d) are guided by facilitators who scaffold the learning process (Hmelo-Silver, 2004). For students to be successful in PBL, critical skills include knowing the elements of the inquiry process, managing the procedural and content tasks associated with the inquiry process, and negotiating with peers during discussions to provide warranted explanations. Thus, effective engagement in PBL requires attending to (a) the PBL inquiry process, and (b) high quality discursive practices supported by accountable talk (Michaels et al., 2010). Below, we highlight the characteristics of each dimension and discuss challenges that learners face when engaging in the processes of inquiry and accountable talk.

1.1 | The inquiry process in problem-based learning

In PBL, students are guided through an inquiry learning cycle that includes: (a) orienting to the problem by identifying relevant facts and ideas, (b) generating possible hypotheses that could explain the problem, (c) identifying gaps in knowledge, (d) applying newly discovered knowledge to the problem, and (e) engaging in self-directed learning. Central to PBL is a real-world problem that provides a goal and shapes students' inquiry process. In working towards this goal, students must begin with what they do or do not know and engage in fact-finding explorations to construct their understanding of what may be occurring. However, there are multiple challenges associated with collaborative inquiry. Students may not (a) have background knowledge, (b) be aware of the elements in the PBL cycle, (c) recognize which analytical strategies are appropriate, or (d) be able to engage in specific disciplinary practices such as argumentation and generating explanations (Bell et al., 2010). The challenges of managing the inquiry process are further compounded when students must work with one another but are unsure of what it means to collaborate effectively.

Scaffolds are therefore critical to support successful group management of the PBL inquiry process. Some scaffolding strategies include providing (a) collaborative tools or visual representations that organize tasks into manageable steps for the group, (b) encouraging group awareness of individual and group progression towards goals and tasks, and (c) externalizing expectations associated with collaborative inquiry (Järvelä & Hadwin, 2013; Quintana et al., 2004). In PBL, the physical whiteboard has traditionally provided a shared collaborative space that allow groups of students to share their findings with one another and supported regulation of the group's problem-solving process (Azer, 2005).

1.2 | Facilitating accountable talk in problem-based learning

However, it is often the case that additional scaffolds are needed to support effective social interactions (Kollar, Wecker, & Fischer, 2018). The PBL facilitator is crucial in scaffolding students' learning, by using questions and modeling good strategies for students to adopt (Hmelo-Silver & Barrows, 2008). The interactions between facilitator and students suggest that another integral element of PBL is a set of discursive practices (Savery, 2019). One approach to supporting high-quality discursive practices is through accountable talk (Michaels et al., 2010). Accountable talk is a type of structured discussion that supports collaborative knowledge generation. The goal of accountable talk is to develop students' ability to reason by practicing the skills and habits of argumentation through structuring social interaction and classroom tasks. Students are socialized into learning communities, one at the level of small groups and another at the larger classroom community. Effective engagement in accountable talk requires scaffolding accountability to three categories: (a) the learning community, (b) accurate knowledge, and (c) rigorous thinking. Accountability to the learning community emphasizes how participants listen to and understand the different perspectives that are shared during classroom discussions. Discourse moves include how students share their ideas and respond to contributions by building on or offering alternative ideas. Accountability to knowledge refers to how the group can provide appropriate and relevant evidence in support of their shared ideas, whereas accountability to rigorous thinking refers to how students explain their thinking and make logical connections among shared ideas.

Accountable talk has been demonstrated to be an effective support for computer supported collaborative learning (Dyke et al., 2013; Gillies, 2019). As students engage in the PBL inquiry cycle, they draw on principles of accountable talk to manage group tasks and address problems that are otherwise too complicated to solve individually (Jonassen & Hung, 2008). Because complex problems in PBL do not have a single solution, students must negotiate with their peers and rely on evidence to substantiate their claims. This means that students' talk must be held accountable to disciplinary standards so that students are better able to engage with science practices such as argumentation (Michaels et al., 2010). Although the teacher plays a critical role in scaffolding learning, accountable talk can be challenging to support in classrooms because teachers must scaffold multiple groups of students. Thus, it is critical to understand how computer-based hard scaffolds might assist in supporting accountable talk in the classroom.

2 | FUNCTIONS AND FORMS OF SCAFFOLDS FOR COLLABORATIVE INQUIRY

Although PBL has been successful in supporting disciplinary content understanding, research in PBL environments that feature games to date has focused on science knowledge, and less on the collaborative processes that unfold as students engage in these environments (Liu, Horton, Kang, Kimmons, & Lee, 2013). Thus, this study focused on collaborative processes related to the PBL inquiry process and accountable talk. Here, we will clarify how to support these collaborative processes by unpacking the functions and forms of scaffolds.

2.1 | Function of scaffolds

In prior research on scaffolding, the functions of scaffolds commonly refer to supporting specific types of learning processes, such as procedural, cognitive, or social practices (Kim et al., 2018). Identifying these processes is an important first step in delineating the function of scaffolds. In the context of our work, engaging in both inquiry and accountable talk require unique configurations of activity and processes. Thus, it is important to clarify how scaffolds are instantiated for these specific dimensions of collaborative inquiry. In other words, what are the specific processes of the PBL inquiry cycle and accountable talk that students must engage in, and how can we structure these activities so that they are visible for students? More importantly, it was critical to determine whether processes in the inquiry cycle and accountable talk were truly unique or if there were overlapping practices in either dimension.

2.2 | Form of scaffolds

The configurations of activity involved in the PBL inquiry process and accountable talk also mean the modality or form in which the scaffold is delivered influences how groups of students respond to them. Scaffolds can take the form of hard and soft scaffolds (Saye & Brush, 2017). Hard or fixed scaffolds are pre-designed instructional materials designed to guide students in their learning processes. Hard scaffolds can take the form of paper- or technology-based supports that reduce task complexity. Complex tasks are made more manageable by structuring the task using visual representations such as graphic organizers. Soft scaffolds on the other hand, are just-in-time supports provided by teacher and peers in discussions. Although soft scaffolds are traditionally considered more flexible and adaptive, student actions in computer-supported learning environments can be contingent on pre-planned soft scaffolds. Facilitators can utilize pre-planned prompts in their discussions with students or engage in more responsive actions that the system cannot detect, such as confusion. The combination of hard and soft scaffolds is critical in reducing task complexity and make thinking visible by alerting students to the tasks that they must engage in as part of the inquiry and accountable talk process. In the next section, we introduce Crystal Island: EcoJourneys and discuss how we attended to the function and form of scaffolds in our design.

3 | OVERVIEW OF CRYSTAL ISLAND: ECOJOURNEYS

In Crystal Island: EcoJourneys, students arrive on an island in the Philippines as part of a school field trip. There, students learn that the locals on the island depend on tilapia fish farming for a living. Students also discover that the fish technician, Jasmine, has a problem: her tilapia fish are falling sick at alarming rates. Students work in groups of four to resolve the aquatic ecosystems problem by exploring the game environment and talking to in-game characters. To engage students in the PBL inquiry cycle and accountable talk, the story was divided into two inquiry phases, the Investigation Phase and Brainstorming Phase. After completing three cycles of these phases, students explain why the fish are sick.

