EMPOWERING COLLABORATIVE LEARNING: INNOVATIVE INTEGRATION OF REAL-TIME COMMUNICATION INTO HOLOLENS-BASED LEARNING SYSTEM

Jiajia Guo, Kien Tsong Chau*, and Siti Nazleen Abdul Rabu

Centre for Instructional Technology & Multimedia,
Universiti Sains Malaysia, Penang, Malaysia

ABSTRACT

This study primarily aims to investigate the effectiveness of the HoloLens-based learning system, RTC-HoloLS, in enhancing collaborative learning skills in undergraduate photography courses. It provides empirical evidence showing how RTC-HoloLS addresses pedagogical challenges and improves collaborative learning outcomes, offering a holistic approach to photography education. Although Augmented Reality (AR) technology helps students theoretically understand camera operations in photography courses, it lacks in promoting collaborative learning skills during hands-on practice. To address this limitation, this study introduces the RTC-HoloLS, a HoloLens-based learning system with Real-Time Communication, and compares it to the conventional video streaming-based HoloLS (CVS-HoloLS). The results indicate that RTC-HoloLS significantly enhances collaborative learning skills compared to CVS-HoloLS, highlighting the importance of integrating Real-Time Communication technologies in AR learning environments. Additionally, RTC-HoloLS was equally effective for both male and female students, whereas CVS-HoloLS showed greater benefits for male students. This suggests the need to consider gender differences in design and development to ensure the learning system accommodates all students. The findings have significant implications for instructional technology design and implementation, suggesting that educational institutions should prioritize real-time communication features in AR learning tools to enhance collaboration and interaction.

KEYWORDS

Real-Time Communication, HoloLens, Augmented Reality, Collaborative Learning, Collaborative Learning Skills, Undergraduate Photography Courses

1. INTRODUCTION

With the advancement of instructional technology, immersive technologies are becoming increasingly prevalent in university education. In undergraduate photography courses, Augmented Reality (AR) technology is highly appreciated and widely adopted for its interactivity, real-time shareability, and prompt responsiveness [1]. AR technology significantly enhances students' visual experiences and understanding of theoretical principles in camera operation for photography courses. However, past studies indicate that AR technology is insufficient in promoting collaborative learning skills during hands-on practice. These AR-based learning systems often lack hands-on training with real cameras. They do not support multi-camera collaborative capture, which is crucial for providing diverse perspectives in camera photography [2]. They often fail to replicate the haptic and spatial interactions necessary for mastering camera movements [3], thus limiting their effectiveness in practical skill development.

DOI:10.5121/ijma.2024.16401

To address the limitations of AR technology in undergraduate photography courses, a special type of AR technology, the HoloLens-based learning system (HoloLS), has been developed for photography majors in Chinese universities. HoloLS combines virtual objects with real-world elements (Figure 1). Unlike traditional AR learning systems, HoloLS offers an additional degree of immersive experience, allowing learners to interact with virtual objects in real time while seamlessly linking to real objects [4][5]. The University of Technology Sydney's "SCENECAM" system demonstrates the potential of HoloLS to enhance remote collaboration and learning outcomes [6]. By providing an augmented overlay of virtual instructions and real-world practice, HoloLS bridges the gap between theoretical knowledge and real-world practices, making it a more effective tool for integrated learning experiences.

Figure 1. HoloLens-based learning system

While HoloLS shows significant potential for improving collaborative skills in undergraduate photography courses, it is still in the developmental stage and requires further improvements and optimizations to address specific challenges. One of the most prominent challenges is the quality of connectivity between devices [7]. Specifically, frequent delays occur in the real-time transmission of audio and video information between learners' devices. Prompt responses are necessary for effective online communication and behavior sharing during collaborative learning. Otherwise, negative emotions such as misunderstanding, confusion, isolation, frustration, helplessness, and anxiety may arise [8], consequently affecting learning outcomes. This issue has motivated research into HoloLS, which incorporates robust networking technologies, specifically RTC streaming, to enhance the reliability and responsiveness of real-time communication in collaborative learning.

2. PROBLEM STATEMENT

Conventional video streaming typically relies on prerecorded content. Processing and rendering streaming content require high-performance computational resources. Consequently, conventional video streaming often leads to delays that adversely affect remote collaboration [9]. As a result, students are unable to effectively share their visual perspectives with peers and observe each other's shooting environments and actions in real time. Additionally, camera-captured video streaming data may be ineffective in low-light or complex environments, further impacting the learning experience [10]. Integrating Real-Time Communication (RTC) mechanisms with HoloLS can address these video streaming drawbacks. RTC minimizes the latency of information exchange, creating a more reliable learning environment. This integration enhances students' ability to interact in real time, enabling immediate feedback and adjustments, which are critical for developing collaborative skills in dynamic educational environments [11]. Given its potential benefits and current research gaps, this paper explores HoloLS integrated with Real-Time Communication (RTC-HoloLS).

