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Promoting collaborative learning in architectural engineering design through multi-user augmented reality

Yichen Li

Yichen Li is a second-year Ph.D. student at Worcester Polytechnic Institute. Her current research interests include immersive human-computer interaction within AR and VR environments.

Soroush Farzin

Shichao Liu

Promoting collaborative learning in architectural engineering design through multi-user augmented reality: a case study

Abstract

As a highly interdisciplinary industry, architecture, engineering, and construction (AEC) require effective and seamless collaboration to deliver projects timely and with high quality. To better prepare students with the demanding cooperative skill, collaborative learning has always been an integral part of the education of undergraduate students. Augmented reality (AR) technology has matured rapidly in recent years and has been widely used in various fields such as medical, manufacturing, entertainment, and education. The seamless combination of the real world and virtual environment is one of the most important characteristics of AR technology [1]. In this study, we utilized this characteristic to develop a multi-user design application in Microsoft HoloLens. The AR application enables students to participate in the collaborative architectural design by manipulating architectural objects in virtual environment as well as directly communicating with teammates in physical environment. The objective of the research is to enhance collaborative learning in architectural engineering design through multi-user AR. In order to test the feasibility of integrating the AR application into the traditional collaborative design process, we deployed an AR module based on the AR application into two architectural design studio courses including 19 participants as a preliminary case study. This paper reports the effectiveness of the AR module on students' active participation and engagement in collaboration, skills and knowledge gains, and the comfort level of collaborative design in AR. In addition, students' communication behaviors during collaborative design have been assessed by analyzing recorded videos of users' view in AR.

Background

Importance of Collaborative Learning in Architecture, Engineering, and Construction (AEC)

AEC is an interdisciplinary field that demands students to learn and work collaboratively, such as conceiving ideas from different perspectives, receiving and providing feedback to peers through smooth communication, synthesizing information, and making collective decisions. According to the Association of American Colleges and Universities (AAC&U), 71% of employers identified 'teamwork skills and the ability to collaborate with others in diverse group settings' as a learning outcome that necessitated increased emphasis in college and university programs [2].

However, the demanding skills of teamwork and collaboration can pose a certain level of challenge in the learning and teaching in AEC. Vassigh et al. [3] summarized these challenges in three specific categories: *a) knowledge silos, b) critical thinking skills, and c) interpersonal and self-directional skills,* and then concluded that AR integrated building information modeling (BIM) can facilitate collaboration in AEC through an experiment observing student groups' learning process.

Why Augmented Reality?

Augmented reality (AR) is defined as a technology that supplements reality by rendering 3D virtual objects superimposed upon the real world [1], which has been evolving rapidly and is being adopted in numerous fields (e.g., education, healthcare, field service, design). As a transition between the real environment and virtual environment (Figure 1) [4], Augmented reality (AR) combines the advantages of reality and virtual reality. By sharing the same objects in the virtual environment, as well as seeing each other through the real-world environment, users can engage with each other as if there is no barrier of the headset [5], which brings the great potential of utilizing the technology within collaborative design.

Previous research has established that AR has great benefits to augment the teaching and learning environment [5][6], and has been applied in higher education settings to increase students' motivation [7]. A systematic review [8] on 42 studies concluded that AR can contribute to STEM education in four categories: "contribution to learner, educational outcomes, interaction, and other advantages (e.g., ease of use, reduction of costs and suitability of use in laboratory courses)." The benefits of interaction were manifested through increased interaction between students and course content [9], a sense of presence [10], and increased interaction among students [11].

Despite the great success of AR in STEM education, its advantages and benefits in collaborative learning and teaching, especially in the field of engineering design, can be further explored and leveraged. With the tangible interface metaphor, AR enables users to manipulate objects in the virtual environment in an intuitive manner as what they did in the real world [5], which reduces the cost of learning about how to use the application and makes seamless learning possible [12]. For example, Januszka and Moczulski [13] applied AR for aiding product design and development of machinery systems by presenting design prototypes in AR. Students using AR were able to find and place relevant points in construction sites more than 60% faster and with significantly less cognitive workload compared to when using paper plans [14]. Through case studies, Domínguez et al. [15] found that AR increased students' motivation levels and academic performance in the field of Architecture and Building Construction. Educators in building science found that their AR visualization tool had a positive impact and increased students' motivation and understanding of building science principles [16].