3.1 | Delineating the functions of scaffolds in Crystal Island: EcoJourneys

To design the scaffolds in our game-based learning environment, we began with a one-to-one mapping of the form of a scaffold to its function. Given that hard scaffolds are pre-planned, we utilized this form to scaffold the PBL inquiry process. Moreover, the inquiry process can be explicitly visualized in the context of our game-based learning environment. We then utilized soft scaffolds, or just-in time scaffolds, provided by facilitators as a means of supporting accountable talk. In designing this one-to-one mapping, we hoped to better understand how to coordinate across the forms and functions of scaffolds.

3.2 | Hard scaffolds for the PBL inquiry cycle

Our design for the PBL inquiry cycle in Crystal Island: EcoJourneys attended the following: (a) collecting data in the investigation phase, and (b) sharing and evaluating data in the brainstorming phase. In the investigation phase, students interacted with in-game characters and objects in the game environment to collect data that might have been pertinent to the problem.

3.2.1 | Collecting notes in the investigation phase

To provide a visible and actionable structure for students, we designed several hard scaffolds that structured students' inquiry process through the (a) to-do list, (b) notebook, and (c) pre-planned worksheets. As students explored the game world, steps of the inquiry process were provided to them in the form of a to-dolist (Figure 1). In their to-do list, students were guided on what they had to do, such as collecting notes that consist of observations and facts, by talking to in-game characters and interacting with objects in the virtual environment. The to-do list allowed students to track their progress in their inquiry steps. Once tasks were completed, the item was checked off on students' to-do lists. During this process of data collection, students collected notes using the notebook tool. Students' data were collected as sticky notes that students could use to share with their peers. In addition to sticky notes, students could also take written notes in pre-planned worksheets. Together, these tools scaffolded individual student engagement in inquiry, by attending to the processes of exploring the environment, and gathering data from in-game characters and objects for entry in their virtual notebooks.

3.2.2 | Placing and evaluating notes in the brainstorming phase

After exploring and collecting data, students engaged Phase 2, the brainstorming phase. In this phase, students used an adapted PBL whiteboard called the brainstorming board, an in-game hard scaffold that structured collaboration. The brainstorming board scaffolded the inquiry

FIGURE 1 Tools from left to right, the chat (green), notebook (blue), and the to-do list (orange) [Color figure can be viewed at wileyonlinelibrary.com]

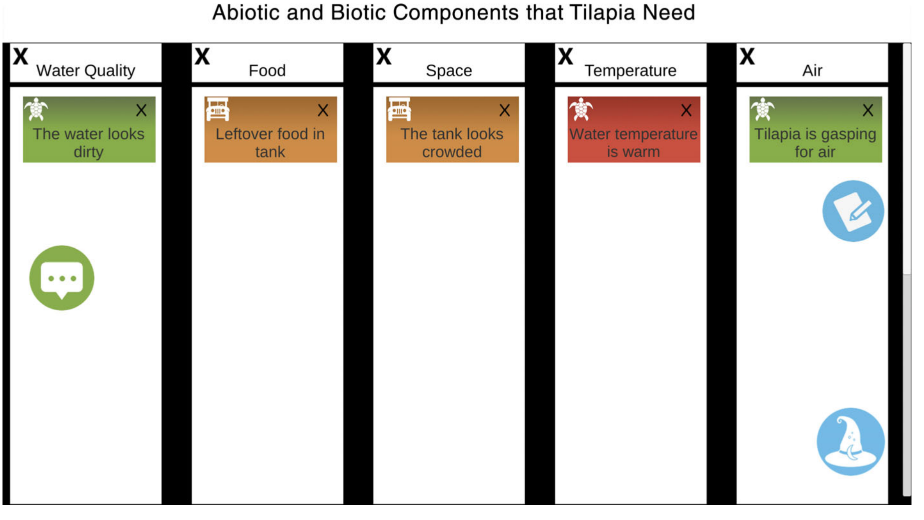

FIGURE 2 The brainstorming board [Color figure can be viewed at wileyonlinelibrary.com]

process in two ways. First, when using the brainstorming board, it was necessary for students to share the notes they had individually collected during the investigation phase. The brainstorming board featured columns that aligned to components that the tilapia fish needed to survive (Figure 2). Students had to drag their notes from their notebook onto the board and placed the notes in the most appropriate columns. In doing so, the board made visible how students were thinking about the relevance of the information to the problem. After placing their notes, students could click on other notes to examine more detailed information and evaluate their peers' notes.

Second, after all students have placed their notes on the board, each student evaluated and voted on each note. Students voted on whether the notes were relevant, might be relevant, or not relevant to the associated component. Students' aggregate votes per note were represented visually. If all students in the group agreed with one another, the note turned green. If one student did not agree, the note turned red. If students otherwise were ambivalent or had not evaluated the notes, the note remained orange (see Figure 2). Thus, the voting feature was a hard scaffold that alerted students about consensus or lack thereof via the color indicators.

3.3 | Soft scaffolds for accountable talk

During the brainstorming process, a facilitator delivered soft scaffolds supporting accountable talk using a text-based chat tool. Soft scaffolds included encouraging students' explanations, marking or highlighting relevant information, and revoicing students' ideas to support accountable talk (Hmelo-Silver & Barrows, 2008; Michaels et al., 2010). In their discussions, students shared the information they gathered, presented their ideas about why the tilapia may be sick, provide evidence to support these ideas, and resolve disagreements. In our design, PBL facilitators were assigned to each group of students. Facilitators used an interface to select prompts which they could use to shape discussions with students (Figure 3).

3.4 | The coordination of hard and soft scaffolds for inquiry and accountable talk

By structuring steps in the inquiry process and making agreement visible to the group, the hard scaffolds in the investigation and brainstorming processes were important in triggering soft scaffolds for talk that attend to the regulation of the inquiry process and accountable talk.