3. RESEARCH OBJECTIVES

The main objective of this paper is to investigate whether HoloLS integrated with Real-Time Communication (RTC-HoloLS) is effective in improving undergraduate students' collaborative learning skills in photography courses. This study also aims to provide empirical evidence on how the innovative RTC-HoloLS can address existing pedagogical challenges, thereby offering a more holistic approach to education in photography courses. To fully realize these objectives, this study compares RTC-HoloLS with conventional video streaming-based HoloLS (CVS-HoloLS) with the following specific objectives:

1) To investigate whether there is a significant difference in collaborative learning skills between students using the RTC-HoloLS and those using the CVS-HoloLS.
2) To investigate whether there is a significant difference in collaborative learning skills between students of different genders when using the RTC-HoloLS and CVS-HoloLS.

4. RESEARCH HYPOTHESES

There are no previous similar studies involving HoloLens-based learning system characterized by RTC for reference. Therefore, this study sets the null hypothesis, assuming that RTC-HoloLS will not produce significantly different effects on students. The significance level for the study was set at 0.05 ($\alpha = 0.05$). In accordance with the research objectives, the following hypotheses were developed:

$H_0$1: There is no significant difference in collaborative learning skills between students using RTC-HoloLS and those using CVS-HoloLS.
$H_0$2: There is no significant difference in collaborative learning skills between students of different genders when using RTC-HoloLS and CVS-HoloLS.

> $H_0$2.1: There is no significant difference in collaborative learning skills assessments between male and female students using RTC-HoloLS.
> $H_0$2.2: There is no significant difference in collaborative learning skills assessments between male and female students using CVS-HoloLS.

5. RESEARCH FRAMEWORK

In this study, a 2×2 quasi-experimental factorial design was used to assess the learning effects of RTC-HoloLS. The independent variable (IV) is the HoloLens-based learning system, which comprises of RTC-HoloLS and CVS-HoloLS. The dependent variable (DV) is collaborative learning skills, measured using Chopra and Kauts' (2023) Collaborative Learning Scale [12]. Past studies showed differences in learning outcomes for students of different genders using AR technology [13][14][15]. As such, to further explore the variability in performance of students of different genders when using the HoloLens-based learning system, the gender of the students was included as a moderator variable (MV), as shown in Figure 2.

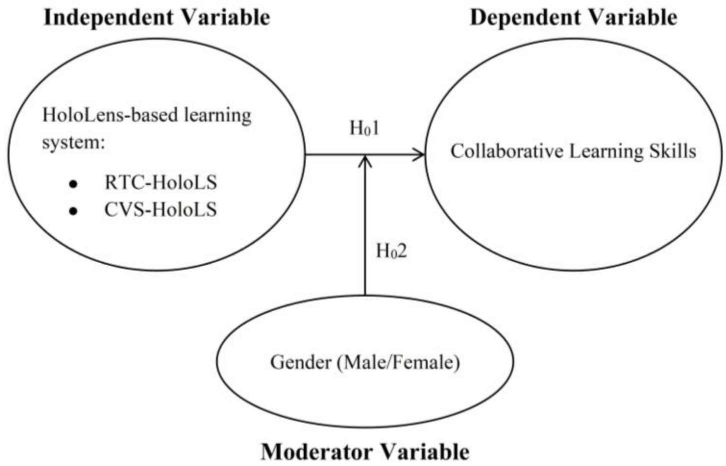

Figure 2. Research Framework

6. THE CONCEPT OF HOLOLENS-BASED LEARNING SYSTEM

HoloLens is a head-mounted device that integrates Augmented Reality (AR) developed by Microsoft to create immersive learning experiences, as shown in Figure 3.

Figure 3. The HoloLens

Unlike traditional AR devices that only superimpose digital information onto the real world, HoloLens allows users to seamlessly interact with both digital and real objects [16]. This capability gives HoloLens learning advantages over traditional AR devices in the education field. Firstly, it creates highly immersive environments where students can interact with 3D models, enhancing their understanding of complex concepts. Secondly, HoloLens supports gesture, voice, and eye tracking for intuitive interactions. Thirdly, HoloLens facilitates real-time collaboration among students in different locations, allowing them to share learning experiences, work, and feedback instantly as if they were in the same room. Finally, HoloLens allows students to visualize and interact with the real world while engaging with digital content. For example, students can see enhanced overlays of camera settings and receive real-time tips on framing, composition, and lighting techniques. The multi-camera setup capability also allows students to collaborate while capturing different camera perspectives. All these functionalities are crucial for photography, which requires hands-on training with actual camera operation while receiving virtual instruction.

