Computers & Education 177 (2022) 104365

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

iVisit-Collaborate: Collaborative problem-solving in multiuser 360-degree panoramic site visits

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ARTICLE INFO

Keywords:
360-Degree panoramas
Virtual field trips
Multiuser virtual reality
Collaborative problem-solving skills
Construction education

ABSTRACT

Collaborative problem-solving skills are required from learners in the 21st century, particularly in construction graduates upon entering the workforce. However, challenges associated with spatiotemporal contexts of construction sites and resource limitations of educational programs reduce the opportunities available for students to practice these skills. This study focuses on using 360-degree panoramic virtual environments enhanced with virtual humans to produce realistic site visits for practicing collaborative problem-solving opportunities (iVisit-Collaborate). The goal of this phenomenological research study is to understand the collaborative problem-solving process of student dyads within iVisit-Collaborate. The findings suggest that student collaborative behaviors did not directly result in successful problem-solving. A hierarchical relationship between student problem-solving and collaborative behaviors was observed, indicating that problem-solving behaviors must take place to enable the occurrence of collaborative behaviors. Moreover, it was also observed that instructor scaffolding helped reduce the degrees of freedom in complex problem-solving activities. Finally, it was observed that student discussion engagement supported the creation and maintenance of shared mental models.

1. Introduction

Learning collaborative problem-solving is an increasing necessity within the 21st century skills framework. The Organization for Economic Cooperation and Development, the Partnership for 21st Century Learning, and other prominent educational organizations have pointed to collaborative problem-solving skills as a high priority for learners across multiple educational and training settings (Sun et al., 2020; Stoeffler et al., 2020). The need to learn collaborative problem-solving skills also applies in the construction engineering and management disciplines, as a new generation of professionals transitions into the workforce. Construction is a multidisciplinary industry that requires diverse experts to work together to complete a project (Harty, 2005). These construction experts are required to work together on complex problems daily, using their expertise to find an appropriate solution. Therefore, collaborative problem-solving is essential skill required in the construction industry to complete construction project. Accreditation programs for construction engineering and management programs such as ABET (Criterion 3–5) (ABET 2020) and ACCE (Criterion 3.1.5–9) (ACCE 2020) have recognized this need and require graduates to understand collaborative work to establish goals, plan tasks, and meet objectives. In construction education, collaborative problem-solving activities are used to increase student conceptual learning, knowledge retention, and critical thinking (Tucker & Rollo, 2006; Gol & Nafalski, 2007; Stump et al., 2011). Consequently, instructors

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https://doi.org/10.1016/j.compedu.2021.104365
Received 1 April 2021; Received in revised form 25 October 2021; Accepted 30 October 2021
Available online 5 November 2021

have focused on providing opportunities for students to practice collaborative problem-solving skills through in-class role-playing interventions (Korkmaz, 2012) or computer-mediated tools (Boeykens et al., 2013). These interventions aim to connect class learning with the spatiotemporal context (spatial, temporal, and social conditions) of the real-world construction site. Nevertheless, such learning opportunities are frequently unfeasible to attain within the constraints of in-class instruction.

In response to limitations of in-class instruction, construction site visits or field trip interventions have been a common approach to deliver such situated learning opportunities (Gunhan, 2014). Although site visits provide direct exposure to spatiotemporal contexts of construction sites, many challenges remain that limit student access to these sites. Often, visiting construction jobsites demands that students travel to inaccessible, dangerous, or expensive-to-reach locations. Moreover, teachers and institutions have limited financial resources, time constraints, and standardized educational curricula that reduce the opportunities to incorporate such construction site visit interventions in their programs (Eiris & Gheisari, 2017-a). These limitations inherent to traditional face-to-face programs further broaden when using online delivery methods. Geographically-dispersed students have significant barriers in reaching and connecting with the required spatiotemporal locations and professionals on construction sites.

Virtual environments have been employed in the construction domain to address the learning impediments within real-world contexts. These virtual environments are composed of 3D representations of construction sites, allowing users to navigate the digital space and manipulate virtual objects (Wen & Gheisari, 2020). To simulate construction professionals within these virtual environments, virtual humans have been utilized as embodied depictions of real humans that convey expert knowledge to students (Eiris & Gheisari, 2018-a). These digital spaces enhanced with virtual humans have been used in construction education to offer active learning opportunities for various applications such as design (Van Nederveen, 2007), coordination (Woksepp & Olofsson, 2006), planning (Anderson et al., 2014), and safety (Guo et al., 2012). Across all these different applications, virtual environments aim to foster behaviors conducive to solve problems collaboratively as knowledge building, problem analysis, communication, and coordination (Care et al., 2016; Montoya et al., 2011). Even though these virtual environments have been widely utilized for collaborative problem-solving skills, limitations in construction site representation realism create challenges for students to perform with the same proficiency as they would in real-world situations (Wang & Dunston, 2007). 360-degree panorama is an emerging technology that addresses the lack of realism and remains unexplored as an environment with the potentials to facilitate collaborative problem-solving.

This research aims to explore the use of 360-degree panoramic sites enhanced with virtual humans to produce realistic site visits for practicing collaborative problem-solving opportunities – iVisit-Collaborate. Existing approaches have limited success in offering students situated practice collaborative problem-solving opportunities because of the impracticalities and impossibilities of performing these activities within the real world and on active construction sites. This study discusses the development of the iVisit-Collaborate to create a construction educational intervention centered on practicing situated collaborative problem-solving skills. A phenomenological research design was used to explore student dyads and instructor behavior patterns during collaborative problem-solving activities within iVisit-Collaborate. The contribution of this research focuses on providing educators and researchers an understanding of how to develop and refine multiuser 360-degree panoramic site visit interventions to foster student collaborative problem-solving and develop an understanding of student development of collaborative problem-solving behaviors within similar learning virtual site visit approaches.

2. Literature review

2.1. Collaborative problem-solving

Existing literature defined problem-solving as the process of using a sequence of cognitive operations with a directed goal to obtain value (Anderson, 1993). Within these value-gaining processes, cognitive operations support the development of a mental model of the problem (Simon & Newell, 1971). This mental model is iteratively evaluated until a satisfactory solution that delivers the desired value is obtained (Newell et al., 1958). For collaborative problem-solving, the definition of this mental model must be shared across collaborators to successfully reach a problem solution. Through the collaborative process, the team of individuals must coordinate their activities to produce, structure, and maintain this collective problem mental model (Dillenbourg, 1999). Social activities are essential to engage the participants in a coordinated effort to solve the problem together (Roschelle and Teasley, 1995). One of the central pillars of collaborative problem-solving is the discussion and argumentation of knowledge to reach a consensus on ideas or concepts. Peers communicate how they conceptualize the problem-solving activities and elaborate a common set of knowledge through interaction (Hausmann et al., 2004). Moreover, collaborators often use think-aloud mechanisms to assess their mental representation of the problem, producing self-directed learning. This benefits the speaker and also aids the team participants who listen to internalize the team's cognitive processes (Chi et al., 1989). Collaboration not only depends on the participants' interaction with each other but is also influenced by the interactions with the situated context (space and time) where the activities are embedded. The observations of the situated context that surrounds the collaborators in the environment help in the shared conceptualization of the shared mental models (Smith & MacGregor, 1992). As an outcome, participants acquire behaviors that contribute to effective collaborative problem resolution that includes knowledge building, problem analysis, hypothesis testing, communication, cooperation, and coordination (Montoya et al., 2011; Care et al., 2016). In construction practice, these processes become important as professionals are required to perform extensive amounts of collaboration to complete any project (Harty, 2005). These professionals often engage in collaborative activities to approach problems that occur in the spatiotemporal context of jobsite. The spatiotemporal context refers to a situation that is inherently defined by its spatial, temporal, or social constraints (e.g., particular locations in the jobsite, changes through a month in the project, the interactions between engineers, managers, and workers to complete a task) (Mutis, 2018). Consequently, spatiotemporal contexts are central to many problem-solving activities in construction.

In construction education, practice opportunities for collaborative problem-solving skills have been identified as effective methods for students to develop behaviors such as discussion engagement, teamwork, planning, and decision-making (Chan & Sher, 2014; MacLaren & Chrisp, 2017). Students learn these collaborative behaviors by leveraging role-playing interventions with instructors and fellow students while performing classroom exercises or employing computer-mediated tools. These traditional interventions aim to connect in-class learning to real-world contextual situations. These interventions are often done following the existing face-to-face instruction frameworks that utilize 3D models, 2D drawings, text descriptions, and site images. In this context, Korkmaz (2012) demonstrated that effective learning of sustainable building construction could be achieved by implementing collaborative problem-solving activities in class. In another example, Boeykens et al. (2013) implemented Building Information Modeling (BIM)--based interventions to enable student learning of teamwork and information exchange as part of the building design process. Other researchers have approached collaborative problem-solving skills learning by providing on-site interactive opportunities to the students. Site visits are a very common strategy used in construction disciplines to expose learners to real-world knowledge, providing an ideal context for student familiarization with construction means and methods. For example, Gunhan (2014) used a construction field trip to provide students with experiences about the request for information (RFI) mechanisms, solving real-world problems on-site. The study concluded that students benefited from learning in the field, as they had the opportunity to work on the problem within its context, engage in discussion with construction professionals, and collaborate with their peers (Gunhan, 2014).

Although learning within construction spatiotemporal contexts has been recognized as beneficial (Messner & Horman, 2003; Forsythe, 2009), many educational barriers still exist to deliver student exposure to critical construction activities for practicing collaborative problem-solving skills. Often, real-world construction sites are not suitable for student learning due to safety concerns or the inaccessibility of their location. Furthermore, the spatiotemporal processes associated with personnel machinery and materials in these construction site environments are only available on-site for limited periods of time (Eiris & Gheisari, 2017-a). Moreover, these dynamic construction contexts introduce unique challenges for learning with the spatial conditions of the site as learners have reported challenges for observing, recognizing, and evaluating associations of processes that cross multiple spatial locations (Fruchter, 2018). Further obstacles derive from the educational institutions – limited financial resources, time constraints, and standardized educational curricula (Eiris & Gheisari, 2017-a). Because of all these difficulties in existing classroom and field trip interventions, virtual environments have been utilized as an alternative tool to introduce collaborative problem-solving skills learning opportunities in construction education.