In terms of the inquiry process, students do not naturally begin by questioning their peers without guidance from hard scaffolds. In our design, the break down of tasks and the use of notes were hard scaffolds that helped students evaluate their next inquiry actions. For instance, when students finish their investigation phase, they must wait for their other peers to finish

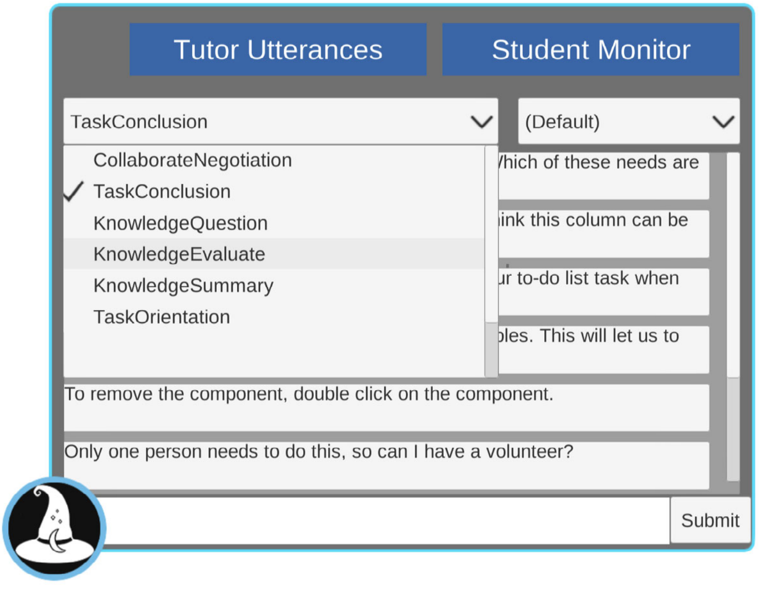

FIGURE 3 The facilitator panel [Color figure can be viewed at wileyonlinelibrary.com]

their individual tasks so that the group can then share and discuss their findings. This meant soft scaffolds can be spontaneously provided by students to their peers. These soft scaffolds can include asking group members about their progress in the game or marking the need to share notes, thereby regulating the inquiry process. Because students must wait for one another, group members become aware that they must finish their first inquiry task, to collect data, before they can move on to the next task (i.e., brainstorming together). Similarly, when using the brainstorming board, students often regulate the group inquiry process by asking their peers if they have shared or evaluated notes.

In terms of accountable talk, the visual representation of student agreement triggered discussions in several ways. First, if students disagreed about the placement of a note, only the person in charge of the note could move it. This meant that students must hold each other accountable, in terms of the relevance of the note and if they were able to convince their peers to move the note based on the information that they had access to. Second, because the notes and columns in the brainstorming board were organized around the relationship between biotic and abiotic components in an ecosystem, students could articulate the relationship among these factors. This was particularly salient when discussing which factor might be the reason for the tilapia fish being sick. Students could then choose to remove a column as a potential contributor to the problem but needed to convince their team members.

Lastly, based on actions at the brainstorming board, facilitators would provide prompts that supported accountable talk. For example, prompts associated with accountability to the learning community asked students to build on each other's ideas and to reach consensus about the different ideas presented in the group or whenever there was disagreement. Prompts related to rigorous thinking asked students to evaluate the group's notes, explain the content, and relationships among the notes. Similarly, prompts focusing on accountability to knowledge held students responsible to the veracity of the information and asked students to make explicit connections between the notes (i.e., evidence) and group hypothesis. The visual representation of the columns and the available notes (i.e., hard scaffolds) combined with the soft scaffolds supported students' understanding of inquiry and triggered accountable talk. Taken together, our design allowed us to address the following questions, (a) How do hard scaffolds provided in the game-based learning environment contribute to students' engagement in inquiry, (b) How do soft scaffolds provided by facilitators contribute to students' engagement in accountable talk, and (c) How does the coordination of hard and soft scaffolds support engagement in inquiry and accountable talk?

4 | METHODS

4.1 | Study design

To address our research questions of how the form and function of scaffolds can support engagement in the PBL inquiry cycle and accountable talk, we adopted a mixed-method approach (Johnson, Onwuegbuzie, & Turner, 2007). To answer the first question, we relied on descriptive statistics of student trace data: in-game student interactions that were logged as they engaged in the game-based learning environment. The trace data statistics, such as the number of notes collected, allowed us to examine quantitative patterns across all groups and to understand the distribution of group in-game interactions. To address the second question, we conducted verbal analysis to determine the relationship between soft scaffolds delivered by facilitators and accountable talk (Chi, 1997). To understand the coordination across form and function of scaffolds, we conducted interaction analysis (Hall & Stevens, 2015). We content-logged all video data and matched these with log file interactions. We analyzed episodes in the content log to identify the ways that hard and soft scaffolds coordinated to support engagement in the PBL inquiry learning and accountable talk. We then used summary statistics to select two cases with the highest and lowest descriptive statistics of indicators associated with collaborative inquiry process and accountable talk. We generated examples from these cases to corroborate identified trends and highlight how there may have been coordination among the scaffolds in supporting inquiry and accountable talk. Rather than being generalizable, this study is an initial exploration of the coordination among scaffolds and their effects on supporting inquiry and accountable talk.

4.2 | Participants

Students from two class periods participated, with 45 sixth-grade students (23 males, 22 females) consenting to participate. Students worked in groups of four, with one single group of five, for a total of 11 groups. Each group was assigned an alphabetical code (i.e., A, B, C, etc.) and each student had a username. For example, a student from Group A was identified as Eagle-A, whereas their peers would be Jeepney-A, Turtle-A, and Sun-A. The groups were formed primarily based on teacher feedback on students' science academic performance and whether the students were likely to engage collaboratively.

Each group of students had a trained human facilitator whose role was to support group inquiry processes. There were seven facilitators, five graduate students and two researchers. The two researchers each have over 10 years' experience designing game-based learning environments and one of them was an experienced PBL facilitator. Among the graduate students, two were experienced PBL facilitators, and the other three were trained over four sessions. Each facilitator had a minimum of 5 years working with youths.

4.3 | Data collection

There were eight 55-minute classroom sessions across 2 weeks in which students engaged in our implementation of Crystal Island: EcoJourneys. These sessions occurred in students' regular classrooms in place of science enrichment topics. Students played Crystal Island: EcoJourneys on individual Chromebooks and were seated together with peers in the same group (i.e., Group A members sat together). In the first session, each group discussed norms for collaboration. Students then played the game for the next six classroom sessions and their interactions in the game-based learning environment were collected. In the last session, students drew a model explaining why the tilapia fish might be sick. All classroom sessions were video-recorded and written artifacts such as the worksheets and models were collected.

4.4 | Data sources

4.4.1 | Trace data

Students' in-game interactions, or trace data, was used as a primary data source to understand how the hard and soft scaffolds supported engagement in the PBL inquiry cycle and accountable talk. Student interactions in the game-based learning environment were time-stamped and their in-game clicks were logged. Interactions during the investigation phase included click-stream data of individual interactions with in-game characters and objects, including the to-do list. Interactions at the brainstorming board included the (a) mean time that each group spent across all their notes, (b) mean number of times that each note was moved, (c) mean number of votes across all notes, (d) lines of chat, and (e) time on chat. There were 29 notes that each group of students could have collected in their investigations in the game-based learning environment. Each group's chat data were logged and provided an overview of how the scaffolds were utilized by students as they engaged in collaborative inquiry.