6.1. RTC-HoloLS

Real-Time Communication (RTC) refers to technological protocols that empower seamless and low-latency communication between users over the Internet. It enables instantaneous transmission of audio and video data, videoconferencing, online gaming, and collaborative work environments requiring instant interaction and responsiveness [17]. By integrating RTC, RTC-HoloLS supports more responsive communication. This is critical for dynamic and interactive educational environments that require precise and timely intervention, such as adjusting camera settings, compositing footage, and setting up multi-camera systems [18].

6.2. The Difference between RTC-HoloLS and CVS-HoloLS

One of the most critical differences between RTC-HoloLS and CVS-HoloLS is their communication latency. RTC-HoloLS utilizes RTC technology, which is designed for low-latency, point-to-point connections, instantaneous transmission of audio and video data, and real-time interaction. In contrast, CVS-HoloLS relies on conventional video streaming technology, which typically requires buffering to process and transmit data through a centralized server. Higher latency and less responsiveness in communication cause interruptions and quality degradation.

Another difference is that CVS-HoloLS typically requires high-performance computing resources to process and render video for streaming. This includes significant bandwidth and server capacity to handle the data load, which may be limited in environments with restricted resources or unstable Internet connections. In contrast, RTC-HoloLS utilizes resources on direct peer-to-peer connectivity and adaptive bit-rate streaming, which dynamically adjusts transmission quality based on network conditions.

7. METHODOLOGY

7.1. Research Design

This study used a quasi-experimental design to compare the effects of HoloLens with integrated real-time communication (RTC-HoloLS) and HoloLens based on conventional video streaming (CVS-HoloLS) on undergraduate students' collaborative learning skills in a photography course.

7.2. Participants

Participants were 40 first-year undergraduate photography students from a university of technology in China. They were selected through stratified sampling and randomly assigned to either an experimental group (RTC-HoloLS) or a control group (CVS-HoloLS), with 20 participants in each group. Participants were between 19 and 21 years old and had similar experiences using AR devices and engaging in collaborative learning. Before the intervention, all participants completed a pre-test to assess their baseline photography knowledge, and their gender was analyzed as a moderator variable.

7.3. Instruments

The study utilized Chopra and Kauts' Collaborative Learning Scale to measure students' perceptions of collaborative learning across three dimensions: knowledge negotiation, social interaction, and positive interdependence [12]. The scale contains 23 questions, and its published Cronbach's alpha value of 0.73 indicates favorable reliability.

The Basic Camera Examination Questionnaire, compiled by the Department of Photography at a university of technology in China, was used as a pre-test to measure participants' prior knowledge about the photography course. The pre-test questionnaire consisted of 20 questions covering basic camera-related topics such as adjusting camera settings, composition, and capturing images under different conditions. The validity of the questions was confirmed by two professors specializing in photography at a university of technology in China.

7.4. Procedure

The study lasted nine days and was divided into three phases. During the pre-intervention phase (Day 1), participants were instructed on the use of the HoloLens device and the learning schedule, also referred to as the ice-breaking phase. At the end of the pre-intervention phase, participants completed a pre-test assessment of photographic knowledge.

During the intervention phase (Days 2 to 7), the experimental group used RTC-HoloLS, while the control group used CVS-HoloLS for the photography course. Both groups engaged in collaborative learning activities, including group projects, peer reviews, and hands-on camera operations, with instructors providing real-time feedback and support through their respective HoloLens systems. During the post-intervention phase (Day 9), participants completed the photography course and the Collaborative Learning Skills Scale, concluding the experiment.

Ethical guidelines for studies involving human participants were followed throughout this study. Informed consent was obtained from all participants to ensure they were aware of the study's purpose, procedures, and their right to withdraw at any time. Confidentiality was ensured by anonymizing all collected data and using it only for study purposes.

7.5. Data Analysis

To test Hypothesis 1 ($H_0 1$), which states that there is no significant difference in collaborative learning skills between students using RTC-HoloLS and those using CVS-HoloLS, an analysis of covariance (ANCOVA) was conducted. Pre-test scores on prior knowledge were used as covariates to control for initial differences between groups.

To test for gender differences in collaborative learning skills ($H_0 2$), a two-way ANCOVA was conducted. This analysis included an interaction between HoloLS types (RTC-HoloLS and CVS-HoloLS) and gender (male and female) to determine if the effectiveness of the HoloLS varied by gender. Pre-test scores were again used as covariates to control for any pre-existing differences in prior knowledge.

To test sub-hypotheses $H_0 2.1$ and $H_0 2.2$, which investigate whether there are significant differences between male and female students in the assessment of collaborative learning skills in each HoloLS group, separate ANCOVAs were conducted. Specifically, one compared the collaborative learning skills of male and female students using RTC-HoloLS, and the other compared the collaborative learning skills of students using CVS-HoloLS, with both analyses using pre-test scores as covariates.

8. RESULTS AND DISCUSSION

8.1. Descriptive Statistics

Table 1 presents the descriptive statistics of the a priori knowledge on the pretest and the collaborative learning skills (CLS) scores.