2.2. Collaborative problem-solving in virtual environments

In response to the existing challenges for exposing students to real-world sites, virtual environments have been utilized in construction education. Literature defines virtual environments as digital spaces where users can navigate the digital space and manipulate virtual objects, including text, audio, and 3D models (Wen & Gheisari, 2020). Typically, virtual humans are embedded within these virtual environments to facilitate interaction between the users and with the environment. These virtual humans have embodied representations of humans within the digital environment. These virtual representations of people are used as a medium to interact with other objects, humans, or systems and convey information in the virtual environments (Eiris & Gheisari, 2017-b). Learning affordances such as spatial visualization, cognitive exploration, and reflexive feedback have been identified as some of the core pedagogical outcomes of such virtual environments (Gee, 2003; Squire, 2005; Dalgarno & Lee, 2010). In the construction domain, researchers have increasingly found that digital environments facilitate collaborative problem-solving skills similar to real-world situations. Several benefits have been reported in the literature about using these digital spaces in construction, including learner experiential discovery and creativity (Merrick et al., 2011), ease of visualization (Woksepp & Olofsson, 2006), the practice of verbal and non-verbal communication (Le & Park, 2012), and effective knowledge gain and retention (Anderson & Dossick, 2014, pp. 793–800; Castronovo et al., 2017).

Even though important efforts in construction education have explored virtual collaborative problem-solving activities, there are serious challenges about the ability of these virtual environments to create a sense-of-presence (Taylor et al., 2018, chap. 10). Presence is defined as the feeling of "being there" in the location although physically located elsewhere (Slater et al., 1994). Researchers have identified realism as one of the main barriers to deliver presence in virtual environment-based learning applications (Du et al., 2016, Eiris, Gheisari, & Esmaeili, 2020-). Because of the realism limitations of current digitally modeled construction sites, users that learn in these virtual environments frequently do not perform with the same proficiency as they do in the real world (Wang & Dunston, 2007). To achieve an accurate representation of reality, digital settings necessitate considerable resources from the development perspective. Individual components of the virtual environment require to be modeled using BIM tools (e.g., Autodesk Revit®, Tekla Structures®, or ArchiCAD®) or CAD tools (e.g., Autodesk Inventor®, Dassault Systemes Solidworks®, or Trimble Sketchup®), and then arranged with attention to fine details to produce a cohesive context in the digital setting (Hilfert & König, 2016). This demands significant expertise and large amounts of time from the virtual environment creator to achieve a sufficiently accurate representation of reality (Sacks et al., 2013). Additionally, high computational power for rendering all the elements in end-user location is often needed. Depending on the technology targeted for delivering the virtual environment, the end-user might require powerful computational means to render and interact in the virtual environment. One emerging technology that can address these limitations associated with traditional virtual spaces is 360-degree panoramic environments.

2.3. Learning in 360-degree panoramic virtual environments

360-degree panoramas are omnidirectional views of the complete environment encircling an observer, creating a virtual environment that replicates the real world. These 360-degree panoramas can be easily captured using cameras with multiple fisheye lenses, generating equirectangular projections of their surrounding spaces. The produced equirectangular projections can be visualized in their omnidirectional spheric representation using various platforms or devices (e.g., computer monitors, head-mounted displays, smartphones). These omnidirectional representations provide a pronounced sense-of-presence in contrast to modeled virtual reality environments (Higuera-Trujillo et al., 2017; Eiris, Gheisari, & Esmaeili, 2020-). Sense-of-presence varies across the devices used to visualize the 360-degree panoramas, with head-mounted displays providing a higher sense-of-presence with respect to computer screens (Voigt-Antons et al., 2020). However, the adoption of head-mounted displays has been limited due to the hardware costs and the potential training needs required to operate such technologies (Kavanagh et al., 2017).

Construction educational applications have been increasingly using 360-degree panoramas due to the accuracy of representation from the real world captured spaces. Researchers in the construction education domain have used 360-degree panoramas as a backdrop of reality to demonstrate augmented concepts within the virtual space. Gheisari et al. (2015) utilized 360-degree panoramas for student learning of free-body diagrams. A 360-degree panorama was used to display the whole structure of a building while superimposing free-body-diagram information. Other applications have focused on using 360-degree panoramas to provide construction safety-related learning opportunities for hazard awareness and identification. Eiris et al. (2018-b) demonstrated this application by creating a safety training platform using augmented panoramas of reality. This system allowed users to actively navigate construction sites, visualizing highly realistic environments with augmented interactions. More recently, 360-degree panoramas have been utilized to provide realistic virtual site visits for students to construction sites. Kim et al. (2019) explored the use of 360-degree panoramas to deliver in-class field trips, evaluating the student perceptions of the experience in terms of immersion and realism. It was found that students reported high levels of immersion and realism using the 360-degree panoramic field trips. In another study, Eiris, Wen, and Gheisari (2020-) developed a digital platform to offer 360-degree panoramic field trips guided by virtual humans. Through an experimental evaluation, the study found that these guided virtual tours are easy to utilize, produced highly realistic representations of the jobsite, and offered a high sense-of-presence to the participants. Although 360-degree panoramas have been explored for various aspects of learning in construction, no studies have explored their use for collaborative problem-solving.

3. Project Overview

The goal of this study is to explore the pedagogical use of 360-degree panoramic site visit experiences enhanced with virtual humans – iVisit-Collaborate – to produce realistic site visits for student practice of collaborative problem-solving skills. To gain an in-depth understanding of educational use for iVisit-Collaborate, this research seeks to answer the following two research questions:

- RQ1: How does iVisit-Collaborate enable students to develop collaborative problem-solving behaviors?
- RQ2: How does instructor scaffolding behaviors facilitate students to develop collaborative problem-solving within iVisit-Collaborate?

Three phases were completed in this study to answer these two research questions (see Fig. 1). First, the iVisit-Collaborate platform was developed to support online multiuser interactions in a 360-degree panorama-based virtual environment. Second, iVisit-Collaborate was used to examine student dyad behaviors during two collaborative problem-solving activities based on a phenomenological study design. This phenomenological approach was selected to study the complex set of factors that affect student collaborative problem-solving behaviors and instructor scaffolding within iVisit-Collaborate activities. Video recordings of the educational intervention were recorded for further analysis. A codebook was developed by observing the students within the iVisit-Collaborate educational intervention, resulting in a set of key behaviors that contribute to collaborative problem-solving in such virtual settings. In addition to observing the students, the instructor was also observed during the intervention to identify a set of critical behaviors that supported the instructor's role in student learning of collaborative problem-solving skills. The video recordings were then analyzed by employing the codebook to detect patterns and commonalities regarding student behaviors during collaborative problem-solving activities across multiple study participant dyads. Quantitative and qualitative data were obtained from the analysis, on which descriptive statistics and correlation analysis were used. The analysis results were utilized to discuss student behavioral approaches to

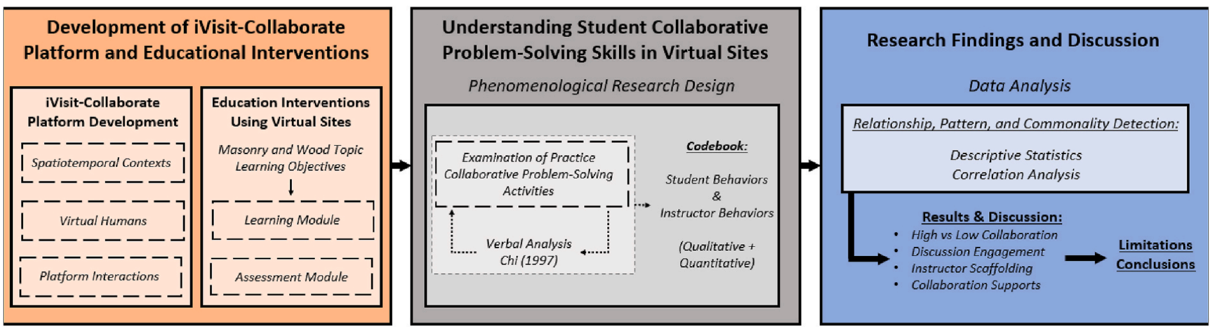


Fig. 1. Project overview.

collaboratively solve problems in iVisit-Collaborate online virtual environments and review the instructor's approaches to support such interventions. Finally, the study limitations and conclusion were outlined for this study.

4. Development of iVisit-Collaborate platform and educational interventions

4.1. iVisit-collaborate platform development

The development of the iVisit-Collaborate platform entailed creating two components (Fig. 2): (1) augmented spatiotemporal contexts, and (2) and online multiuser interaction affordances. The Unity3D® game engine and the Photon® networking engine were employed to build the virtual site visit multiuser sessions within the iVisit-Collaborate platform. Desktop-based computer screens and mouse-&-keyboard interactions were targeted for the development of iVisit-Collaborate to remove potential hardware limitations and guarantee maximum access to potential users of the platform. The technical description for each of the iVisit-Collaborate components is contained in the following subsections.

(1) *Augmented Spatiotemporal Contexts:* The platform employs 360-degree panoramas augmented with layers of information to visualize the complex spatiotemporal context of the construction site. A three-step methodology was used to create these virtual construction sites. First, data was captured from real-world construction site locations using 360-degree panoramic cameras (e.g., Insta360 One®, Samsung GearVR®, or Ricoh Theta V®). Second, the captured data was processed into an equirectangular projection and then was remapped into spherical coordinates in a 3D virtual environment. Third, augmented information in the forms of texts, objects, sounds, superimposed signifiers, or virtual were utilized in the Unity3D® game engine as layers in the virtual environment. Finally, these information layers were manipulated to visually emphasize concepts in the virtual site or provide more detailed knowledge about elements existing on the 360-degree images.