4.4.2 | Video data and written artifacts

We utilized convenience sampling and selected six groups for video data capture. Although the convenience sampling may limit our claims, we found it necessary given the exploratory nature of our study. The video data shed light on how the groups took up the scaffolds differently, highlighting how certain scaffolds might be beneficial for certain groups of students. The trained facilitators, who were also part of the research team, took field notes to describe how they facilitated the groups and described the nature of the face-to-face discussions. We also collected written artifacts, such as students' worksheets and models that were created by the students. The written artifacts, video data, and field notes were used as secondary sources to answer our research questions.

4.5 | Data analysis procedures

4.5.1 | RQ1: How do hard scaffolds provided in the game-based learning environment contribute to students' engagement in inquiry?

In our design, hard scaffolds in the investigation and brainstorming phases were designed to support steps in the inquiry process. These inquiry processes included collecting notes and negotiating the placement of their notes in relation to the components that the tilapia fish need that were collected as students engaged in Crystal Island: EcoJourneys. To address how the hard scaffolds supported students' engagement in inquiry, group-level statistics derived from students' trace data interactions in the game were analyzed.

To understand the effectiveness of the scaffolds in supporting collection of data, we inspected the *total number of notes that each group collected* and *the number of times the to-do list was accessed*. These statistics provided insights into whether students regulated their inquiry learning. Collecting notes for instance indicated the extent to which students gathered data, as expected in the PBL inquiry cycle, whereas referring to the to-do list was indicative of whether students monitored the tasks that they needed to complete. Because there were only 29 notes available from in-game resources, we expected that the groups would collect all the notes.

To understand the extent to which students negotiated the placement of their notes, we examined the *mean number of times that each note was moved*. This statistic reflected not only the first time that students placed their notes but more importantly, the number of times that students moved the notes. Moving notes likely indicated that the group of students have evaluated the placement of the notes, an important step of the PBL inquiry process. Thus, we could compare the extent to which different groups of students negotiated the placement of the notes on the board. A higher number likely indicated that students were engaging in these negotiations. We also looked at two additional group statistics to understand how students negotiated where the notes should be placed: *mean time that the group spent on the notes* and *mean votes per note*. The mean time spent on the notes reflected how long the group spent on a note. The mean vote statistics indicated the extent to which students agreed with one another, and could mean that the students were engaging in productive talk. A higher amount of time and vote count likely meant that students took more time to negotiate ideas whereas a lower amount of time and vote count may have indicated that students came to consensus more quickly.

4.5.2 | RQ2: How do soft scaffolds provided by facilitators contribute to students' engagement in accountable talk?

To identify how soft scaffolds may have supported accountable talk, we examined group statistics in chat and undertook a verbal analysis of chat data. We examined the overall time spent in chat and the proportion of contribution to lines in chat to determine how participants in the group contributed to chat. The number of lines in chat was likely inflated, especially since it did not account for repetitions and off-task communication by students. Moreover, some turns at talk spanned more than one line. However, reporting this count helped determine if students or facilitators were leading discussions in chat.

We also coded students' chat data to quantify the patterns observed across the groups and determine how soft scaffolds delivered by facilitators supported students' accountable talk. We coded the chat data for discourse actions based on the PBL and accountable talk literature. There were two classes of codes with 16 sub-codes: facilitator and student codes (see Table 1 for an overview). Utterances were coded according to conversational turn. Facilitator codes consisted of six mutually exclusive sub-categories, including moves that (a) elicited information from students, (b) marked important information, (c) asked students to provide explanations, (d) revoiced statements, (e) talk that built rapport, and (f) utterances that could not be coded under these categories. Student codes consisted of eight mutually exclusive categories: (a) *accountability to learning community* (two sub- categories), (b) *accountability to rigorous thinking* (three sub-categories), (c) *socio-affective* talk, (d) talk related to *regulation of inquiry tasks*, and (e) *Other*. The *accountability to learning community* codes were a total count of the consensus and rebuttal codes, whereas the *accountability to rigorous thinking* codes consisted of student explanations, statements, and questions. Consensus and rebuttal utterances often involved building on ideas, which highlighted how students can be accountable to the learning community. Because *rigorous thinking* often included the use of evidence to support explanations, we included *accountability to knowledge* under this category.

Two researchers coded 483 lines of chat together to generate a codebook, trained using the codes and resolved differences. The second author coded all utterances (3,845 in total) whereas the first author coded 15% of the total utterances for interrater reliability. All kappa coefficients were evaluated using the guideline outlined by Landis and Koch (1977). Student codes had 86.7% agreement (249 utterances, $\kappa = .85$) and *Facilitation* codes had 95.9% agreement (145 utterances, $\kappa = .94$).

Based on the frameworks that guided our design moves and the work on computer-based scaffolds in PBL (Kim et al., 2018), we expected relationships between certain soft scaffolds such as prompts and forms of accountable talk (Potter & Levine-Donnerstein, 1999). Because the literature has indicated that questioning prompts had the smallest effect size on supporting

TABLE 1 Code categories of group chat data

Student codes	Facilitator codes
Consensus: Agreement on tasks and/or content; talk that builds on prior utterances by others	*Social*: Socio-affective talk, building rapport
Rebuttal: Utterances offering alternative ideas and/or actions	*Elicit*: Solicit information and /or actions; includes asking students to summarize ideas, to build on ideas or agree / disagree
Statements: Descriptions of learned content, such as claims and elaborations	*Marking*: Statements that highlight attention to content, actions, or tools
Explain: Claims supported by evidence	*Reasoning*: Moves that promote rigorous thinking and connections to evidence; often posed as "why" questions
Questions: Queries on tasks, content, etc. may be in the form of statements	*Revoice*: Repeating students' contribution to foster responses
Social: Socio-affective talk, building rapport *Regulation*: Regulating tasks, norms, action plans and progress	*Other (Facilitation)*: Utterances not codable as any of the facilitation codes
Other: Utterances not codable as any of the student codes	

student performances, we tested the relationship between marking moves and *accountability to learning community*, as well as marking and *accountability to rigorous thinking* (Kim et al., 2018). Marking is when the facilitator highlights certain information for students to attend to (Michaels et al., 2010). We opted to only test for accountability to rigorous thinking because these codes also included accountability to knowledge (i.e., ensuring that students use reasonable facts). We are not claiming that these relationships will be generalizable to other settings but testing for these relationships helped detect patterns of how soft scaffolds were taken up by the students. We assumed a correlation of 0.75 and a power of 0.80, for a minimum number of 11 groups, which was the number of groups that participated in the study.

4.5.3 | RQ3: How does the coordination of hard and soft scaffolds support engagement in inquiry and accountable talk?