Table 1. Descriptive statistics

Group	Gender	N	Mean		Std. Deviation	
			Pre-test	CLS	Pre-test	CLS
RTC-HoloLS	Male	10	5.00	93.4	1.491	6.186
	Female	10	3.50	88.0	1.716	4.000
	Total	20	4.25	90.7	1.743	5.777
CVS-HoloLS	Male	10	4.60	84.2	1.713	2.251
	Female	10	3.70	77.4	1.418	3.204
	Total	20	4.15	80.8	1.599	4.408

8.2. ANCOVA Results for $H_0 1$

To test $H_0 1$, which hypothesized that there is no significant difference in collaborative learning skills between students using RTC-HoloLS and those using CVS-HoloLS, an ANCOVA was conducted. The pre-test scores were used as covariates to control for initial differences in knowledge of photography between groups. The results are shown in following Tables.

Table 2. Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
0.066	1	38	0.798

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a. Design: Intercept + Group + Pretest

Levene's test shown in Table 2 indicated that the assumption of homogeneity of variance was valid, $F(1, 38) = 0.066$, $p = 0.798$ ($p > 0.05$), suggesting that the dependent variable (CLS) had equal variance across groups.

Table 3. Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1478.181[a]	2	739.090	54.117	0.000	0.745
Intercept	30775.990	1	30775.990	2253.451	0.000	0.984
Pretest	498.081	1	498.081	36.470	0.000	0.496
Group	936.828	1	936.828	68.596	0.000	0.650
Error	505.319	37	13.657			
Total	296106.000	40				
Corrected Total	1983.500	39				

a. R Squared = 0.745 (Adjusted R Squared = 0.731)

The results shown in Table 3 indicate that there is a significant effect on the collaborative learning skills of students using RTC-HoloLS and CVS-HoloLS [$F(1, 37) = 68.596$, $p < 0.05$].

The effect size, expressed as partial eta squared ($\eta^2 = 0.65$), indicated that 65% of the difference in collaborative learning skills was attributable to the types of HoloLens-based learning system (HoloLS) used. This effect size suggests that the type of HoloLS had a moderate to large effect on collaborative learning skills. This indicates that students using RTC-HoloLS have significantly higher collaborative learning skills than students using CVS-HoloLS. Therefore, $H_0 1$ is rejected.

8.3. Two-Way ANCOVA Results for $H_0 2$

To test $H_0 2$, which hypothesizes that there is no significant difference in collaborative learning skills between students of different genders when using RTC-HoloLS and CVS-HoloLS, a two-way ANCOVA was conducted. Pre-test scores were used as covariates to control for initial differences between groups of students in photography knowledge. The results are shown in the tables below.

Table 4. Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
1.062	3	36	0.377

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a. Design: Intercept + Group + Pretest + Gender + Group * Gender

Levene's test in Table 4 showed that the assumption of homogeneity of variance was valid [F(3, 36) = 1.062, p = 0.377], indicating that the dependent variable (CLS) had equal variance across groups.

Table 5. Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1634.913[a]	4	408.728	41.039	0.000	0.824
Intercept	28094.482	1	28094.482	2820.838	0.000	0.988
Pretest	277.813	1	277.813	27.894	0.000	0.444
Group	944.771	1	944.771	94.86	0.000	0.730
Gender	138.368	1	138.368	13.893	0.001	0.284
Group * Gender	14.839	1	14.839	1.49	0.23	0.041
Error	348.587	35	9.96			
Total	296106	40				
Corrected Total	1983.5	39				

a. R Squared = 0.824 (Adjusted R Squared = 0.804)

The results of ANCOVA shown in Table 5 indicate that the main effects of both group [$F(1, 35) = 94.860$, $p = 0.000$ ($p < 0.05$), $\eta^2 = 0.730$] and gender [$F(1, 35) = 13.893$, $p = 0.001$ ($p < 0.05$), $\eta^2 = 0.284$] showed significance. Pre-test score was also a significant covariate, indicating that initial a priori knowledge influenced collaborative learning skills. However, the interaction effect between group and gender was not significant overall [$F(1, 35) = 1.490$, $p = 0.230$, $\eta^2 = 0.041$], suggesting that the type of HoloLS did not affect collaborative learning skills differently by gender.