Even with the success of AR in numerous fields, most studies in AEC, to our best knowledge, employed AR on smartphones or tablets as a visualization tool for engineering design instead of allowing students/users to design directly in the immersive holographic AR environment (such as using HoloLens), especially in a collaborative manner. This might be attributed to the lack of a design platform. Mobile AR such as phones and tablets can offer a unique combination of market penetration and convenience. They are accessible to a large population. However, research found that mobile AR presents difficulties when users must perform select (or tap) functions due to hand jitter, limited field of view, object occlusion, and other factors [17]. These limitations can be alleviated with HoloLens that can display complex and holographic visualization and has hands-free control. The benefit of holographic AR is the stereoscopic and immersive display that cannot be created by material- or CAD-based models.

This paper presents our first efforts to improve collaborative learning in AEC through multi-user AR. In particular, the objective is to prove the validity of connected augmented reality in architectural engineering design to promote collaborative learning. To that end, a multi-user AR application was designed and developed in Microsoft HoloLens2 to allow students to design simultaneously in a common virtual platform. Then, the team developed an AR learning module based on the application and deployed it in two architectural engineering design courses.

Methods

System Design

The AR application was developed in Unity3D with MRTK 2.7 to implement HoloLens features. MRTK is a toolkit developed by Microsoft that provides a set of components to accelerate cross-platform Mixed Reality development in Unity3D. Figure 1 shows the user interface of the design application that consists of a *Menu, "LEGO" preview table,* and *DesignStation.* By defining the shape/size/color/rotation on the *Menu* bar, a customized "LEGO" block can be created and viewable on the *"LEGO" preview table*. The students can pick up and move the "LEGO" blocks from the *preview table* to the desired location on *DesignStation* using his/her hands. The base plane of the *DesignStation* is changeable by superimposing a Google map capture of a geographic site on it so that students can design with realistic site constraints including boundaries, neighborhood, transportation, etc.

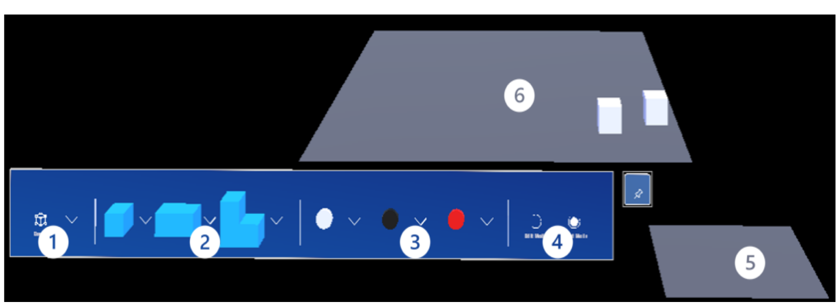

Figure 1. User interface and of the collaborative architectural design module.: Menu (①: preset models; ②: "LEGO" blocks; ③: Color palette; ④: Mode selection); ⑤: "LEGO" preview table; ⑥: DesignStation

The DesignStation can be "moved" at the users' desire, such as on the top of a physical table or floating in the air. The interface is identical and available for all the users, which provides equal opportunities for each user to directly manipulate the blocks/bricks such as color and shape selection, size change, and relocation. Equal access is the key to collaborative design since an idea can be evolved, critiqued, and developed collectively and smoothly.

Multi-user Implementation

Supported by Photon Unity Networking (PUN) and Microsoft Azure Spatial Anchor, multiple students can develop an architectural conceptual design including form, massing, and program simultaneously in the same virtual environment with very low latency.