To explore this question, we examined three interrelated aspects; whether (a) hard scaffolds could be distributed across multiple functions, (b) soft scaffolds could be distributed across multiple functions, and finally, (c) the extent to which hard and soft scaffolds were distributed across multiple functions. In the first instance, it was likely that the hard scaffold targeting the evaluation of data as identified in the inquiry process also reflected the extent to which students engaged in accountable talk. Although we had ascribed the function of the hard scaffolds that supported evaluating notes to the inquiry process, accountable talk also involves engaging students in reasoning by asking them to account for their explanations by using data (i.e., accountability to rigorous thinking and knowledge). In these discussions, students must also build on their data provided by others (accountability to the learning community). To explore the extent to which hard scaffolds aimed to support inquiry can also support accountable talk, we utilized the group summary statistics for game interactions and the verbal count of chat data. We tested to see if there was a relationship between the *mean votes* and students' *accountable talk*. We chose the mean number of votes because it was likely more sensitive to how students interacted with the ideas presented at the brainstorming board. This was because students' votes were visually represented whenever they agreed, disagreed, or were neutral, and in turn, triggered accountable talk.

Second, to determine if soft scaffolds can also support regulation of the inquiry process, we utilized the verbal count of chat data to test for the relationship between soft scaffolds (i.e., marking) and group talk that involved the regulation of inquiry processes. Finally, to illustrate the extent to which hard and soft scaffolds were distributed across multiple functions, we engaged in interaction analysis (Hall & Stevens, 2015). We first created content logs of group interactions that allowed us to determine which interactional sequences demonstrated the coordination of soft and hard scaffolds to support multiple functions. These content logs included creating a sequential overview of multiple sources of data, including their in-game interactions, chat, available video data, and written artifacts. Using a temporal approach, we identified and analyzed episodes to determine how hard scaffolds may have prompted the need for soft scaffolds. To ground our findings, we selected groups based on statistics that were above or below one standard deviation of the grand mean for a given category.

5 | RESULTS

5.1 | RQ1: How do hard scaffolds provided in the game-based learning environment contribute to students' engagement in inquiry?

To address this question, we present the group summary statistics from students' in-game interactions (see Table 2). To understand the effectiveness of hard scaffolds in supporting collection of data, we inspected the *total number of notes that each group collected*, and the *number times the to-do list was accessed*.

Across all the groups, five groups collected all 28 of the available notes, six groups were missing one to three notes, and one group collected only 17 notes. On average, each group accessed the to-do list 59 times, with a range of 15 to 103 times that the tool was accessed. Except for Group K, we can surmise that process of data collection was a simple undertaking for most groups. Based on the number of times that students accessed the to-do list, we can also surmise that the to-do list may have scaffolded students' inquiry process (except for Group B).

To understand the extent to which students negotiated the placement of their notes at the brainstorming board, we examined three statistics across the groups, the *mean time spent on notes, mean number of times that each note was moved*, and *mean votes per note*. At the brainstorming board, groups averaged over a minute on each note. On average, groups also moved notes 36 times across all the sessions, and voted on each note 10 times. To determine if the hard scaffolds encouraged students to share and move their notes based on votes and discussions, we identified outliers. Groups with statistics above one standard deviation from the mean may indicate that students are engaging more with the notes, either in terms of moving or voting on them, whereas the reverse is true for group statistics below one standard deviation from the mean. The following groups had statistics one standard deviation below the mean, (a) groups A and B for the lowest amount of time spent on notes, (b) groups B and D for lowest counts in moving notes, and (c) groups B and C for lowest recorded votes across all notes. After accounting for these four outliers, these statistics suggest that in general, the hard scaffolds appeared to support at least eight groups of students in evaluating and negotiating with the notes.

TABLE 2 Summary statistics of in-game group interactions

Group	Total # of notes	# of times accessing to-do list	Mean time per note (seconds)	Mean # of times each note was moved	Mean votes per note
A	26	58	28[a]	43	9
B	27	15[a]	36[a]	20[a]	5[a]
C	29	66	39	28	5[a]
D	29	103	41	19[a]	7
E	29	48	72	47	8
F	26	54	76	36	9
G	26	49	80	31	11
H	29	103	81	32	17
I	26	42	89	37	12
J	29	40	93	56	11
K	17[a]	74	154	47	20
Mean (SD)	27	59 (25)	72 (34)	36 (11)	10 (4)

[a]Statistics that are one standard deviation below the mean.

5.2 | RQ2: How do soft scaffolds provided by facilitators contribute to students' engagement in accountable talk?

We present the group summary statistics of chat interactions to provide an overview of how students and facilitators participated (see Table 3). Across all the sessions, groups averaged almost 117 min in the chat and contributed 433 lines. Of these, facilitators had the highest proportion of talk in five groups, compared to six student-led groups.

To understand the relationship between soft scaffolds that supported students' accountable talk, we analyzed the frequency counts of coded chat data (see Table 4).

Based on the literature, marking moves were more effective soft scaffolds. We found that there was a significant strong positive relationship between the facilitator's *marking* of information and *accountability to learning community*, $r(9) = 0.78$, $p = .004$, and a significant strong positive relationship between facilitator's *marking* of information and *accountability to rigorous thinking*, $r(9) = 0.80$, $p = .003$. The results suggest that soft scaffolds, especially information-marking moves, may have been successful in supporting accountable talk.

5.3 | RQ3: How does the coordination of hard and soft scaffolds support engagement in inquiry and accountable talk?

To address how hard and soft scaffolds can coordinate to scaffold across the different functions, we first explored whether (a) hard scaffolds for inquiry can support accountable talk and (b) soft scaffolds for accountable talk can support regulation of inquiry. We first tested the relationship between the mean votes per note (i.e., hard scaffolds) and accountable talk. There was a significant moderate negative correlation between the votes and students' accountable talk, r

TABLE 3 Chat statistics across all groups

Group	Total time in chat (mins)	Lines of chat	Highest % of talk in chat
A	59.1	387	Facilitator
B	156.7	985	Student
C	130.9	413	Facilitator
D	108.1	289	Facilitator
E	154.0	524	Student
F	111.1	422	Facilitator
G	94.6	272	Student
H	68.7	347	Student
I	174.9	528	Student
J	72.7	180	Facilitator
K	152.6	417	Student
Mean	116.7	433.1	

(9) = −0.63, $p = .04$. This suggested that if groups had less votes per note, students in the group engaged in more accountable talk. This suggests that groups with a lower vote count may have been more careful in their deliberations. We then tested the relationship between facilitator's marking moves, a soft scaffold for accountable talk, and counts of talk centered on regulating the inquiry process. There was a significant strong positive correlation between marking moves and regulation of inquiry, $r(9) = 0.82$, $p = .002$. We interpret these relationships cautiously because we did not design an experiment that could address these questions more effectively. Despite the lack of comparison groups, these results are encouraging and indicate that it may be possible to design scaffolds that have multiple functions. To explore these results further, we conducted an interaction analysis to understand how hard and soft scaffolds coordinated to support engagement in the inquiry process and accountable talk.