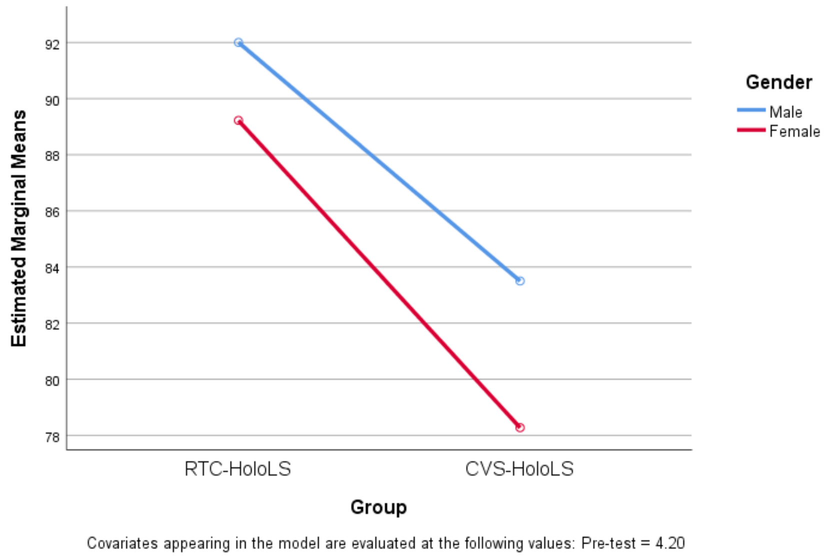

Figure 4. Estimated Marginal Means of Collaborative Learning Skills

Figure 4 shows that male students using RTC-HoloLS had the highest collaborative learning ability, followed by female students using RTC-HoloLS. Male and female students using CVS-HoloLS had lower collaborative learning skills, with female students scoring the lowest.

In summary, the results of the statistical analysis showed that there were significant differences in collaborative learning skills between students using different types of HoloLS (RTC-HoloLS and CVS-HoloLS) and between students of different genders. Therefore $H_0 2$ was rejected.

8.4. Separate ANCOVA Results for $H_0 2.1$ and $H_0 2.2$

8.4.1. Results for $H_0 2.1$

To test Hypothesis $H_0 2.1$, an ANCOVA was conducted to compare the collaborative learning skills (CLS) between male and female students using the RTC-HoloLS. The pre-test scores were used as a covariate, which both assessed gender differences in students, collaborative learning skills and accounted for the potential impact of prior knowledge.

Table 6. Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
0.353	1	18	0.560

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a. Design: Intercept + Group + Pretest

Levene's test in Table 6 showed that the assumption of homogeneity of variance was met [$F(1, 18) = 0.353$, $p = 0.56$ ($p > 0.05$)], indicating that the dependent variable (CLS) had equal variance across groups.

Table 7. Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	425.284[a]	2	212.642	17.303	0.000	0.671
Intercept	14699.775	1	14699.775	1196.155	0.000	0.986
Pretest	279.484	1	279.484	22.742	0.000	0.572
Gender	11.946	1	11.946	0.972	0.338	0.054
Error	208.916	17	12.289			
Total	165164	20				
Corrected Total	634.200	19				

a. R Squared = 0.671 (Adjusted R Squared = 0.632)

The ANCOVA results shown in Table 7 indicated that there was a significant effect of pretest scores on collaborative learning skills [$F(1, 17) = 22.742$, $p = 0.000$ ($p < 0.005$), $\eta^2 = 0.572$]. The main effect of gender was not significant [$F(1, 17) = 0.972$, $p = 0.338$ ($p > 0.005$), $\eta^2 = 0.054$], which suggests that there was no significant difference between male and female students in collaborative learning skills in the RTC-HoloLS group. Therefore, $H_0 2.1$ is failed to reject.

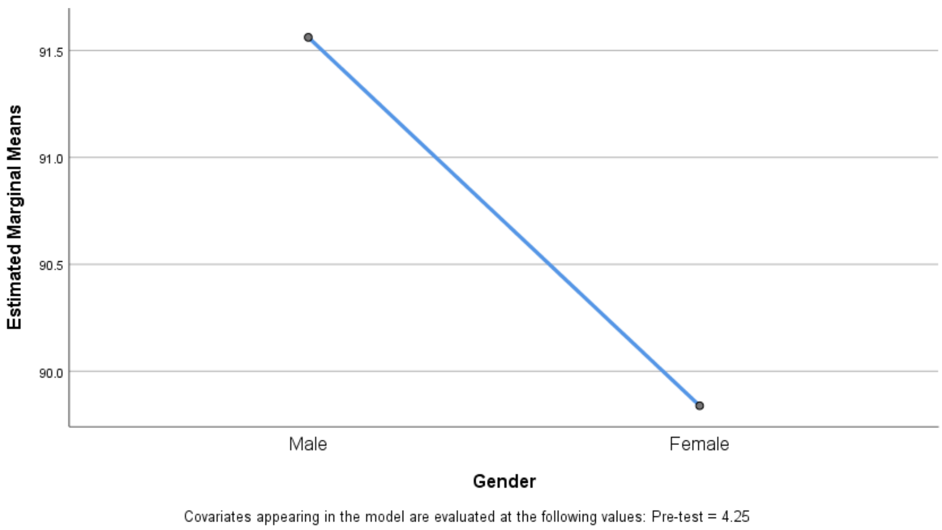

Figure 5. Estimated Marginal Means of Collaborative Learning Skills

Figure 5, Estimated Marginal Means of Collaborative Learning Skills, further reveals that male students using RTC-HoloLS have slightly higher collaborative learning skills than females, but this difference is not statistically significant.