Photon is a network framework for multi-player game development. Photon Unity Networking (PUN) is a flexible plugin built based on the Photon engine, which provides some interfaces that are simple and convenient to be integrated into the Unity3D project. Consisting of features such as a real-time cloud host and client-to-server service, Photon engine enables multiple users to interact with each other with low latency and high speed through the Internet [18]. Microsoft Azure Spatial Anchor is a cloud service that maps and restores virtual points at the real-world scale [19], which enables multiple users to view and manipulate the rendered virtual objects within the same physical context. Figure 2 shows how PUN and Microsoft Azure Spatial Anchor are integrated into this application. The user's manipulations with the virtual environment are synchronized through the PUN server while the 3D virtual objects are rendered based on the Azure Spatial Anchor.

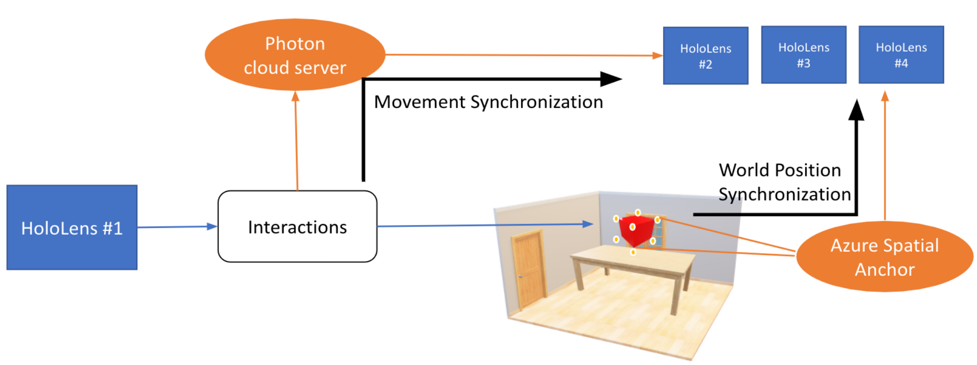

Figure 2. Multi-user AR implementation with Photon cloud server and Azure Spatial Anchor

Implementation in Course Curricula

To assess the effectiveness of the multi-user AR application, an AR design module was developed and implemented in two courses: *Architectural Design Studio I - Introduction to Design* and *Architectural Design Studio IV - Building Energy Simulation.* In each course, student groups were asked to use either AR or desktop/laptop to design a group project. The students using AR served as the "experiment group", while the others using desktop/laptop were assigned as the "control group."

In *Architectural Design Studio I*, students were asked to work in a group of three and use the application to develop a conceptual cube. The objective of the cube exercise was to encourage design thinking beyond the box but exploring within constraints (10 in × 10 in × 10 in). The form of the 'Cube' must be clearly evident through the actual bearing of its 8 corners, or the visual suggestion of corners. Non-linear elements were not allowed. Figure 3 shows a design session in AR in *Architectural Design Studio I* where students worked on the conceptual cube together. In *Architectural Design Studio IV*, three students in a group were asked to design a conceptual form and massing of a library for energy efficiency on an allocated site (e.g., Chicago) (Figure 4). Students had to consider site constraints, climate, and potential energy consumption related to the form shapes.