Virtual humans augmentations were used to connect the spatiotemporal contexts with conceptual information displayed in the augmented 360-degree panoramas. These virtual site visit guides represent construction professionals involved in various aspects of a given project (e.g., project engineer, safety inspector, superintendent). Animated 3D character models were used to replicate the human physically within the virtual environments. Computer software such as Adobe Fuse CC® and Adobe Mixamo® were used to generate the virtual human models and animations. The animations designed for the virtual humans aimed to convey non-verbal cues (e.g., pointing, waving, walking) ingrained in typical human communication. Additionally, voice recording narrations that corresponded to those animations were used to guide the students during the site visit. These narrations were audio files generated using natural language processing software. The IBM Watson® text-to-speech tools were employed to synthesize natural-sounding human voice articulations. Combining the 3D model, the animations, and the audio narrations resulted in realistic representations of

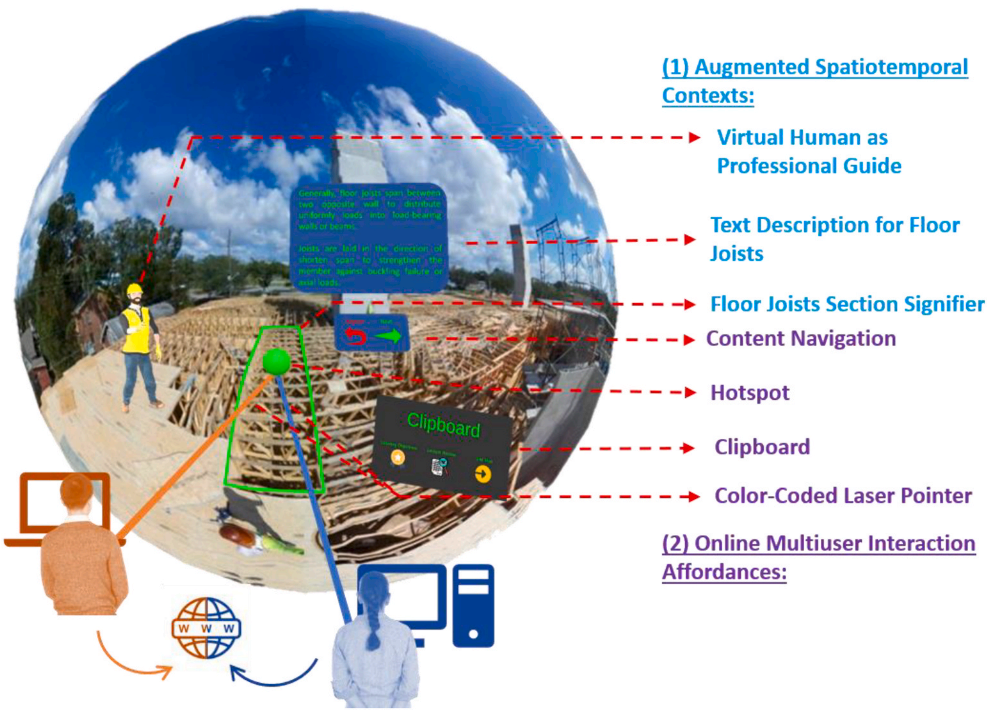


Fig. 2. iVisit-Collaborate Platform Components.

construction professionals guiding the site visits.

(2) *Online Multiuser Interaction Affordances:* Students interacted with the augmented spatiotemporal contexts and with each other using an online desktop-based application. The online desktop-based application was developed to be a remote collaboration platform, allowing students to use their computers to work together over the internet within the augmented spatiotemporal context. Within the desktop-based application, students used their keyboard & mouse interfaces to direct a color-coded virtual laser pointer. The color-coded virtual laser pointers facilitated information communication in the virtual locations, enabling students (one pointer in blue and another in orange, as show in Fig. 2) to point to augmentations or 360-degree panoramic content in the virtual environment while denoting describing their thoughts. All voice communications were handled through a third-party voice system (Zoom®) executed in each local computer before using iVisit-Collaborate.

The virtual environments provided three interactable objects: hotspots, clipboards, and content navigation (Fig. 2). Hotspots (green spheres) were interactable objects that showed augmented spatiotemporal content in the virtual environment (e.g., texts, images, signifiers) and played an audio narration by the virtual human. The audio narration was an expanded version of the contents described by the augmented spatiotemporal context to deliver the information in the location using the audio format. The hotspot also controlled the flow of the information presented in the virtual space, requiring students to completely listen to the virtual human narration before allowing them to continue to the next hotspot.

The clipboard provided each student with an interactive menu that supported the site visit information management with details on site visit progress, learning objective tracker, related text contents, and site map. Fig. 3 illustrates the possible clipboard actions as seen by the students in iVisit-Collaborate. On the clipboard first page (Fig. 3-a), students could select three options: "Learning Objectives", "Lecture Review", or "Site Map". In the "Learning Objectives" panel (Fig. 3-b), the students could read the learning objectives specified for the site visit. In the "Lecture Review" panel (Fig. 3-c), students could read the information provided by the virtual humans in text format. And in the "Site Map" panel (Fig. 3-d), students could change their location within the site, exploring other areas that contained more information regarding the topic.

Finally, the content navigation object contained buttons to advance to the next hotspot or repeat information. The green arrow was used to advance, and the red arrow was used to repeat the information (see Fig. 2). To interact with a hotspot, the clipboard actions, or the content navigation buttons, students had to simultaneously use a mouse click on the object to be manipulated. The requirement to perform simultaneous interactions promoted students' interactions and discussions during the content manipulation in the platform.

4.2. Development of educational interventions: masonry and wood construction

An online educational intervention was situated within the contents of a construction techniques course. This course was selected due to the close relationship between its core contents and real-world construction spatiotemporal contexts, necessitating multiple site visits to effectively convey the materials to the students (Eiris & Gheisari, 2017-a). Two of the course topics were targeted for the

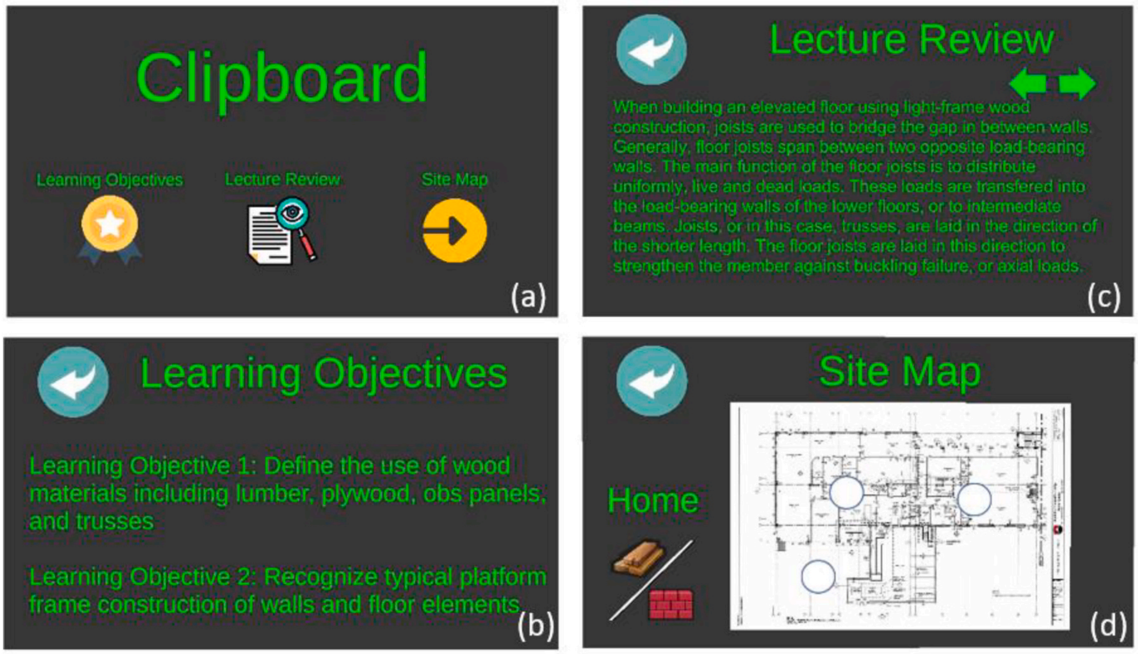


Fig. 3. Clipboard Panels: (a) Clipboard first page; (b) Lecture Review panel; (c) Learning Objectives panel; and (d) Site Map panel.

iVisit-Collaborate educational interventions – masonry and wood construction. These two topics were chosen based on the course instructor's indication of requiring site visits for those topics and considerations of topic simplicity and ease of visualization. Because of the course requirement and scope, remember and understand categories of Bloom, (1956) were mainly used for the masonry and wood topics:

- *Masonry Topic:* (1 – Remember) Define the properties and uses of concrete masonry units (CMU), clay masonry units, and masonry mortar; and (2 – Understand) Recognize the construction of masonry walls, including reinforcement and control joints.
- *Wood Topic:* (1 – Remember) Define the use of wood materials including lumber, plywood, oriented strand board (OSB) panels, and trusses; and (2 – Understand) Recognize typical platform frame construction of wall and floor elements.

4.2.1. iVisit-collaborate learning module

The iVisit-Collaborate learning module was developed for the masonry and wood topics focusing on conveying the learning objectives defined for this study. A set of 360-degree scenes were collected from two distinct jobsites using multiple 360-degree cameras (e.g., Insta360 One®, the Ricoh Theta V®, and the NCTech Fusion®). Within the masonry construction site, students experience a guided tour to observe locations that employed concrete and clay masonry units in their construction processes (Fig. 4). Within the wood construction site, the students observed wood-based materials, including lumber, plywood, OSB panels, and trusses for the construction of floors, walls, and roofs (Fig. 5). The 360-degree scenes of those two sites were visually augmented with layers of information to demonstrate the knowledge associated with each learning objective. On each scene, students were guided through the information contained in the site visit by the virtual human. The hotspots provided the information within the spatiotemporal context using audio narrations and augmented text.