8.4.2. Results for $H_0 2.2$

To test Hypothesis $H_0 2.2$, an ANCOVA was conducted to compare the collaborative learning skills (CLS) between male and female students using the RTC-HoloLS. The pre-test scores were used as a covariate, which both assessed gender differences in students, collaborative learning skills and accounted for the potential impact of prior knowledge.

Table 8. Levene's Test of Equality of Error Variances

F	df1	df2	Sig.
0.380	1	18	0.545

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.
a. Design: Intercept + Group + Pretest

Levene's test in Table 8 showed that the dependent variable (CLS) had equal variance across groups [F(1, 18) = 0.380, p = 0.545 (p > 0.05)].

Table 9. Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	276.706[a]	2	138.353	25.429	0.000	0.749
Intercept	13427.402	1	13427.402	2467.889	0.000	0.993
Pretest	45.506	1	45.506	8.364	0.010	0.330
Gender	158.985	1	158.985	29.221	0.000	0.632
Error	92.494	17	5.441			
Total	130942	20				
Corrected Total	369.200	19				

a. R Squared = 0.749 (Adjusted R Squared = 0.720)

The ANCOVA results shown in Table 9 indicated that the pre-test scores had a significant effect on collaborative learning skills [F(1, 17) = 8.364, p = 0.010 (p < 0.05), η^2 = 0.330]. The main effect of gender was significant [F(1, 17) = 29.221, p = 0.000 (p < 0.05), η^2 = 0.632], which suggests that there was a significant difference in collaborative learning skills between male and female students within the CVS-HoloLS group. Therefore, $H_0$2.2 is rejected.

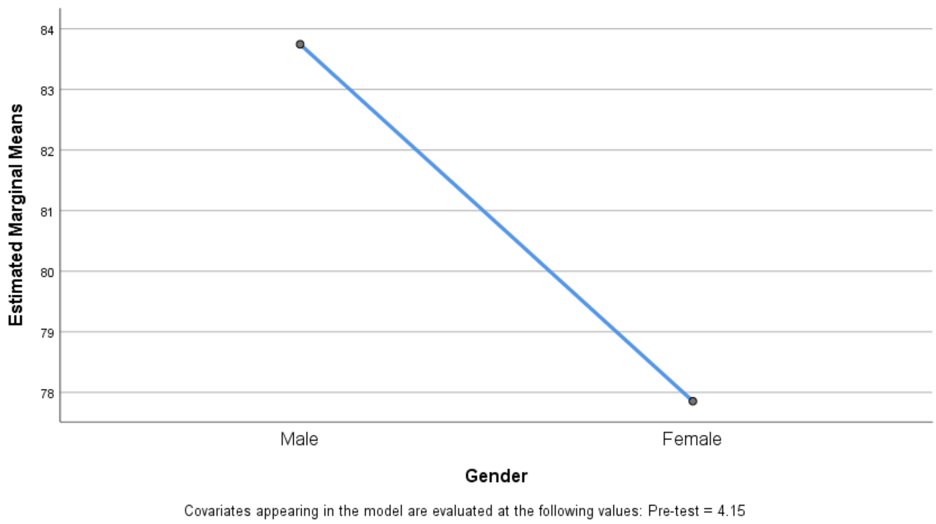

Figure 6. Estimated Marginal Means of Collaborative Learning Skills

The results in Figure 6 indicate that male students using CVS-HoloLS had significantly higher collaborative learning skills than females. The significant gender effect suggests that male students benefit more from CVS-HoloLS compared to female students.

8.5. Discussion

8.5.1. Interpretation of Results

The analysis of collaborative learning skills of students using different HoloLens-based learning systems revealed several significant findings. Firstly, the results of the ANCOVA for hypothesis $H_0$1 showed a significant difference in collaborative learning skills between students using RTC-HoloLS and those using CVS-HoloLS, with RTC-HoloLS being more effective. This demonstrates that integrating real-time communication (RTC) into HoloLS enhances collaborative learning skills more effectively than conventional video streaming (CVS). The partial eta squared (η^2) value of 0.650 indicates a large effect size, confirming the substantial impact of RTC-HoloLS on students' collaborative learning skills.

For hypothesis $H_0$2, the analysis revealed significant gender differences. Within the RTC-HoloLS group, the ANCOVA results for hypothesis $H_0$2.1 showed no significant difference between male and female students in terms of collaborative learning skills, suggesting that RTC-HoloLS was equally effective for both genders. However, the ANCOVA for hypothesis H02.2 indicated a significant difference in collaborative learning skills between male and female students using CVS-HoloLS, with male students outperforming female students. This significant gender effect ($\eta^2 = 0.632$) highlights the differences in the effectiveness of CVS-HoloLS across gender. These findings suggest that CVS-HoloLS has a more unfavorable impact on female students' learning outcomes than on males due to inherent limitations. In contrast, RTC-HoloLS provides a generalizable and effective platform for improving students' collaborative learning skills, regardless of gender.