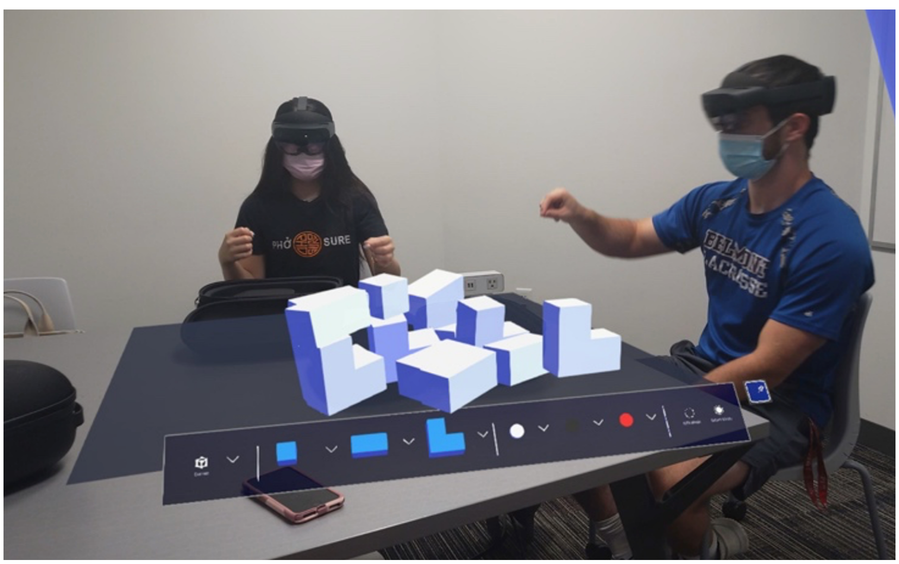

Figure 3. Students working collaboratively in the AR application in Architectural Design Studio I

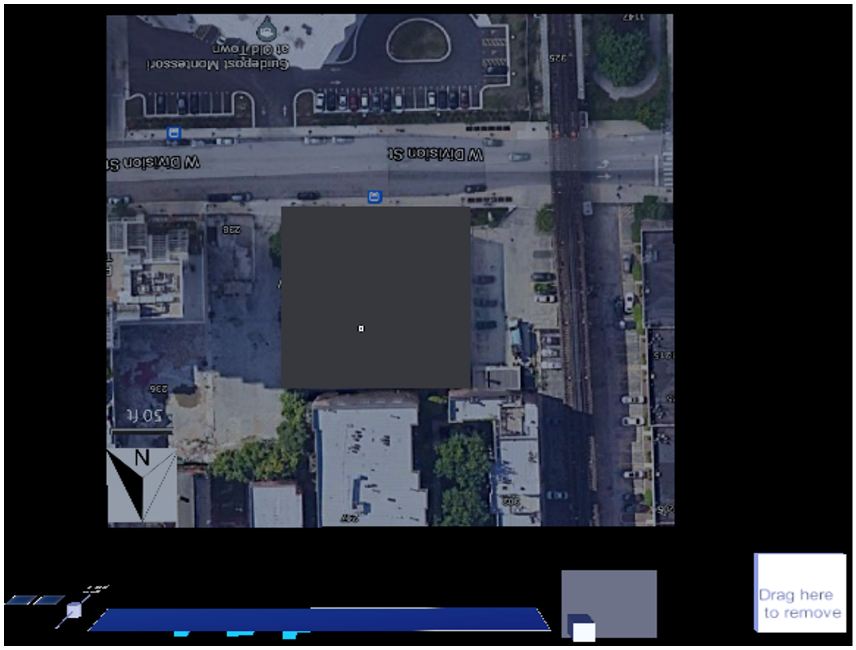

Figure 4. Superimpose Chicago Google Map to DesignStation plane in Architectural Design Studio IV

Assessment

The effectiveness of multi-user AR in enhancing collaborative learning is assessed through a survey at the end of course projects and students' communication behaviors by analyzing recorded user views of each AR design session.

The self-reported survey examines the following facets regarding *1) engagement and motivation, 2) learning gains*, and *3) attitudes and comfort levels*. We consulted with previous studies on the topic during the survey design [20][21][22][23][16]. The survey consists of 12 five-point Likert scale questions as described in Table 1.