5.4 | Patterns in the coordination of scaffolds across all groups

Because of the visible structure provided by the hard scaffolds, interaction analysis indicated that the hard scaffolds for inquiry were likely to trigger soft scaffolds that would then support accountable talk and regulation of the inquiry process. Soft scaffolds triggered by hard scaffolds were instantiated in several ways. First, when students were engaged in the investigation phase, they would often provide soft scaffolds to their peers when taking notes in their worksheets. The hard scaffolds embedded in the worksheets focused on supporting the inquiry process by making sure that students recorded additional information. These prompts then triggered student-generated discussions that pertain to the information being collected. In these discussions, students engage in talk related to inquiry processes and held one another accountable to rigorous thinking and the learning community. These productive discussions reflect how hard and soft scaffolds can be effectively coordinated to achieve the desired results.

However, hard scaffolds that visually represented group agreement sometimes had the unintended effect of supporting token agreement. In the first few days of the implementation,

TABLE 4 Overview of code counts for all categories of talk

	Student codes					Facilitator codes				
ID	Learning community	Rigorous thinking	Regulation	Social	Other- student	Elicit	Marking	Reason	Social	Other-facilitator
A	2	65	26	16	71	37	41	12	3	5
B*	31	227	88	56	313	62	80	0	10	24
C	12	81	34	25	135	5	29	0	2	5
D	14	53	18	0	47	26	40	5	4	2
E	15	93	35	72	150	16	35	3	9	3
F	7	108	12	21	53	55	34	3	6	8
G	2	58	5	22	79	29	13	4	2	0
H	10	35	16	22	126	9	23	1	3	1
I	13	89	21	34	194	25	59	10	7	3
J	1	35	0	12	36	27	10	4	4	1
K	0	23	31	47	170	23	33	1	13	6
Mean	10	79	26	30	125	29	36	4	6	5

students were more focused on turning the notes green (which marked agreement), instead of spending time to evaluate the notes. Fortunately, because each group was working with a facilitator, the facilitators were able to utilize soft scaffolds to encourage students to be attentive to the inquiry process. Facilitators often asked students to evaluate the information and hold them accountable to using evidence to support their claims. This indicated that the hard scaffolds were not always effective on their own, and that soft scaffolds were necessary additions to support the evaluation process.

5.5 | Selecting the groups to illustrate observed patterns

To ground our findings, we present examples from two groups. To select these groups, we first inspected the group summary statistics to determine if the group statistics were divergent from the grand mean for each of the summary statistic. We then examined the coded chat data to determine if we could verify these patterns with those seen in the trace data. We also cross-referenced the group profiles with background information and field notes. Based on these criteria, we identified two groups, B and K, who were also supported by experienced facilitators.

Group B consisted of two boys and two girls who were described by the teacher as academically high performers and would go above and beyond on assigned tasks. An experienced facilitator, Avery, supported the group. The field notes from Avery corroborated the teacher's description of the students; Group B students were highly engaged in their tasks, and often regulated their shared learning experiences. In terms of game interaction summary statistics Group B exhibited several divergent patterns from the grand mean: highest number of lines in chat yet the lowest total votes on the notes that were collected. We had assumed that the votes could be an indicator of whether students were reasoning about the problem. At first glance, the low votes might have meant that students are simply agreeing with one another. However, it became clearer that we needed to understand the group's low votes, especially since the group had the highest number of lines in chat. Moreover, the group also had the highest proportion of verbal counts for talk when compared to other groups (29% for accountability to learning community, 26% for accountability to rigorous thinking, and 31% on task regulation). In terms of participation, Eagle-B was absent for the first 4 days. The group was student-led, with one student, Jeepney-B leading most discussions (32.3%), with her peers contributing 26.9% and 20.5%, respectively, and facilitator talk comprising 17.4% of chat. We draw examples from Group B to illustrate the strengths and limitations of the scaffolds in supporting the group, especially since the game-based learning environment was optimized for four students.

Group K consisted of two girls and two boys who were described as academically at or below sixth grade level. Field notes indicated that the students got along well, with one student, Jeepney-K actively helping her peers in sharing and evaluating notes. The students often talked verbally, had to be reminded to use chat, and were supported by another experienced facilitator, Jingli. We selected Group K because the group was a direct contrast to Group B. Group K had the highest amount of time spent on notes and votes per note. These high counts were because the group collected 17 notes as compared to the average of 27. This was because Group K did not appear to finish the final phase of investigation and brainstorming. When compared to the other groups, Group K did not contribute at all to the overall counts for accountability to learning community, contributed 3% to the overall rigorous thinking counts, and 11% to group regulation talk. Members in group K contributed 417 lines to chat, with one student contributing the most (34%) followed by the facilitator (24.3%) and other students contributing 21.1, 15.2, and 5.4%, respectively. However, interaction analysis highlighted that students did get to the final board, and that the group often engaged in verbal discussions. This suggest that using the chat summary statistics alone was not sufficient to determine the quality of collaboration in the group.

5.6 | How soft scaffolds were triggered by hard scaffolds in the investigation phase

A key observation across all groups that is that soft scaffolds often accompanied hard scaffolds to support student engagement in either the inquiry process or accountable talk. Although we expected facilitators to provide these soft scaffolds, we also observed that across all the groups, students were taking on the role of leaders and facilitating inquiry as well as accountable talk (Sun, Anderson, Perry, & Lin, 2017). In Excerpt 1, three students from Group B were engaging in Eagle-B's path through the story because Eagle-B was absent. In the game, each student was assigned a unique path that provided students with different perspectives on the problem. Rather than having students miss the information, the facilitator, Avery, asked students to use the worksheet and investigate Eagle-B's path.

Although asking students to play another assigned role in the game-based learning environment was unplanned, this was a strategy that the facilitators in all the groups utilized. This was also necessary since it would be difficult for the group to solve the problem without information from all students. The combination of the embedded scaffolds in the worksheets and student-initiated soft scaffolds allowed students to attend to the information and engage in inquiry practices effectively. For example, Jeepney-B's act of reading on-screen and marking information (Line 1) was a practice observed across all the groups. In Excerpt 1, marking information. (i.e., soft scaffold) prompted Turtle-B to realize what he needed (Line 3). Throughout this excerpt, students voiced out questions or re-voiced statements based on what they read in the story or worksheets (Lines 6–8, 9–10). Students also held each other accountable to the learning community by making sure that members in the group did not proceed without gathering the required knowledge (Lines 11–17). This suggests that hard scaffolds may be more effective in supporting engagement in the inquiry process and accountable talk when coupled with specific soft scaffolds. These soft scaffolds include strategies such as reading aloud (i.e., marking information), allowing students to collect notes and at the same time, work collaboratively to discuss and complete worksheets.