Additionally, the significance of the pre-test covariate in all statistical analyses indicates that prior knowledge plays a crucial role in determining collaborative learning outcomes, emphasizing the importance of considering initial knowledge levels in educational interventions.

8.5.2. Practical Implications

The results of this study have several practical implications for implementing HoloLens-based learning systems in educational environments, especially in courses that require a high degree of collaboration, such as undergraduate photography courses. The evident advantages of RTC-HoloLS over CVS-HoloLS in developing collaborative learning skills suggest that educational institutions should integrate real-time communication technologies into AR learning platforms. This integration enhances real-time interaction, instant feedback, and dynamic collaboration, thereby improving learning outcomes.

Additionally, the gender differences observed in the CVS-HoloLS group suggest the need for targeted interventions to support female students in collaborative learning environments. Educational practitioners should be aware of these gender differences and implement strategies to mitigate them, such as providing additional support or modifying pedagogical approaches to better meet the needs of female students. This may involve improving the usability and accessibility of AR tools and ensuring that the learning environment is conducive to all students.

8.5.3. Limitations and Future Study Directions

This study has several limitations that should be addressed in future research. First, the sample size was relatively small, consisting of students from specific demographic and educational backgrounds. Future studies should include larger, more diverse samples to increase the generalizability of the findings. Additionally, the study focused solely on undergraduate photography courses, limiting the applicability of the findings to other disciplines. Future research should explore the effectiveness of HoloLens-based learning systems across various disciplines and educational levels.

Another limitation is the reliance on self-reported measures of collaborative learning skills, which can be biased. Future research should combine self-reported data with objective measures, such as performance assessments and observational data, to provide a more comprehensive assessment of learning outcomes. Additionally, longitudinal studies are needed to examine the long-term effects of RTC-HoloLS and CVS-HoloLS on collaborative learning skills and overall academic achievement.

Finally, future research should investigate the underlying causes of the gender differences observed in the CVS-HoloLS group and explore strategies to address these differences. Understanding the factors contributing to the differential impact of AR learning systems on male and female students can inform the design of more equitable educational technologies.

9. CONCLUSIONS

The results showed that RTC-HoloLS significantly improved collaborative learning skills compared to CVS-HoloLS, highlighting the value of integrating real-time communication technologies into AR learning environments. The findings indicated that RTC-HoloLS was equally effective for both male and female students, whereas CVS-HoloLS showed significant gender differences, with male students benefiting more than female students. The superior performance of RTC-HoloLS suggests that educators and educational institutions should prioritize real-time communication features in AR learning tools to enhance collaboration among students. Additionally, the observed gender differences in the effectiveness of CVS-HoloLS highlight the need for targeted interventions to provide equitable support for all students and ensure that educational technology does not inadvertently disadvantage any group.

ACKNOWLEDGEMENTS

The authors would like to thank everyone involved in the preparation of this research.

REFERENCES

[1] J. Carmigniani and B. Furht, “Augmented Reality: An Overview,” in *Handbook of Augmented Reality*, B. Furht, Ed., New York, NY: Springer, 2011, pp. 3–46. doi: 10.1007/978-1-4614-0064-6_1.

[2] A. L. Casanovas and A. Cavallaro, “Audio-visual events for multi-camera synchronization,” *Multimed Tools Appl*, vol. 74, no. 4, pp. 1317–1340, Feb. 2015, doi: 10.1007/s11042-014-1872-y.

[3] T.-H. Yang, J. R. Kim, H. Jin, H. Gil, J.-H. Koo, and H. J. Kim, “Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality,” *Advanced Functional Materials*, vol. 31, no. 39, p. 2008831, 2021, doi: 10.1002/adfm.202008831.

[4] T. Mainelli, “How augmented reality drives real-world gains in services, training, sales and marketing, and manufacturing,” *US43844418, IDC*, no. 43844418, p. 10, 2018.

[5] A. Hietanen, R. Pieters, M. Lanz, J. Latokartano, and J.-K. Kämäräinen, “AR-based interaction for human-robot collaborative manufacturing,” *Robotics and Computer-Integrated Manufacturing*, vol. 63, p. 101891, Jun. 2020, doi: 10.1016/j.rcim.2019.101891.

[6] T. A. Rasmussen and W. Huang, “SceneCam: Using AR to improve Multi-Camera Remote Collaboration,” in *SIGGRAPH Asia 2019 XR*, in SA ’19. New York, NY, USA: Association for Computing Machinery, Nov. 2019, pp. 36–37. doi: 10.1145/3355355.3361892.