Table 1. Student self-reported survey questions

Questions		Never	Sometimes	Usually	Regularly	Always
Teamwork is behaviors under control of the individual team members. In your experience in the class project, how often does your peer demonstrate the following?	Participates actively and accepts a fair share of the group work	1	2	3	4	5
	Gives timely, constructive feedback to team members, in the appropriate format	1	2	3	4	5
	Communicates actively and constructively Encourages all	1	2	3	4	5

	perspectives be considered and acknowledges contributions of others					
	Constructively builds on contributions of others and integrates own work with work of others	1	2	3	4	5
	Clarifies goals and plans the project reports to team on progress	1	2	3	4	5
	Ensures consistency between words, tone, facial expression and body language	1	2	3	4	5
Questions		No Gains	A Little Gain	Moderate Gain	Good Gain	Great Gain
As a result of your work in this Architectural Design class, what gains did you make in the following knowledge and skills?	Knowledge about the architectural design process	1	2	3	4	5
	Considerations for design, such as site analysis & zoning	1	2	3	4	5
Questions		No Gains	A Little Gain	Moderate Gain	Good Gain	Great Gain
As a result of your work in this Architectural Design class, what gains did you make in the following?	Enthusiasm for engineering	1	2	3	4	5
	Confidence that you understand the course material	1	2	3	4	5
	Your comfort level in working with complex ideas	1	2	3	4	5
	Willingness to seek help from others (professor, classmates, friends) when working on academic problems	1	2	3	4	5

As for students' communication behaviors during collaborative design, the authors manually reviewed all the recorded videos by HoloLens and evaluated communication dynamics by labeling the frequencies of certain design operations and behaviors, such as manipulating virtual bricks, making face-to-face contact, communicating with gestures or verbally.

The average length of the videos is about 20 min. We divided each one into 30-second time windows. Within each time window, we labeled the frequency of operations or behaviors into four levels based on the duration (x): always (20s < x <= 30s), often (10s < x<=20s), and sometimes (0 < x <= 10s), and none. Moreover, we evaluated the actual participation of each student in the collaborative work, including how many decisions they made and how much they contributed to the final work.

Results and Discussion

On a voluntary basis, 19 out of 21 students in *Architectural Design Studio I* participated in the study, while the sample size in *Architectural Design Studio IV* was 16 (out of 27). The data from the students in *Architectural Design Studio I* were not analyzed due to the lack of a "control group" because all students used AR in the project design. On the contrary, half students (8 students) chose to apply AR, while the other half (8 students) stuck to traditional design using desktops/laptops in *Architectural Design Studio IV*.

Figures 5-7 depict the distributions of survey responses and comparisons between the "control group" and "experiment group." The results show that the responses from AR groups have a larger variation among student participants than the control groups. Though statistical tests cannot be conducted due to the small sample size (N = 16 in total), the students in the AR groups generally experienced better collaborative learning, including more active participation and engagement in cooperation (Figure 5), higher knowledge gains in the architectural design process (Figure 6), and more positive attitudes in engineering learning in a group setting (Figure 7).