5.7 | How soft scaffolds were triggered by hard scaffolds in the brainstorming phase

Another key observation across all the groups was how hard scaffolds that aimed to structure evaluation as part of the inquiry process sometimes encouraged surface agreement, instead of deeper engagement in inquiry or accountable talk. In these cases, students were often content to match the words in their notes to the biotic or abiotic components, instead of examining the conceptual ideas. It was thus important for the hard scaffolds to function in coordination with soft scaffolds that supported deeper reasoning. Consider the in-game chat in Group K—one of the groups with the lowest proportion of accountable talk, yet highest engagement with the

EXCERPT 1

Ln	Speaker	Verbal discussion
1	Jeepney-B	((reads from the screen)) Did you know plants are producers?
2	Sun-B	((Turns to look at Jeepney)) I know that.
3	Turtle-B	That's the word I'm looking for! ((writes on the worksheet))
4	Sun-B	Producers?
5	Jeepney-B	You know where producer comes from? Patrick Star.
6	Sun-B	Wait... Who's "they?"
7	Turtle-B	It's the plants ((Sun-B looks down on his notes)).
8	Sun-B	Plants! ((looking at his notes))
9	Turtle-B	In the ecosystem. During photosynthesis.
10	Jeepney-B	Yeah if we're talking about photosynthesis.
	((Ten seconds of reading))	
11	Jeepney-B	Oh there's a question, though!
	Turtle-B points at the screen.	
12	Jeepney-B	((looks and reads from the worksheet)) The bacteria uses o:: ... Did he ((Sun-B)) just miss the bacteria one?
13	Turtle-B	He just missed it.
14	Sun-B	((looks between screen and worksheet)) No, it wasn't about this one, I looked at it.
15	Turtle-B	No, it's for the first one ((in the worksheet)), you just missed it.
16	Sun-B	What was it then?
17	Jeepney-B	Yeah, Turtle-B couldn't read it because you're clicking through it too quick.
18	Sun-B	I am not!
19	Jeepney-B	Yeah you are.
20	Facilitator	Remember to look at your notebooks too to see what notes he's collected.

notes. In Excerpt 2, the group had started their second brainstorming board session and were summarizing what they had learned.

In Excerpt 2, the facilitator prompted for an explanation based on Jeepney-K's observation (accountability to rigorous thinking, Line 1). The facilitator's prompt for more information was first met with a non-normative science response from Jeepney (Line 4). This then prompted the facilitator to ask the other students in the group (accountability to the learning community, Line 5). However, given that students were still not referencing observations from the shared notes (Line 7), the facilitator prompted students to examine the notes and continued to engage the other students (Lines 8–14). It was clear that the ability for the students to reference the notes was critical in ensuring that they could use them in explanations. However, Jeepney-K maintained a simplistic approach to reasoning, highlighting that the note about tilapia was in a specific column because it matched the title of the column (Lines 17 and 21).

This suggests that additional soft scaffolds should coordinate with hard scaffolds to assist students' engagement in accountable talk and the process of inquiry. We see further evidence of this in Excerpt 3 below from group B, which occurred on day three. In the excerpt, students in Group B were at the brainstorming board after finishing their second investigation.

As a hard scaffold, the visual indicator of agreement was critical in allowing the facilitator to provide a soft scaffold to mark the red note (Line 1) and to reveal students' gaps in knowledge (i.e., PBL inquiry process). Although Group B had the lowest vote count, our analysis revealed that the group was carefully deliberating ideas instead of quickly generating token agreement. This suggests that the hard scaffolds prompted soft scaffolds, such as marking notes, which were crucial for supporting engagement in discussion about inquiry and accountable talk. In Excerpt 3 for instance, the consensus was that the students did not know what the slime was and therefore could not decide where the note should be placed (Lines 2–6). The facilitator then suggested that students read the note (Line 7). This soft scaffold held students accountable to the evidence, and students responded by referencing the note (Lines 10 and 11). Students also demonstrated accountability to the learning community by attending to suggestions and agreeing with ideas (Lines 24–26). The excerpt also highlighted how students sometimes struggled with keeping “red notes” on the board, because this sometimes meant that the group could have a “wrong” answer (Lines 23–25). This meant that scaffolds on how to engage in effective science inquiry (e.g., sharing notes and evaluating claims with evidence) must be more explicit, especially in attending to how hypothesis are testable and can be wrong.

6 | DISCUSSION

Scaffolding, as it was originally framed by Wood, Bruner, and Ross (1976), was characterized as a process of making the task manageable and “reducing the degrees of freedom” (p. 98). Furthermore, as scaffolding is integrated into learning environments, it can serve to guide, structure, and limit the scope of failure (Schmidt, Rotgans & Yew, 2011; Songer & Gotwals, 2012; Wu & Pedersen, 2011). In our work, we first began by designing specific forms of scaffolds that aimed to make two interrelated processes, the PBL inquiry cycle and accountable talk more manageable. Because of the need to support engagement in the inquiry process, hard scaffolds were embedded in materials such as worksheets and the game-based learning environment (e.g., task list, representations in the brainstorming board). Similarly, we designed soft scaffolds to promote accountable talk among students. We then explored how the coordination of hard and soft scaffolds can trigger engagement in inquiry and accountable talk. In so doing, we

EXCERPT 2

Ln	Speaker	In-game chat
1	Facilitator	So, Jeepney, you said that tilapia can live if crow(d)ed. Can you explain more about that?
2	Sun-K	i do not have any to do things checked
3	Jeepney-K	yes
	((Four lines of chat about assigned tasks on the next day))	
4	Jeepney	tailapia can live if crowded because they are born with thousands of brothers an(d) sisters so they have to live with it
5	Wizard	Okay, what (do) others think?
6	Jeepney-K	Eagle-K, anwser
7	Eagle-K	I agree with Jeepney-K, but they might of been born in a crowded area so they might be used to it
8	Wizard	So you are saything that you agreed that they can live in crowed place, correct?
9	Jeepney-K	what do you think Eagle-K
10	Wizard-K	Sun-K
11	Jeepney-K	Yes
12	Wizard	And Eagle-K.
13	Eagle-K	Yes
14	Wizard	can you point out which note tell you about the information? Tell Jeepney-K and Sun-K.
	((Talk about student nicknames spanning three lines))	
15	Eagle-K	one note says that the tilapia are healthy if crowded
16	Wizard	Great!
17	Jeepney-K	it is in ovelapping ideas ((column))
18	Wizard	So everyone, click the note and take a look. Do you think it is placed at the correct place?
19	Jeepney-K	Yes
20	Wizard	Why?
21	Jeepney-K	because it is overlappping other ideas