4.2.2. iVisit-collaborate assessment module

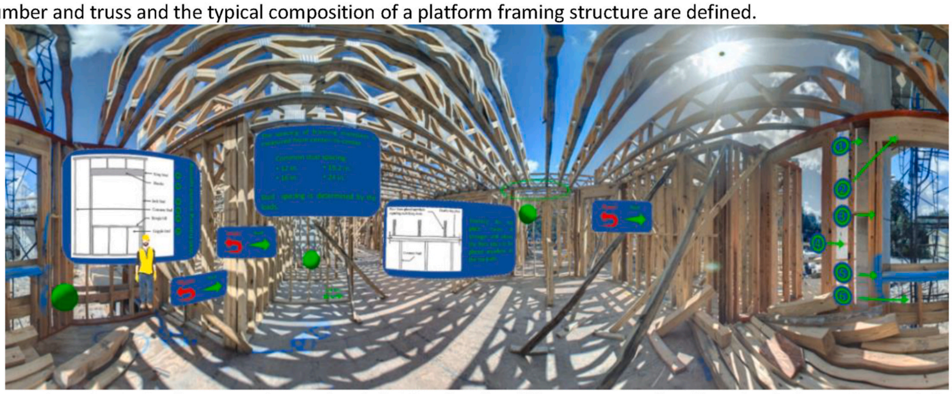
Two additional 360-degree scenes were captured from the same sites used in the learning module. The scene locations in these assessment modules were similar to those in learning modules but provided a new, fresh context. A situated problem-solving activity

Scene Location 1: Students are introduced to masonry construction. Concrete and masonry units are defined, including part naming and typical dimensions. The typical spacing of the units is also described.

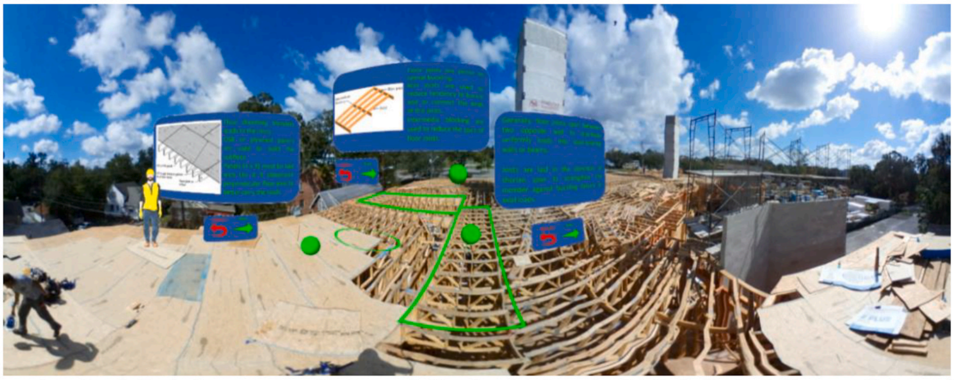
Scene Location 2: Students are shown the composition and use of masonry mortar to construct walls. Additionally, the use of wall reinforcement, grounding, and control joints is defined.

Fig. 4. iVisit Collaborate Learning Modules for the Masonry Topic.

Scene Location 1: Students are introduced to wood platform framing construction. The properties and uses of lumber and truss and the typical composition of a platform framing structure are defined.



Scene Location 2: Students are shown the definition for the different types of wall studs, their spacing, and their uses in regular walls or the ones with openings. Furthermore, the use of double top plating to transfer loads to walls is shown.

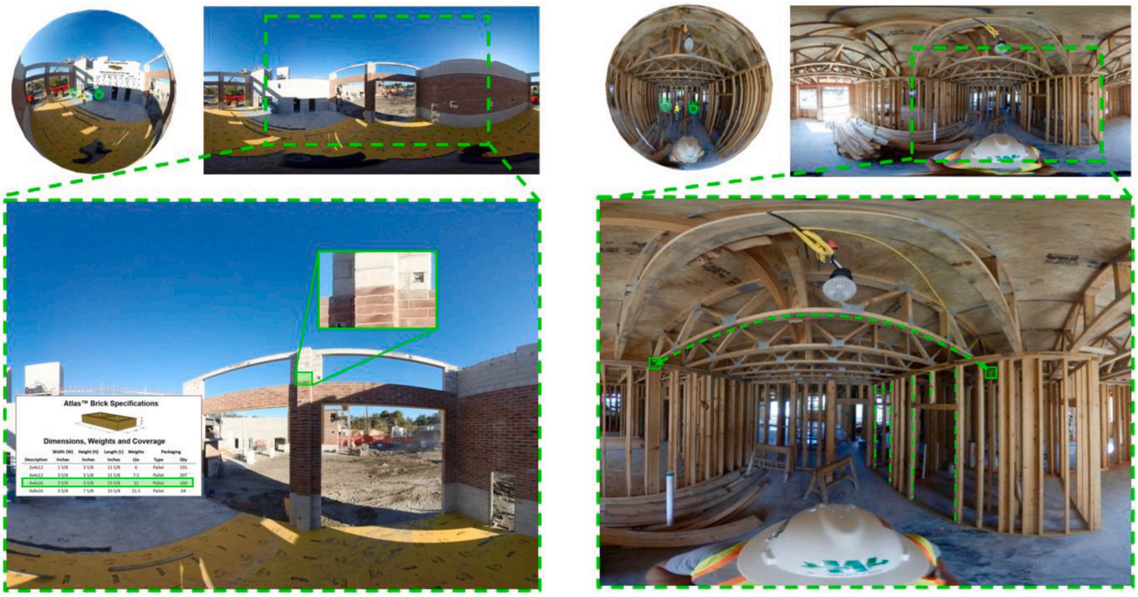


Scene Location 3: Students are exposed to trusses in flooring structures to distribute the load. The use of intermedia blocking is displayed to better distribute loads. Finally, the use of the OBS panels is demonstrated to finish floor systems.

Fig. 5. iVisit Collaborate Learning Modules for the Wood Topic.

was created for each assessment scene location. The collaborative problem-solving activities for each module require that the students inspect and analyze the detailed information provided by the 360-degree surroundings:

- *Collaborative Problem-solving activity for the masonry topic* (Fig. 6-a*):* In this assessment module, students were asked to investigate the clay bricks dimensions in a wall. A specification sheet was presented to the students to evaluate the potential size of the clay brick on site. To approach this problem in the masonry site, the panoramic environment had to be examined by the students to identify the brick and recall the dimensions of masonry units described in the learning module. To complete this assessment module, students were required to discuss the site's conditions, reflecting on their knowledge regarding bricks and blocks.
- *Collaborative Problem-solving activity for the wood topic (*Fig. 6-b*):* In this assessment module, the students were required to identify the number of jack and cripple studs in a particular wall in the room. To solve the wood problem, students had to recall and understand the wood framing paradigm, including concepts such as load-bearing walls, intermedia blocking, and double top



(a) Masonry Topic (b) Wood Topic

Fig. 6. iVisit-Collaborate Assessment Modules for Masonry and Wood Topics.

platting. Once the correct wall was identified, students had to remember the positioning of jack and cripple studs within the wood framing structure of the location. To complete the assessment module, students were required to discuss the concept of wood platform framing, associating the knowledge of wood material relationships with their contextual observations of the location.

To perform the collaborative problem-solving assessment modules, the students were initially guided by a virtual human. The virtual human verbally provided the problem explanation that detailed the use of visual inspection within the digital environment. The students were able to review the information again using a repeat button (glowing green sphere). The student also had the possibility of reading the information within the clipboard lecture review panel. A help button (glowing white sphere) appeared after 3 min of starting the activity to offer supplementary information that pointed towards resolving the problem. The goal of having the help button was to provide an instructional scaffold for students to get started with the collaborative problem-solving process.

5. Study methodology

The effects of iVisit-Collaborate for collaborative problem-solving learning were explored using a phenomenological qualitative study. The phenomenological research design facilitated the development of an understanding of student collaborative problem-solving in 360-degree panoramic environments. Prior publications in educational technology have employed similar qualitative study design methods when the intent of the research is to explore a phenomenon and the varied perspectives, experiences, or meanings that participants hold (e.g., Robinson, 2013; van Deursen et al., 2013; Huang et al., 2010). For iVisit-Collaborate, multiple student dyads were observed to obtain a rich understanding of their experiences during the iVisit-Collaborate interventions. The examination across multiple student dyads enabled the researchers to offer a broader depiction of the student behaviors during the collaborative problem-solving activities, facilitating the identification of similarities and dissimilarities in students learning strategies and increasing the reliability of the study analysis and findings (Creswell, 2013; Gustafsson, 2017). To implement the phenomenological research design, direct observations of students were performed during the collaborative problem-solving interventions to explore their behavioral patterns and relationships. Unfortunately, these observations are impossible to obtain in active construction sites, as students are not allowed to perform such collaborative problem-solving activities in real-world sites due to safety concerns, inaccessibility to jobsite locations, limited financial resources, time constraints, and standardized educational curricula constraints outlined in the literature.

Fig. 7 illustrates the methodology used to evaluate the collaborative problem-solving iVisit-Collaborate interventions. The collaboration process contained the series of actions performed by the students and the instructor during the iVisit-Collaborate collaborative problem-solving intervention. The collaboration process measures centered on communications and procedures performed by the students and the instructor, which helped define the unit of analysis based on the problem-solving steps required to resolve the intervention. The collaboration outcome was composed of behavioral themes and patterns within the collaborative problem-solving intervention, obtained through iterative data analysis. The outcome measures focused on behavior coding to form a codebook that demonstrated the patterns in collaboration and discussion engagement for students, and scaffolding used by instructors. There was a causal relationship between the collaboration process and the collaboration outcome, as the video data gathered provided