[7] T. Ahsen, Z. Y. Lim, A. L. Gardony, H. A. Taylor, J. P. de Ruiter, and F. Dogar, “The Effects of Network Outages on User Experience in Augmented Reality Based Remote Collaboration - An

Empirical Study," *Proc. ACM Hum.-Comput. Interact.*, vol. 5, no. CSCW2, p. 313:1-313:27, Oct. 2021, doi: 10.1145/3476054.

[8] P.-S. Soon, W. M. Lim, and S. S. Gaur, "The role of emotions in augmented reality," *Psychology & Marketing*, vol. 40, no. 11, pp. 2387–2412, 2023, doi: 10.1002/mar.21884.

[9] X. Jiang, F. R. Yu, T. Song, and V. C. M. Leung, "A Survey on Multi-Access Edge Computing Applied to Video Streaming: Some Research Issues and Challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 871–903, 2021, doi: 10.1109/COMST.2021.3065237.

[10] S. Liu *et al.*, "AdaEnlight: Energy-aware Low-light Video Stream Enhancement on Mobile Devices," *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 6, no. 4, p. 172:1-172:26, Jan. 2023, doi: 10.1145/3569464.

[11] C. Pidel and P. Ackermann, "Collaboration in Virtual and Augmented Reality: A Systematic Overview," in *Augmented Reality, Virtual Reality, and Computer Graphics*, L. T. De Paolis and P. Bourdot, Eds., Cham: Springer International Publishing, 2020, pp. 141–156. doi: 10.1007/978-3-030-58465-8_10.

[12] S. Chopra and A. Kauts, "Development of Collaborative Skills Scale: Reliability and Validity," *MIER Journal of Educational Studies Trends and Practices*, pp. 81–97, May 2023, doi: 10.52634/mier/2023/v13/i1/2376.

[13] A. Ewais and O. D. Troyer, "A Usability and Acceptance Evaluation of the Use of Augmented Reality for Learning Atoms and Molecules Reaction by Primary School Female Students in Palestine," *Journal of Educational Computing Research*, vol. 57, no. 7, pp. 1643–1670, Dec. 2019, doi: 10.1177/0735633119855609.

[14] A. Dirin, A. Alamäki, and J. Suomala, *Gender Differences in Perceptions of Conventional Video, Virtual Reality and Augmented Reality*. International Association of Online Engineering, 2019, pp. 93–103. Accessed: Jul. 10, 2024. [Online]. Available: https://www.learntechlib.org/p/216491/

[15] A. Dünser, K. Steinbügl, H. Kaufmann, and J. Glück, "Virtual and augmented reality as spatial ability training tools," in *Proceedings of the 7th ACM SIGCHI New Zealand chapter's international conference on Computer-human interaction: design centered HCI*, in CHINZ '06. New York, NY, USA: Association for Computing Machinery, Jul. 2006, pp. 125–132. doi: 10.1145/1152760.1152776.

[16] J. Cýrus, D. Krčmařík, M. Petrů, and J. Kočí, "Cooperation of Virtual Reality and Real Objects with HoloLens," in *Advances in Computer Vision*, K. Arai and S. Kapoor, Eds., Cham: Springer International Publishing, 2020, pp. 94–106. doi: 10.1007/978-3-030-17798-0_10.

[17] J. Tideström, *Investigation into low latency live video streaming performance of WebRTC*. 2019. Accessed: Jul. 10, 2024. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-249446

[18] R. Serrano Vergel, P. Morillo Tena, S. Casas Yrurzum, and C. Cruz-Neira, "A Comparative Evaluation of a Virtual Reality Table and a HoloLens-Based Augmented Reality System for Anatomy Training," *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 4, pp. 337–348, Aug. 2020, doi: 10.1109/THMS.2020.2984746.

[19] H. Eriksson, *Remote collaboration within a Mixed Reality rehabilitation environment : The usage of audio and video streams for mixed platform collaboration*. 2022. Accessed: Jul. 10, 2024. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-197231

AUTHORS

Jiajia Guo was born in Sichuan, China, in 1986. From 2010 to 2013, he studied in Sichuan Fine Art institute and received his Master's degree in 2013. He is currently a PhD student at Centre for Instructional Technology and Multimedia, Universiti Sains Malaysia, Malaysia. His research interest includes Digital Media Technology, Augmented Reality Technology and Multimedia Design.

Dr. Chau Kien Tsong is Senior Lecturer at Centre for Instructional Technology and Multimedia, Universiti Sains Malaysia. His research interest includes Educational Technology, Multimedia Courseware, Educational Games, and Visual Communication. He is the corresponding author of this paper.

Dr. Siti Nazleen Binti Abdul Rabu is Senior Lecturer at Centre for Instructional Technology and Multimedia, Universiti Sains Malaysia. Her research interest includes instructional design and technology, multimedia course development and instructional strategies in online learning, online learning discourse analysis, online scaffolding, and computer-supported collaborative learning (CSCL).