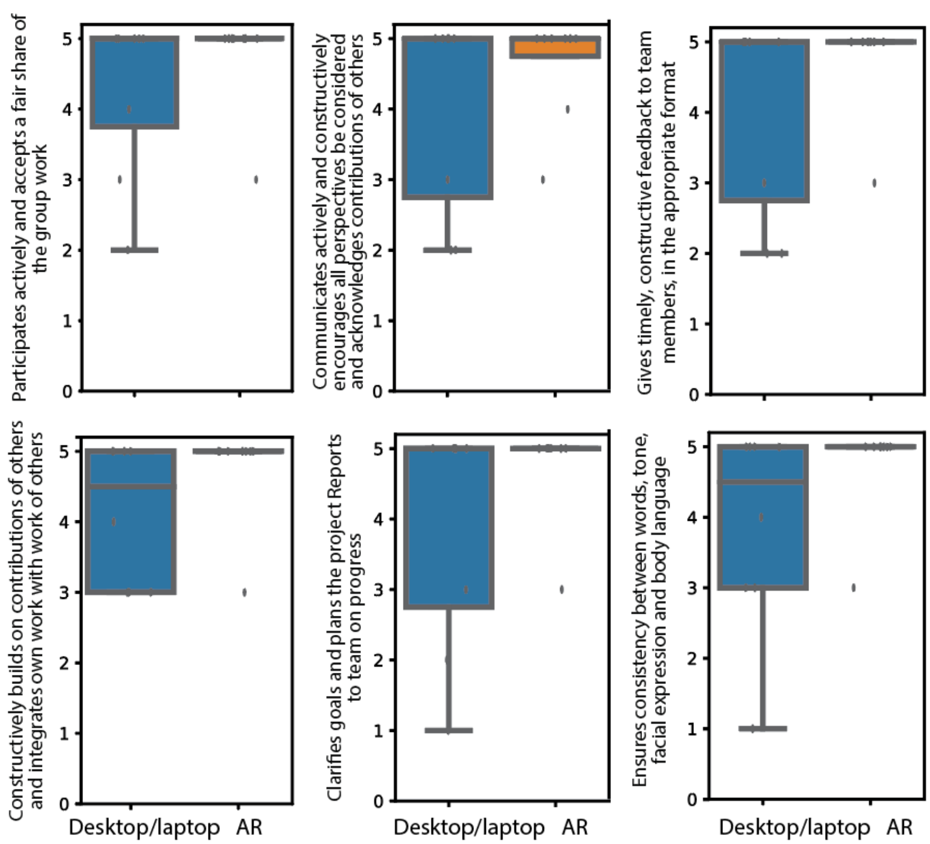

Figure 5. The frequency (1= Never; 5=Always) when student participants demonstrated active and effective collaborative learning; N= 8 for each group.

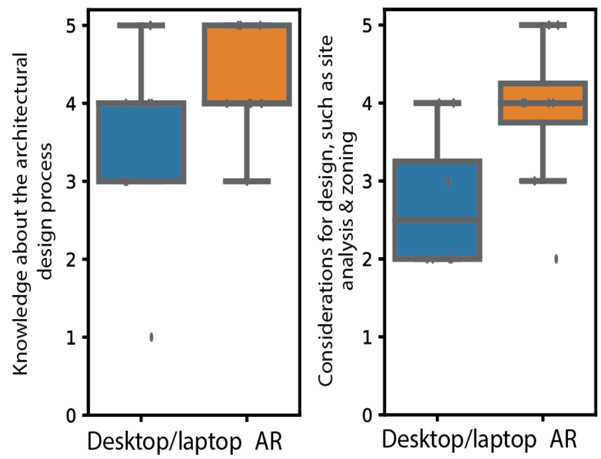

Figure 6. Knowledge gains of architectural design (1= No gains; 5 = Great gains); N= 8 for each group.

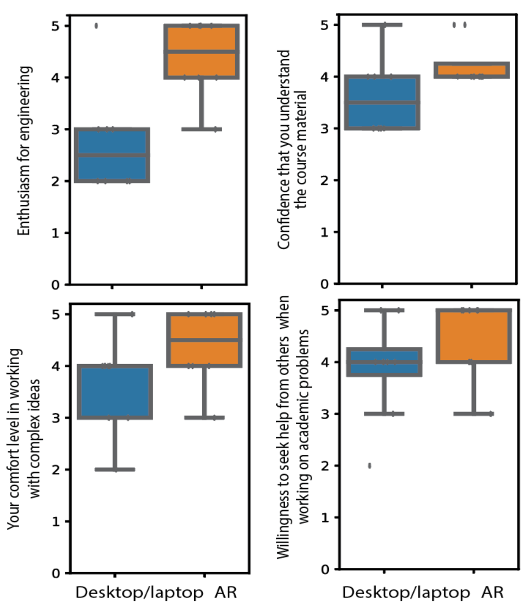

Figure 7. Attitudes and comfort level in engineering learning in a group setting (1= Much lower; 5 = Much higher); N= 8 for each group.