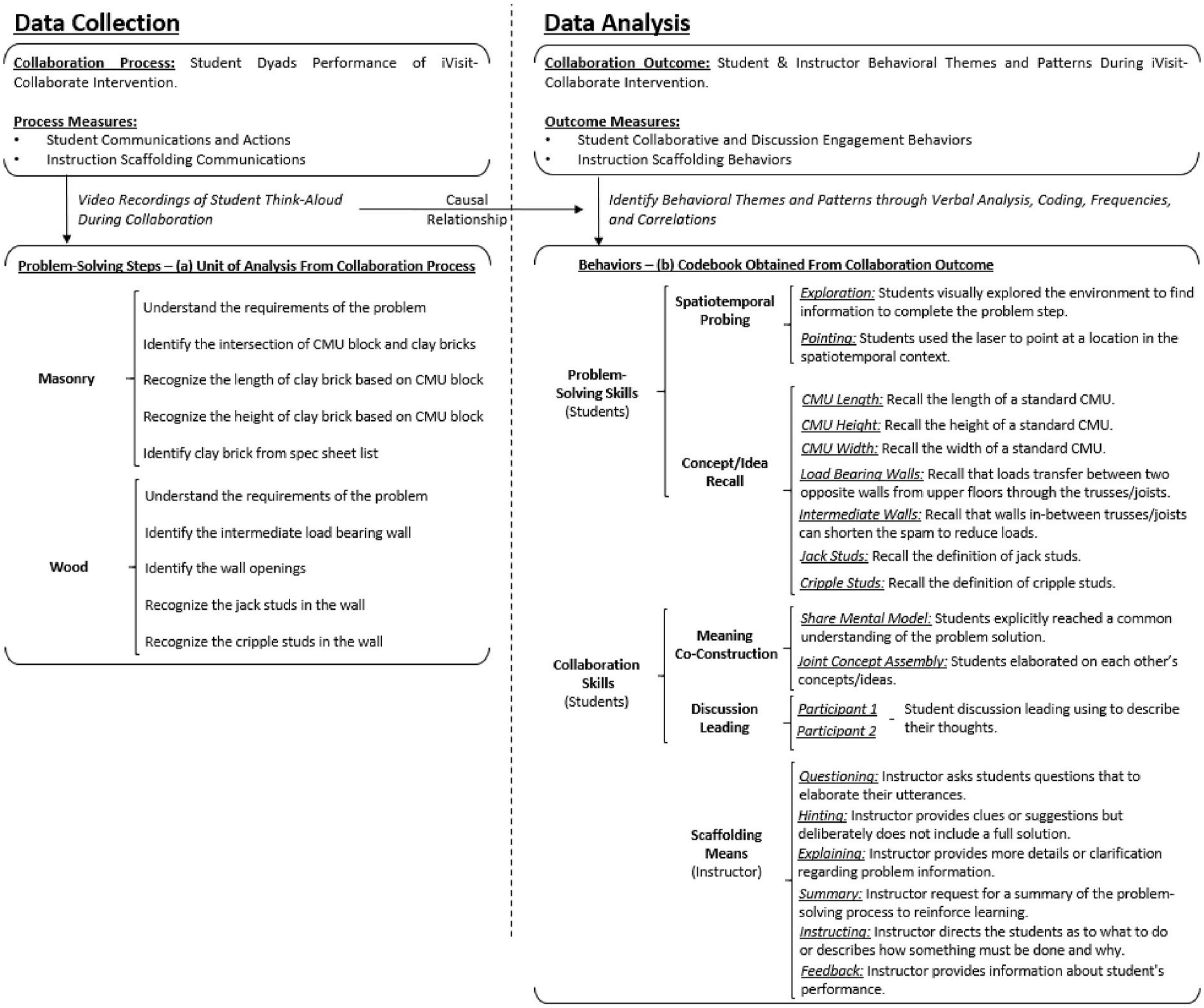


Fig. 7. Study methodology.

direct evidence of how the students and the instructor behaved during the collaborative problem-solving activities. Further details for this study methodology are provided in the following subsections.

5.1. Study participants

A total of 14 dyads of participants were purposefully sampled from a junior-level construction techniques course at the University of Florida (IRB Approval #: 201903043) (Table 1). All study participants were purposefully sampled from this junior-level class, as these students had an equal baseline academic knowledge about construction techniques. The students had an average age of 21 years ($\sigma = 0.7$), predominantly male (82%). Over 50% of the students had low-to-no experience in the construction industry. Overall, a large proportion of students had no-to-low previous experience with virtual reality and 360-degree panoramas. Contrary, most students reported to had medium-to-high knowledge of construction materials and techniques.

5.2. Data collection

Students were paired in dyads or pairs to perform the iVisit-Collaborate intervention and were video recorded remotely using the Zoom® videoconference platform. The video captures were performed on the Zoom® software, employing the screen share and cloud recording tools to depict what students observed in their computer screens. Due to the remote nature of this study, each student used their personal laptop or desktop computer to engage with iVisit-Collaborate. Students were required to be in a quiet room, free of distractions, to start the intervention. The overall data collection section lasted form 1 ½ hours. To start the data collection, students first completed a pre-intervention demographics survey using Qualtrics®. Then the student dyads participated in a 1-h long intervention using the iVisit-Collaborate platform. During the assessment module, student dyads were asked to utilize a think-aloud

Table 1
Student demographics.

Variable	Category	Percentage (Frequency)
Gender	Male	82% (23)
	Female	18% (5)
Construction Industry Experience	No Experience	29% (8)
	Less than 6 months	36% (10)
	6 months to 1 year	18% (5)
	1 year to 2 years	11% (3)
	Over 2 years	7% (2)
Previous Experience with Virtual Reality	None	7%(2)
	Low	50% (14)
	Medium	25% (7)
	High	18% (5)
Previous Experience with 360-degree Panoramas	None	4% (1)
	Low	60% (17)
	Medium	18% (5)
	High	18% (5)
Knowledge of Construction Materials	None	0% (0)
	Low	21% (6)
	Medium	29% (8)
	High	50% (14)
Knowledge of Construction Techniques	None	0% (0)
	Low	21% (6)
	Medium	33% (9)
	High	46% (13)

methodology for expressing their collaborations. The think-aloud was used to assess the cognitive processes during the collaborative problem-solving activity through student thought verbalization. The process of asking a group to do a think-aloud while performing a collaborative problem-solving activity is commonly used in the education and human-computer interaction literature (e.g., Mayhew, & Alhadreti, 2018; Siddiq et al., 2017; Kelly et al., 2015). Think aloud is effective in making explicit the internal cognitive process of each participant to the group and the researchers (Cooke, 2010). Think-aloud protocols have been used to supports the collaboration process by providing a clear outline of each participant's thoughts while solving a problem (Kelly et al., 2015). Furthermore, the researcher assumed the role of an instructor during the interventions, guiding and supporting the collaborative process. If the students did not engage in content discussion independently, the instructor intervened using scaffolding strategies to foster collaboration. The scaffold strategies used (e.g., hint ideas, explain unclear objects within the environment, solicit thoughts on the environment) were adapted for each student dyad according to the engagement they showed during each topic assessment. Qualitative and quantitative metrics were used to identify the behaviors that support student collaborative problem-solving skills learning. Student collaborative problem-solving behaviors were qualitatively examined during the iVisit-Collaborate intervention. Direct observations by the main researcher were performed on the video segments captured during each topic assessment to establish commonalities in student collaborative problem-solving behaviors. Finally, quantitative metrics were derived from qualitative metrics by assigning units of observation to the categorical variables. These categorical variables were composed of behavior frequencies within the segmented video data. The goal of using these quantitative metrics was to quantify the raw data codes into frequency summaries of their occurrences, supporting the characterization of the collaborative problem-solving behaviors observed in the qualitative data (e.g., show relative frequencies of behaviors, look for code co-occurrences, identify code relationships and correlations). These types of frequency counts have been explored by prior researchers studying educational technologies to provide further insights on their qualitative findings (e.g., Bray & Tangney, 2016; Chen & Chen, 2015) and can be found on qualitative research manuals and handbooks (e.g., Namey et al., 2008; Saldaña, 2015).

5.3. Data analysis

A multi-step data analysis method was used to explore the collaborative problem-solving processes within the iVisit-Collaborate intervention. Verbal analysis (Chi, 1997) of the qualitative data was used to understand student and instructor behaviors. The data analysis software MAXQDA2020® was used for the exploration videos to identify themes and patterns in the data. A unit of analysis was selected based on the problem-solving steps required to find a solution for each topic assessment. This unit of analysis was composed of a set of utterances that discussed themes associated with a particular problem-solving step within the collaborative process. For this study, an utterance is defined by a phrase said by a single person that indicates an idea or though. Each unit of analysis composed of these utterances was defined following the "Understand" category of Bloom's taxonomy (1956) to reflect the actionable character of the collaborative problem-solving process (Fig. 7-a). Subsequently, an iterative process was followed to develop codes representing behavioral occurrences within each unit of analysis (Fig. 7-b). A behavior occurrence is the combination of two data types – utterances externalized by the students and/or iVisit-Collaborate platform images obtained from the video recordings. These behavior occurrences illustrate student intentionality within the collaborative problem-solving processes. To detect the behaviors occurrences, both utterances and images were analyzed during the dyad collaborative problem-solving tasks. For example, in the

"Exploration" behavior, students spent time observing the virtual environment to gather information. This behavior example is completely image-based and does not contain student utterances. On the other hand, "Discussion Leading" was the utterances instances performed by a student to lead the discussion. In "Discussion Leading" the utterances demonstrated how students took turns in leading the problem-solving activity. Finally, for the "Joint Concept Assembly" behavior students used their prior knowledge and the information visualized in the virtual environment to co-construct an idea that advances the problem state. For "Joint Concept Assembly" the students performed utterances while visibly referencing the visual content within the system images to develop an idea and agree on that. Other behaviors observed in this study (e.g., Pointing, Shared Mental Model) used a similar approach to define their occurrences employing both utterances and images. The selection of these coded behavior occurrences was intended to demonstrate the student dyad behaviors during the collaborative problem-solving process and the scaffolding means used by the instructor to support the topic assessment. Tables A1 and A2 in Appendix A contain detailed criteria and examples for each code shown in Fig. 7.

The categories that emerged from the analysis for the coded behavior occurrences were similar to existing frameworks for collaborative problem-solving, demonstrating a combination of Cognitive and Social skills (Heidegger et al., 1962; Graesser et al., 2018). The Problem-Solving Skills detected in this study correspond to Cognitive Skills from prior research that point to students' individual level application of planning, executing and monitoring, flexibility, and learning skills (Heidegger et al., 1962). The Collaboration Skills similarly correspond to Social Skills that require participation, perspective-taking, and social regulation skills to move forward the collaboration process (Heidegger et al., 1962). Further analysis was performed on this quantitative data, using descriptive statistics (e.g., mean, median, standard deviation) and correlation analysis to support the understanding of the relationships, patterns, and commonalities observed during the iVisit-Collaborate interventions. Since the quantitative data obtained in this study was ordinal and non-parametric, the correlation analysis was performed using Spearman Rank Correlation Coefficient (Spearman, 1904).