Ln	Speaker	In-game chat
1	Facilitator	what are we thinking about that red note
2	Jeepney-B	So I think it doesn't belong
3	Jeepney-B	Because it's not really talking about food
4	Turtle-B	i think it should go in food and at the same time get removed
5	Sun-B	I dont know where it should go..Mostly because I dont know what it is..
6	Jeepney-B	and it's not talking about anything in our board anyway. So I think it shouldn't be on the board
7	Facilitator	let's read what the note says
8	Sun-B	Thats tricky
9	Eagle-B	it doesnt really fit into any of the collumns
10	Jeepney-B	The note says that it's a green slime that makes its own food
11	Jeepney-B	it isn't really talking about food
12	Eagle-B	Ya
13	Sun-B	I dont know if its food, water quality, or overlapin ideas
14	Facilitator	it might also help you to read some of the other notes in that column
15	Sun-B	my legs are asleep
16	Jeepney-B	It also doesn't mention air, water, or any overlapping idea
17	Facilitator	because they have information that can help you figure out what that green slime is doing
18	Jeepney-B	Sun, was that really necessary?
19	Jeepney-B	Please stop.
20	Sun-B	Oh my apologies your highness
21	Jeepney-B	Well I don't see it belonging in any other columns
22	Sun-B	i will
23	Turtle-B	is there a chance we can remove becasue it doesnt fit anywhere
24	Sun-B	Yeah I agree with Turtle
25	Jeepney-B	Yeah I don't think it belongs in this board, but maybe some other one
26	Facilitator	we can leave it red for now and see if it helps us later, thats fine

EXCERPT 3

observed that we prompted rigor and complexity. In other words, the scaffolding served more than just making the task manageable; when necessary, it also made the task more difficult when students were satisfied with surface thinking (Ertmer & Glazewski, 2015). Our work informs substantive outcomes related to (1) the use of trace data to understand how scaffolds supported collaborative actions, and (2) coordinating hard and soft scaffolds across multiple functions.

6.1 | The use of trace data to understand how scaffolds supported collaborative actions

In our analysis, we highlighted how hard scaffolds that targeted the inquiry process may have supported increased engagement with collecting notes, sharing, and evaluating these notes. We made these inferences based on trace data statistics or logs of student interactions that provided insights into how different groups of students were interacting in our game-based learning environment. This was made possible because the trace data were designed such that we could interpret what the statistic meant in terms of student interactions. For example, we could reasonably assume that moving or placing a note on the brainstorming board was indicative of how students were thinking about the relevance of the note. Even when accounting for random or accidental movement of notes, this statistic was helpful in determining the extent to which students might have been negotiating or discussing the content of the note. Students' interactions with the notes were also not extreme as compared to the other statistics, indicating that this was a good indicator of how students may have interacted with their peers. Furthermore, interactional analysis corroborated the finding that higher interaction with the notes, either in terms of time or placing the notes, may have supported more engagement in inquiry processes.

At the same time, the patterns observed based on statistics from the trace data must be interpreted cautiously, especially in the absence of experimental conditions. For example, there were outliers that appeared to indicate that the hard scaffolds were not as effective in increasing specific interactions. However, interaction analysis indicated that groups with seemingly lower statistics were indeed responding to the hard scaffolds in productive ways. Taken together, our findings corroborate current research highlighting how the analysis of trace data or learning analytics must consider both quantitative and qualitative approaches to provide a more nuanced understanding of how students responds to scaffolds (Wise, Perera, Hsiao, Speer, & Marbouti, 2012).

6.2 | Coordinating hard and soft scaffolds across multiple functions

To understand how scaffolds support different functions, we began with a one-to-one mapping between the form of scaffold and its associated function. In doing so, we could determine how hard scaffolds supported engagement in inquiry process, and how soft scaffolds encouraged accountable talk. Our results indicated that students responded to hard scaffolds positively based on their trace data statistics, whereas soft scaffolds such as marking information had significant positive impact on accountable talk. These results corroborate prior findings suggesting that marking information might be more effective in supporting dimensions of collaborative inquiry learning (Hmelo-Silver & Barrows, 2008; Michaels et al., 2010).

These initial analyses then allowed us to unpack how scaffolds designed for one process could be used for another function. Hard scaffolds focusing on the organization of inquiry have the potential to promote accountable talk, be it to one another (learning community) or in their use of evidence in their explanations (rigorous thinking and knowledge). This was evident based on the relationship between students' votes and verbal counts of chat data. This is likely because hard scaffolds communicated the task of evaluating ideas and made it visible (Quintana et al., 2004). Once the inquiry task was made salient to students, both students and facilitators generated soft scaffolds that fostered accountable talk. Similarly, the verbal counts of the chat data indicated that soft scaffolds provided by facilitators often included attending to accountable talk and the regulation of the inquiry process. These results support prior work that highlight that scaffolds can work together in synergy to support similar functions (Martin, Tissenbaum, Gnesdilow, & Puntambekar, 2019; Reiser & Tabak, 2014). Interaction analysis indicated that hard scaffolds were a good starting point to uncover gaps in students' understanding, be it in terms of their conceptualization of the issue or support engagement in desired practices. Ultimately, we argue that for effective coordination of scaffolds, it might be beneficial to utilize hard scaffolds to initialize soft scaffolds.

7 | LIMITATIONS

Although the findings have been productive in informing the next iteration of our design, we have attended to only two dimensions related to collaborative inquiry learning. We acknowledge that there may be additional dimensions that we need to explore, or perhaps reduce, especially given the overlapping processes across these dimensions. In addition, experiments designed to compare the differences in group performance when scaffolds were used would demonstrate if the hard and soft scaffolds had the intended impact. This will contribute to understanding of how to coordinate form of scaffolds to support across multiple functions.

8 | IMPLICATIONS FOR PRACTICE AND FUTURE RESEARCH

To illustrate the concrete value of designing for synergy in a system of scaffolds, we propose design guidelines and highlight the need for future work:

8.1 | Create a system of co-occurring scaffolds in collaborative learning environments

By integrating the PBL whiteboard into Crystal Island: EcoJourneys, we have begun to explore how a system of co-occurring scaffolds work to create synergy and support collaborative inquiry learning. A virtual collaborative space allowed us to collect rich data to understand how groups supported one another. Future work exploring the integration of hard and soft scaffolds in these workspaces is needed, particularly in exploring other forms of distributed scaffolds (Martin et al., 2019; Reiser & Tabak, 2014).

8.2 | Integrate inquiry processes in multiple narrative roles and whiteboarding activity

From an instructional design perspective, it is critical to integrate the inquiry process into the story and collaborative workspaces in a game-based learning environment. Prior work in game-based learning environments have explored the value of immersive stories and how this motivate students to engage in scientific practices (Sengupta & Clark, 2016). Integrating the inquiry process into collaborative workspaces such as a whiteboard provides additional opportunities for students to engage in science practices.

8.3 | Designing for adaptive scaffolds in computer supported learning environments

Our work is an early exploration in understanding how facilitators deliver adaptive scaffolds to support discursive processes in collaborative inquiry learning. However, adaptive scaffolds can also be delivered by the computer. In our work, computer scaffolds may be triggered by students' in-game interactions such as whether students have voted or the placement of their notes relative to specific ideas. Marking information related to these actions can be another move that is delivered via system prompts. However, a key challenge for orchestrating PBL in a game-based learning environment is understanding how computer scaffolds can work in synergy with human scaffolds. Thus, future work is required to understand how computer and human scaffolds can co-occur to support learning.

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