One common limitation of collaborative design using desktops/laptops is that some group members dominate the execution of the design process, while students with low efficacy might hesitate to express their thoughts. However, Figure 8 shows that students' operation frequencies of bricks were not greatly different among student members in each group, which implies that all students were actively engaged in the design process using multi-user AR.

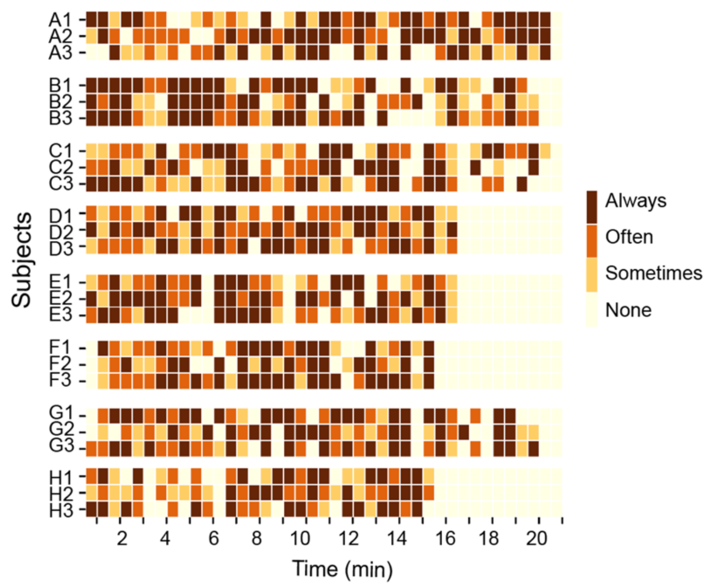

Figure 8. The frequency of students' operation on the bricks in the application in each 30 seconds block for the 8 groups. The participants (N =24) include students in two courses.

In addition, compared to the traditional collaboration mode where the group members are gathered around a computer and focus on the content on one screen, each student in the AR application can have a separate virtual view and face-to-face interaction in the physical environment with other students while designing. Therefore, the communication between the group members can be more dynamic and diverse, such as using face-to-face contact and gestures. The comparisons of the results in Figures 9, 10 and 11 indicate that verbal communication is still the most dominant approach to exchanging ideas, followed by face-to-face contact and gestures. Moreover, gesture communication did not occur frequently during the collaborative work (Figure 11). It might be attributed to the fact that gesture control is primarily used to interact with virtual objects in HoloLens. Nevertheless, virtual hand gestures augment gesture communication in AR. One student can see the virtual hands and fingers of another when interacting with virtual objects. This feature can increase the awareness of intention among the group members and therefore enhance communication efficiency.

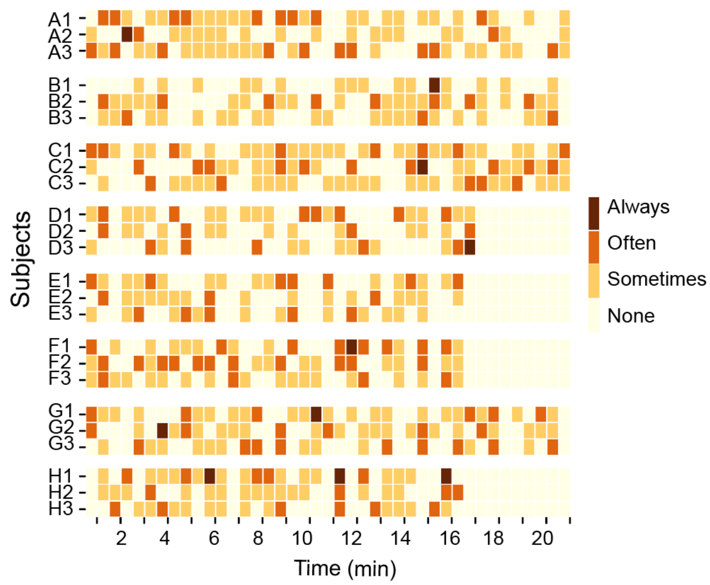

Figure 9. The frequency of students' verbal communication on the blocks in each 30 seconds block for the 8 groups; The participants (N =24) include students in two courses.