6. Results and discussion

6.1. *Behaviors to collaboratively solve problems in iVisit-Collaborate*

The students' and instructor behaviors were coded using the criteria previously established to extract patterns and commonalities. For each topic assessment activity within iVisit-Collaborate, an overview of student and instructor behaviors frequency was generated. Moreover, existing literature has identified discussion engagement as one of the most important indicators of collaborative problem-solving (Hausmann et al., 2004). In the context of this study, discussion engagement is a spectrum that demonstrates the ability of each student to maintain active participation in the problem-solving activity with the intent of finding a solution. Prior researchers have defined discussion engagement at the endpoints of the spectrum – high discussion engagement as co-construction of knowledge (Hausmann et al., 2004), and low discussion engagement as individual self-directed explaining (Chi et al., 1989). Analysis was performed to evaluate the contribution of discussion engagement to reach a consensus on ideas or concepts within the collaborative problem-solving process that occurred on each topic activity. The following subsections illustrate the specifics of students and the instructor behaviors during the collaborative problem-solving process within the iVisit-Collaborate platform with descriptions from the corpus of data.

6.1.1. *Student behaviors to collaboratively solve problems*

The students' behaviors coding helped to understand typical behaviors during the assessment modules. Aggregated frequencies for each coded student behavior within each collaborative problem-solving activity offer a detailed depiction of how collaborative problem-solving occurred across student dyads. Common student behaviors during the problem-solving process can be observed in Tables 2 and 3, highlighting behaviors that supported students to complete particular problem-solving steps. Following is a description of the collaborative problem-solving student behaviors for the masonry and wood topics with illustrative examples for how this process generally occurred.

Masonry Topic: Table 2 illustrates the student behaviors during the collaborative problem-solving process through aggregated frequencies of the masonry topic. Initially, students focused on exploring their environments to understand the problem requirements (Step 1 – Exploration Frequency = 7; and Step 2 – Exploration Frequency = 12). Next, visual inspection of the surrounding location was

Table 2
Student collaborative problem-solving occurrences in the masonry topic.

	Exploration	Pointing	CMU Length	CMU Height	CMU Width	Shared Mental Model	Joint Concept Assembly
Step 1 - Understand the requirements of the problem	7	5	1	1	0	2	2
Step 2- Identify the intersection of CMU and clay bricks	12	14	4	4	1	1	1
Step 3 - Recognize the length of clay brick based on CMU block	8	29	10	1	1	4	3
Step 4 - Recognize the height of clay brick based on CMU block	9	26	1	7	2	5	7
Step 5 - Identify clay brick from spec sheet list	4	4	9	4	2	11	8

Table 3
Student collaborative problem-solving occurrences in the wood topic.

	Exploration	Pointing	Load-Bearing Walls	Intermediate Wall	Jack Studs	Cripple Studs	Shared Mental Model	Joint Concept Assembly
Step 1 - Understand the requirements of the problem	5	5	0	0	0	0	2	0
Step 2- Identify the intermediate load-bearing wall	42	87	15	10	0	3	8	3
Step 3 - Identify the wall openings	5	14	0	0	0	0	2	1
Step 4 - Recognize the jack studs in the wall	1	27	0	0	14	0	8	3
Step 5 - Recognize the cripple studs in the wall	0	25	0	0	0	11	3	3

performed individually by each student to recognize the information contained in the virtual environment. Finally, students leveraged this understanding of the environment to comparatively assess the dimensions of clay bricks from the observed concrete block's size. This comparison was grounded in previously obtained domain knowledge from the training module, recalling the concrete masonry unit (CMU) dimensions – length (Step 2 – CMU Length Frequency = 4; and Step 3 – CMU Length Frequency = 10), height (Step 2 – CMU Height Frequency = 4; and Step 4 – CMU Height Frequency = 10), and width (Step 4 – CMU Width Frequency = 2). The pointing mechanisms within iVisit-Collaborate assisted in communicating the recalled ideas across the overall problem-solving process (Steps 2, 3, and 4 – Pointing Frequency = 14, 29, and 26). For example, one student dyad used the pointing mechanism to explain CMU size at the intersection with the bricks by saying:

(Participant 1): "uh-hm, do you remember the dimension of a CMU?"

(Participant 2): "mmmm"

(Participant 1): [Points at the intersection of clay and CMU bricks] "We should try to match it [the clay brick] with the CMU … to see if it is around the same size."

(Participant 2): "I think it's 15 and 5/8 and 7 by 5/8 [points at CMU]."

(Participant 1): "7 by 5/8?"

(Participant 2): "yes, if you are talking about CMU … "

(Participant 1): "if that is the size of the CMU, which gets to the edge, would it be the same size of the brick?"

(Participant 2): "you mean, right here?" [points at intersection]

(Participant 1): "yes, that is what I'm thinking."

(Participant 2): "yes, that makes sense."

As the students iteratively refined their understanding of the environment and their domain knowledge, the specification sheet was increasingly used to discuss their observations. Ultimately, the student discussions led to a shared mental model or a joint assembly of concepts to define a problem solution (Step 4 – Shared Mental Model Frequency = 5 and Joint Concept Assembly Frequency = 7; and Step 5 – Shared Mental Model Frequency = 11 and Joint Concept Assembly Frequency = 8).

Wood Topic: Table 3 shows the student behaviors during the wood topic collaborative problem-solving process through aggregated frequencies. Initially, each student concentrated on exploring the virtual environment to understand the problem requirements (Steps 1 and 2 – Exploration Frequency = 5, and 42). This was particularly important to identify the wall indicated by the problem, relating the concepts of load-bearing and intermediate walls (Step 2 – Load-Bearing Wall Frequency = 15 and Intermediate Wall Frequency = 10). During the wall selection, students demonstrated the recall of concepts, supporting the generation of a shared mental model (Steps 2 – Shared Mental Model Frequency = 8). The pointing mechanisms assisted student interactions while discussing ideas in this early step of the collaborative problem-solving process (Step 2 – Pointing Frequency = 87). Students used the pointer while expressing thoughts aloud to indicate the location of the wall, saying things such as *"… the truss is sitting on the end of it … and on this [other] one is like, at the very like center of it, so it is intermediate" [uses the pointer to highlight a particular wall]*. Once the wall was identified, pointing continued to assist students in the tasks but exploration was no longer observed (Steps 3, 4, and 5 – Pointing Frequency = 14, 27, and 25). The students iteratively discussed the elements in the wall referring to their domain knowledge, which resulted in a common definition of the jack and cripple stud concepts (Step 4 – Jack Stud Frequency = 14; and Step 5 – Cripple Stud Frequency = 11). For example, one student dyad focused on their prior knowledge of wall studs to identify them in location by saying:

(Participant 2): "uh … yeah, these are cripple studs … " [points at the cripple stud]

(Participant 1) "yeah, these three cripple studs … so there are two doors … so that is six cripple studs … and then these …" [points at the studs] "… that run up to the top of the door are the jack studs."

(Participant 2): “uh-hm"

(Participant 1): “so … I would say that there is four jack studs and six cripple studs."

(Participant 2): “I agree … "

Ultimately, these discussions led to the generation and assembly of concepts for these definitions or creating a shared mental model of the problem solution (Step 4 – Shared Mental Model Frequency = 8 and Joint Concept Assembly Frequency = 3; and Step 5 – Shared Mental Model Frequency = 3 and Joint Concept Assembly Frequency = 3).

These behaviors observed across the masonry and wood topics suggest that student collaboration did not occur directly but required problem-solving to precede collaborative behaviors. For example, most students in the masonry topic needed to individually gain a correct understanding of the problem and the environment before they could collaboratively associate the contextual information. Students examined the relationship between the clay bricks and the CMU block with their corresponding dimensions using prior knowledge before they could successfully collaborate to solve the problem. The shared mental model and joint concept assembly behaviors occurred in higher proportions after identifying the clay bricks and the CMU block information was achieved in the situated context. Similarly, this relationship between problem-solving and collaboration can be found in the wood topic. Students achieved the problem solution by relating their understanding of the wood framing techniques to the existing elements in the spatiotemporal context. The previously-obtained theoretical understanding of the wood framing techniques enabled the students to orient themselves within the spatiotemporal context to characterize the intermediate load-bearing wall. The formation of shared mental models and joint concept assembly occurred after students recognized the information in the environment. These examples point to a ranked association between problem-solving and collaboration, where problem-solving behaviors must initially occur for collaboration behaviors to occur. These findings are consistent with the construction-discipline Spatial-Temporal Cognitive Ability (STCA) model by Mutis (2018), chap. 2, requiring a combination of student spatial and temporal observations in addition to domain knowledge to build a common representational vehicle that fosters solution making. Furthermore, the findings are also consistent with prior research in computer-supported collaborative problem-solving that points to independent Cognitive and Social skills requirements to complete activities like the ones completed by students in iVisit-Collaborate (e.g., Hesse et al., 2015; Care et al., 2016; Graesser et al., 2018). Cognitive skills address the individual nature of problem-solving to create an internal mental model for managing the problem (Hesse et al., 2015), as observed in problem-solving behaviors for iVisit-Collaborate. Social skills focus on the management requirements to formulate or build a shared understanding of the problem (Hesse et al., 2015), similar to the observed collaboration skills detected in iVisit-Collaborate. However, this research diverges from Mutis (2018), chap. 2 in the construction-discipline literature by proposing problem-solving behaviors must first occur before any collaboration starts between members of small teams. This divergence can be explained by the mechanism embedded into iVisit-Collaborate for performing the activities, that required students a cognitive understanding of the spatial-temporal setting to commence the social information sharing.

Within iVisit-Collaborate, the pointer affordance provided a key mechanism that supported student collaborative problem-solving. As observed in Tables 2 and 3, the pointer directly influenced how students communicated observations in the environment. Often students would provide statements such as “over here”, “this”, and “that” accompanied by the pointer to express a thought. These thoughts could either be reflexive – intending to present a general thought without an end receiver – or could be directive – intending to be responded to by a peer or the instructor. Consequently, the pointer contributed to both problem-solving (reflexive thoughts) and collaboration (directive thoughts).

6.1.2. *Instructor scaffolding behaviors to facilitate collaborative problem-solving*

The instructor scaffolding behaviors were also coded using the criteria previously established for the analysis of commonalities. Aggregated frequencies offer an illustration of how the instructor supported the students throughout the collaborative problem-solving process. Common scaffolding behaviors can be observed in Tables 4 and 5. Following is a description of the instructor scaffolding used to support the masonry and wood topic activities with examples for how the scaffolding occurred.

Masonry Topic: Table 4 illustrates the aggregated frequencies for instructor behaviors in the masonry topic. Initially, the instructor focused on questioning the student’s exploratory approaches to solving the problem and explained the ambiguous information to the students (Step 1 – Questioning Frequency = 29 and Explaining Frequency = 23). For example, the instructor questioned the students that indicated that they should start looking at the spec sheet to find the CMU by saying: *“so … in that case … how that [the spec sheet] might help?“*. In another example, the instructor explained that “you can assume that CMU units are standard size”, because that information could not be inferred directly from the virtual environment. Subsequently, the instructor continued to question the students as they incrementally advanced the problem, asking for clarification on vague responses (Steps 2, 3, 4, and 5 – Questioning Frequency = 16, 22, 20, and 47). Hinting that supported the advancement of the problem-solving process was incrementally found on later steps

Table 4
Instructor scaffolding behavior occurrences in the masonry topic.

	Questioning	Hinting	Explaining	Instructing
Step 1 - Understand the requirements of the problem	29	0	23	0
Step 2- Identify the intersection of CMU block and clay bricks	16	6	7	1
Step 3 - Recognize the length of clay brick based on CMU block	22	8	4	0
Step 4 - Recognize the height of clay brick based on CMU block	20	15	1	2
Step 5 - Identify clay brick from spec sheet list	47	18	6	1

Table 5
Instructor scaffolding behaviors occurrences in the wood topic.

	Questioning	Hinting	Explaining	Instructing
Step 1 - Understand the requirements of the problem	27	1	4	0
Step 2 - Identify the intermediate load-bearing wall	78	73	47	23
Step 3 - Identify the wall openings	6	1	11	0
Step 4 - Recognize the jack studs in the wall	17	2	3	0
Step 5 - Recognize the cripple studs in the wall	21	0	1	0

of the problem (Steps 2, 3, 4, and 5 – Hinting Frequency = 6, 8, 15, and 18). Hinting prompted the students to recall information by asking questions such as *"what are the typical dimensions of a CMU block?"*. Instructions that offered clear directions on how to solve the problem were infrequent (e.g., *"Could you find the intersection between the CMU and the clay bricks somewhere?..*") but mainly present in the final steps of the problem (Steps 4 and 5 – Instructing Frequency = 2 and 1).

Wood Topic: Table 5 illustrates the aggregated frequencies for instructor behaviors in the wood topic. At first, the instructor focused on questioning the student's understanding of the problem as they had to identify one of the walls within their environment (Steps 1 and 2 – Questioning Frequency = 27 and 78). For example, the instructor elicited the students' thoughts by asking if they had *"any ideas of which wall is it? … I mean, what are the characteristics that he [the virtual human] described about the specific wall we are looking for?"*. The identification of the wall required highly scaffolded instructor behavior for hinting and explaining. As students iteratively discussed potential options for the wall of the study, the instructor supported their discussions with suggestions (e.g., *"what are the characteristics of the wall that he [the virtual human] is mentioning? … he said that it was load-bearing … intermediate wall … so, how would you use that to your advantage?"*) or by providing explanations that elucidated objects with ambiguous significance on the environment (e.g., "that particular wall has double top plating although it might be hard to see in the image") (Step 2 – Hinting Frequency = 73 and Explaining Frequency = 47). Some students were unable to use the questioning, hinting, or explaining scaffolds to identify the wall; thus, the instructor resorted to providing direct instruction on where to look and what concepts to recall for identifying the wall (Step 2 – Instructing Frequency = 23). For example, after the student declared that they did not know which wall was intermediate, the instructor said, "if you look at your right side …. that one is the intermediate load-bearing wall … as you can see it because it's in the midpoint between the endpoints of load-bearing walls … also, they are load-bearing because of the double top plate". Once the students identified the wall with the stated characteristics, the instructor continued to use questioning scaffolds to support student clarification of vague responses (Steps 3, 4, and 5 – Questioning Frequency = 6, 17, and 21). Instructor explaining behaviors were present in wall opening identification (Step 3 – Explaining Frequency = 11) since its location was in an area of the virtual environment that was difficult to observe. Finally, such scaffolding behaviors (hinting, explaining, and instructing) faded towards the later steps of the problem.

For both masonry and wood topics, the scaffolding provided by the instructor helped support the learning by narrowing the problem space presented to the students. During the initial problem steps, the information examined by students was not necessarily related to the problem, diverting the advancement of the problem due to the proposal of inviable solutions. For example, in the masonry topic, the instructor had to intervene with hints and explanation behaviors to elaborate on ambiguous information. During the student's discussions, many distractors in the virtual environments prompted the student to discuss unrelated information or explore inviable solutions. In response to student distractions, the instructor had to provide some insights on vague answers to keep the discussion grounded in the information available to solve the problem. Similarly, the wood topic instructor had to intervene on multiple occasions to question students' selections. The instructor had to use hinting and explanation behaviors during the identification of the wall in response to the introduction of unrelated ideas by the students. This instructor scaffolding behavior is consistent with Van de Pol et al. (2010) findings, delivering effective scaffolds to support the students' cognitive activities. The instructor scaffolds reduced the degrees of freedom in a problem-solving activity while maintaining a consistent cognitive structure of the problem.

6.1.3. Student discussion engagement within each dyad

Each student dyad was examined to find collaboration patterns in terms of discussion engagement. Within the collaborative problem-solving process, the number of steps required by each student dyad to solve the problem and the number of utterances performed by each student in the dyad were analyzed. Discussion engagement was quantified by the proportionality of utterances between students for a problem-solving process. This proportionality of utterances or delta utterance parameter represents the absolute value of the difference of utterances per student, divided by the total number of utterances for the given dyad. For example, in a particular dyad where student #1 contributed 23 utterances and student #2 contributed 26 utterances, the delta utterances would be 6%; that is $|(23–26)/(23 + 26)| * 100 = 6\%$. This delta utterance ranged from zero percent difference (both students performed an equal number of utterances) to one-hundred percent difference (only one student performed utterances). This parameter was represented as a delta to remove the verbosity variability from dyad to dyad. A correlation analysis was performed between the sum of steps and the delta of utterances using a Spearman rank correlation test. Appendix B Figures B1 through B8 contain detailed collaboration excerpts and descriptions of the discussion engagement during the assessment activities for each topic.

6.1.3.1. Discussion engagement during the masonry topic. Table 6 shows the outcomes of the dyad analysis for the masonry topic. An inversely proportional strong correlation (Akoglu, 2018) was found between the number of steps required to solve the problem and the difference of utterances (coeff = - 0.59, $p < 0.05$, p value = 0.027). This relationship provides insights regarding the level of discussion engagement between students while collaboratively solving the problem – as the number of steps to solve the problem increases, the difference in utterances decreases.

In the high discussion engagement example (Dyad #4 – Figures B1 & B2 in Appendix B), both students contributed to the discussion with a very similar number of utterances. Table 6 also illustrates the interactive nature of the discussion by illustrating the number of times each step was revisited. The high discussion engagement enabled the students to rapidly iterate solution approaches, discover new information, and validate their thoughts and ideas with each other. These benefits from discussion engagement potentially impacted the construction of a shared mental model during the collaborative problem-solving process. In the high collaboration example, the students rapidly iterated through the problem steps to find the brick dimensions. Constant interaction also potentially impacted the way these students maintain a shared mental model, as they agreed on the ideas that were common among them. On the other hand, in the low collaboration example (Dyad #8 – Figure B3 & B4 in Appendix B), only one student led the discussion while performing a large percentage of the utterances. The low discussion engagement resulted in a linear process to reach a solution, reducing the opportunities for students to evaluate all possibilities within the problem space available to them. The low discussion engagement can also be observed in Table 6 by noting that none of the problem steps were revisited during the discussion.

6.1.3.2. Discussion engagement during the wood topic. Each student dyad during the wood topic was examined to discover relationships and patterns. Table 7 shows the number of steps each student dyad required to solve the problem and their corresponding number of utterances. A correlation analysis was performed between the sum of steps and the delta utterances using a Spearman rank correlation test. For the wood topic, no correlation was found between the number of steps required to solve the problem and the difference in utterances (coeff = 0.12, $p > 0.05$, p value = 0.69). Although no correlation was found in this topic, two examples were identified for high and low discussion engagement based on the highest and lowest delta utterances observed (dyads #3 and #5). Both of these selected examples presented an equal number of problem-solving steps but with a widely different proportion of student discussion.

In the high discussion engagement example (Dyad #3 – Figures B5 & B6 in Appendix B), students performed some iteration of the solution approaches and validated their thoughts. Discussion engagement might have impacted the construction of a shared mental model. In the initial steps of the collaboration, both students were engaged while exploring potential ways of identifying the wall, showing a shared mental model. However, in the later steps of the problem-solving process, students suddenly stopped participating in the discussion. The low engagement can be observed in Table 7, with the low number of problem steps revisited across the activity (Steps 4 & 5). The disengagement in discussion could potentially be associated with the lack of direct utterances for recalling the jack and cripple stud concepts from either of the students. Consequently, an interruption of the shared mental model happened towards the end of the problem-solving tasks. In the low discussion engagement example (Dyad #5 – Figures B7 & B8 in Appendix B), this interruption in discussion engagement occurred at the start of the collaboration. Students did not actively engage in discussion, leading to a single student performing all the utterances. The lack of discussion engagement can be observed in Table 7, with the low number of problem step iterations from the beginning of the activity. The interruptions in discussion engagement in both examples highlight the need for maintained interaction between students to support the mutual understanding of the spatiotemporal context. In both examples, students had some utterance exchange, but it did not result in active discussion engagement through all the problem steps. Therefore, collaborative problem-solving became linear as only one perspective of how to solve the problem was voiced. These results are consistent with the existing literature for collaborative problem-solving that emphasizes the importance of peer interactions in a problem-solving process (Kwon et al., 2019) and the quality of those interactions to successfully accomplish the collaborative tasks (Wilczenski et al., 2001).

Table 6
Masonry topic discussion engagement assessment.