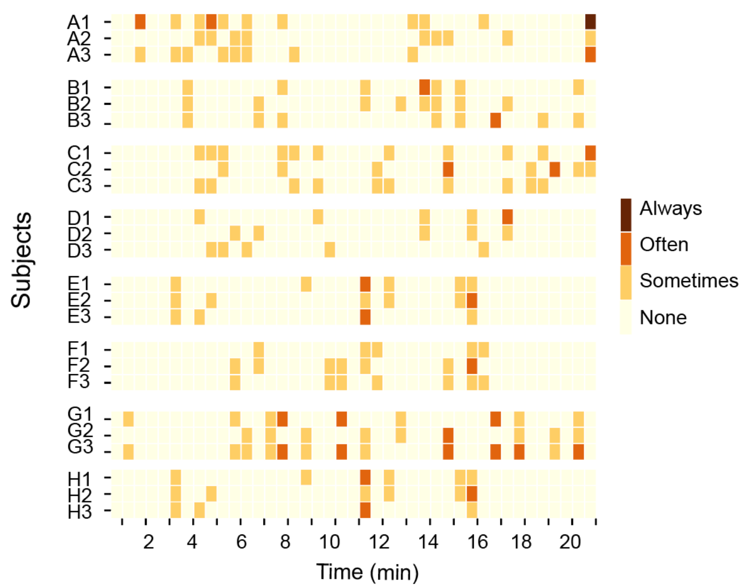

Figure 10. The frequency of students' face-to-face contact on the blocks in each 30 seconds block for the 8 groups; The participants (N =24) include students in two courses.

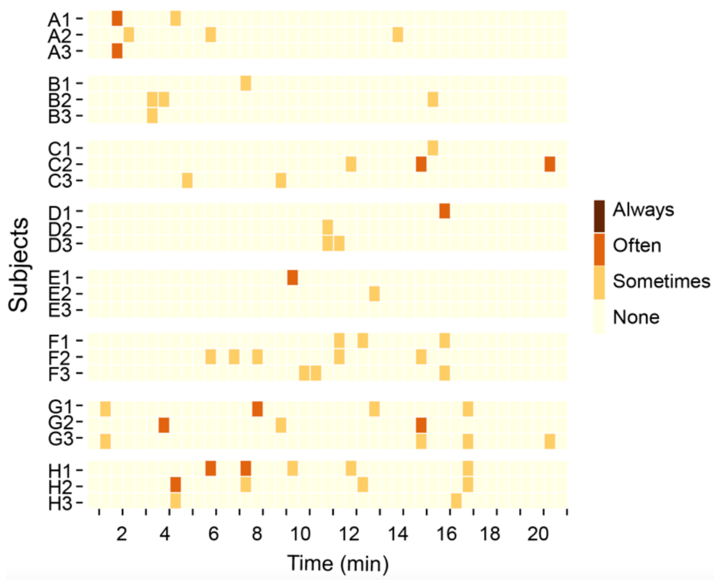

Figure 11. The frequency of students' communication with gestures on the blocks in each 30 seconds block for the 8 groups; The participants (N =24) include students in two courses.

Conclusion

This paper has discussed the validity of utilizing the multi-user AR application in Microsoft HoloLens to promote collaborative learning in architectural engineering design. Compared with traditional collaborative learning such as using desktops/laptops, students in the AR environment have more equal opportunities to design actively. After deploying the AR design module in two architectural design studio courses, we have found the positiveness of using multi-user AR in active participation and motivation, knowledge gains, and attitudes in collaborative design. In addition, the communication in AR among group members is mainly verbal and face-to-face contact. Students mainly applied gestures to control AR operation instead of communication. Nevertheless, real-time virtual hand gestures can increase the awareness of intention of other members and thus collaboration dynamics. The future study will involve more student participants with more design modules using the developed AR application.

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