Dyad #	Number of Steps (Count)					∑ Steps	Number of Utterances (Count)		Δ Utterances
	Step 1	Step 2	Step 3	Step 4	Step 5		Student 1	Student 2	
1	1	1	1	1	4	8	25	12	35%
2	1	1	1	2	2	7	7	14	33%
3	2	1	2	1	2	8	9	17	31%
4	1	1	3	2	2	9	23	26	6%*
5	1	1	2	1	3	8	16	4	60%
6	1	2	2	2	3	10	19	15	12%
7	1	1	2	1	2	7	11	24	37%
8	1	1	1	1	1	5	13	2	73%**
9	2	3	1	1	2	9	21	18	8%
10	1	1	1	1	2	6	14	18	13%
11	1	1	1	1	2	6	6	18	50%
12	1	1	1	1	2	6	20	12	25%
13	1	1	1	2	3	8	21	15	17%
14	1	1	2	2	1	7	29	10	49%

* Lowest Δ Utterance – High Discussion Engagement Example; ** Highest Δ Utterance – Low Discussion Engagement Example.

Table 7
Wood topic discussion engagement assessment.

Dyad	Number of Steps (Count)					∑ Steps	Number of Utterances (Count)		Δ Utterance
	Step 1	Step 2	Step 3	Step 4	Step 5		Student 1	Student 2	
1	2	1	1	1	1	6	20	22	5%
2	2	1	1	2	1	7	16	18	6%
3	2	2	1	1	1	7	27	25	4%*
4	2	1	2	3	3	11	29	26	5%
5	1	1	1	2	2	7	27	3	80%**
6	2	1	1	2	2	8	12	9	14%
7	1	1	1	2	1	6	21	26	11%
8	1	1	1	4	4	11	15	24	23%
9	1	1	2	1	3	8	13	25	32%
10	2	4	1	7	5	19	34	44	13%
11	2	1	1	2	2	8	9	22	42%
12	3	2	2	5	3	15	32	28	7%
13	2	1	1	2	2	8	11	25	39%
14	2	1	1	3	2	9	22	40	29%

* Lowest Δ Utterance – High Discussion Engagement Example; ** Highest Δ Utterance – Low Discussion Engagement Example.

7. Research limitations

Due to the phenomenological design of this study, the collected data cannot be used to provide statistical generalizations. In phenomenological studies, the intent is to explore the participant experiences to understand the variables that influence the investigated phenomena. This generates a trade-off between the generalizability of findings and the discovery of important variables. For iVisit-Collaborate, the emphasis was placed on discovering important variables since this is the first study that investigates collaborative problem-solving within 360-degree panoramic environments. Moreover, the granularity or scope of the units of analysis selected for the verbal analysis might have influenced the observations reported in this study. The selection of the units of analysis directly affects the sensitivity of the data and the resulting analysis (Chi, 1997). In this study, granularity was based on the theoretical understanding of the generated problems for the iVisit-Collaborate platform. However, it is possible that a finer grain of units of analysis could have resulted in identifying additional insights for the collaborative problem-solving behaviors. It is also important to highlight due to think-aloud methodology selected within this study, no differentiation was made between individual thoughts and thoughts directed to a partner as both were vocalized and influenced how the collaborative problem-solving process occurred. Futures studies that utilize such technique should investigate the interaction effects between think-aloud protocols and collaborative problem-solving tasks. Finally, the delivery of instructor scaffolding was intended to be consistent across all students and activities. No fading scaffold strategies were designed for this study. The instructor's utilization of purposely fading scaffolding strategies could have revealed other interesting aspects of collaborative problem-solving activities.

Considering the technological challenges, the 360-degree panoramas had limitations in terms of image quality. Existing commercially available 360-degree cameras are not equivalent to those used for traditional photography or videography, producing image resolutions that are perceived as inferior by users (Eiris et al., 2018b). Additionally, 360-degree panoramic environments restrict the user to only three degrees of freedom, limiting the user exploration of the environment exclusively to a visual rotation, removing the possibility of translation in space. Furthermore, the iVisit-Collaborate platform was utilized on traditional computer monitor-mouse-keyboard for this exploratory study. This selection was made to enable students' participation through online delivery methods. Other devices that provide a higher level of immersion and presence, such as head-mounted displays (HMDs) or cave automatic virtual environment (CAVE) systems, might lead to different outcomes. Ultimately, the online delivery method presented limitations in terms of consistency in the devices used by the participants (e.g., screen resolution, size, refresh rate), as each participant used their personal device to participate in the study.

Although iVisit-Collaborate supported collaborative problem-solving, the observations performed in this study reveal affordance limitations to further assist student learning. Real-world mental models that used physical interactions would become inadequate within iVisit-Collaborate. For example, a common theme observed in the masonry topic was the failure of traditional measurement mechanisms. Many students proposed to measure the brick using a tape measure, a typical action that can be performed in the real-world. However, this was not possible within iVisit-Collaborate due to the technological limitations of 360-degree panorama environments. Another area where traditional mental models were inadequate was in student access to previous learning information. In the real world, students have access to annotations and diagrams that support their knowledge domain while observing environments. During the wood topic, some students asked whether they could access the previously presented diagrams of the wall framing. iVisit-Collaborate did not support access to previously observed learning information. Although student sampling was controlled for academic experience, outside of class experiences were not controlled for, which might have impacted student behaviors due to their prior knowledge. Further study is necessary to understand students' out-of-class experiences and their effects on problem-solving mechanisms to further enhance iVisit-Collaborate digital environments. Ultimately, iVisit-Collaborate was only available for students for a 1-h period before performing the collaborative problem-solving activity. Because collaborative problem-solving skills develop over time, the behaviors observed in this study might vary as students have extend periods of time to practice using iVisit-Collaborate.

8. Design implications for researchers and educators

The results from iVisit-Collaborate presented in the study highlight three areas where researchers and educators must concentrate on developing similar experiences that support collaborative problem-solving behaviors in students: (1) virtual site visit design, (2) platform interactions, (3) instructional scaffolding. Following are details for each of these design implications observed through this investigation:

1. The design of the virtual sites must be intentionally connected to the student learning objectives. Each 360-degree image content, the virtual human dialogs, and the digital augmentations must directly support the intended learning in the digital platform. Furthermore, the collaborative problem-solving activities within the platform should provide adequate visual cues (e.g., masonry block and clay brick intersection, door opening within the platform frame structure) in the virtually situated location for students to connect the knowledge obtained within the site visit with the assessment tasks. Consequently, it is crucial to plan these learning requirements before capturing the real-world construction sites. It is highly encouraged to communicate these learning requirements with the practicing professionals (e.g., project managers, superintends, field engineers) on-site to identify the ideal locations to capture them and plan for accessing those locations.
2. The collaboration interactions provided for the students to solve a problem within the virtual platform should be purposefully designed to support cognitive (problem-solving) and social (collaboration) skills. For example, within iVisit, the pointer was identified as a beneficial method to offer students a method to externalize their thoughts and communicate that information with their peers. These properties of the pointer affordance enabled student discussion engagement to support the rapidly iterative solution approaches and discover new information. However, researchers and educators should explore other collaboration mechanisms that support real-world mental models, such as offering methods to measure objects within the digital space or revisit previous information shown by the augmentations or the virtual human.
3. Instructional scaffolds should be explicitly designed to reduce the degrees of freedom in a problem-solving activity within a virtual platform. Ideally, this degree of freedom reduction can be embedded into the platforms similar to iVisit-Collaborate by carefully designing the virtual humans as scaffolding delivery mechanisms. For this study, the virtual human only delivered a verbal explanation of the problem, but future research can use it to offer questioning, hinting, explaining, instructing behaviors similar to the ones used by the instructor in iVisit-Collaborate. Finally, future research and educators might consider automating these processes by using natural processing language systems that can adapt to student questions and responses similar to prior works presented by Eiris and Gheisari (2018-a).

9. Conclusion and future work

This study aimed to provide an understanding of student behaviors within iVisit-Collaborate, supporting the learning of collaborative problem-solving in a contextualized construction setting. An exploratory phenomenological study was designed to gather evidence of student and instructor behavior outcomes during masonry and wood topic intervention processes in a construction techniques class setting. A verbal analysis technique was used to develop a codebook based on qualitative video recording data. Using the created codebook, collaborative problem-solving was evaluated based on the identified student and instructor behaviors. The findings of this research indicate that collaborative behaviors did not directly generate successful problem-solving. Evidence extracted from each activity topic suggests the existence of a hierarchical relationship between problem-solving and collaborative behaviors; thus, problem-solving behaviors occurred before the emergence of collaborative behaviors. It was also observed that instructor scaffolding for high collaboration dyads reduced the degrees of freedom in a problem-solving activity and maintained consistency in the cognitive structure of the problem. Ultimately, data also demonstrated that discussion engagement served as a conduit for students to rapidly iterate solution approaches, discover new information, and validate their thoughts and ideas.

Although this research demonstrated that iVisit-Collaborate supports student behaviors for learning collaborative problem-solving skills, several knowledge areas remain unexplored. Future researchers should evaluate the long-term effects of learning utilizing iVisit-Collaborate and other similar 360-degree panoramic site visit interventions. Often, graduates are required to solve problems collaboratively once they join the workforce. However, there is no evidence on how digital environments such as iVisit-Collaborate help students after they transition into real-world situations. Moreover, researchers should also compare iVisit-Collaborate interventions or other similar 360-degree panoramic site visit interventions with traditional learning approaches such as real-world site visits, laboratory activities, and in-class assignments. The comparative exploration of learning methods for collaborative problem-solving can help identify advantages and challenges for iVisit-Collaborate and other similar 360-degree panoramic site visit interventions. Moreover, the relationship between student discussion engagement and the creation of shared mental models needs to be further investigated. The study results suggest that discussion engagement might have some impact on the establishment of shared mental models, but the relationship between these two variables should be properly explored in future studies. Finally, the effect of different scaffolding strategies within digital intervention should be investigated in the future. In this study, the level and style of instructor scaffolding was maintained constant during the learning intervention. Other methods of instructor scaffolding (e.g., modeling, reflective, moving) should be explored to evaluate the most effective approach for digital interventions such as iVisit-Collaborate.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. 1821852. The research team would like to thank Kelvin Dover Jr. and James Sullivan from the University of Florida for their help with the technical development of the iVisit platform and the conceptualization of the educational interventions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2021.104365.

Credit author statement

Ricardo Eiris: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision; Wen Jing: Validation, Formal analysis, Investigation; Masoud Gheisari: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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