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Holographic Visual Interaction and Remote Collaboration in Construction Safety and Health

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Holographic Visual Interaction and Remote Collaboration in Construction Safety and Health

Final Report

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ABSTRACT

Identifying hazards that may lead to accidents in construction requires effective communication. This study evaluated the feasibility of applying the mixed-reality (MR) technology in enhancing risk communication at construction jobsites. To this end, it developed a holographic application that runs on Microsoft HoloLens® to enable remote collaboration, real-time information access, and visual annotation in a shared three-dimensional space. This was followed by an evaluation of this holographic application through trials and feedback from participants in the construction industry. The performance metrics designed for assessment included accuracy, efficiency, ease-of-use, and acceptability of the proposed technology benchmarked against the existing communication techniques (i.e., emails, phone calls, walking up to people and talking, and video conferencing). Results from the analysis showed a high potential for the MR technology to enhance risk communication and hazard identification. It may ameliorate the safety management practices thereby reducing the incidences of injuries and fatalities on construction sites.

KEY FINDINGS

- Results showed that the mixed-reality technology has potential to enhance safety risk communication in construction workplace through improvement of the performance of accuracy, efficiency, ease of use, and acceptability benchmarked with the existing methods (i.e., emails, phone calls, face-to-face talk, and video conferencing).
- This study established a positive and quantifiable relationship between communication effectiveness and the mixed-reality technology.
- The participants in this study showed a great degree of immediate willingness to adopt this technology and actively provided feedback and suggestions for improvements.
- Issues relating to narrow field of view, internet connectivity, and safety of the wearer were among the concerns expressed by the participants during site trials.
- This study being evaluation of the feasibility of applying mixed-reality for use in construction settings revealed requirement of certain level of training and education for the participants to adequately master the functionality and deployment of this technology in applicable scenarios.

INTRODUCTION

The U.S. construction industry has long been plagued with a disproportionately high rate of work-related fatalities in comparison to other industries (CPWR 2016). In the practice of construction safety management, one key measure is hazard identification, which plays a fundamental role to prevent accidents and protect workers. However, identifying hazards at construction jobsites suffers from deficiencies. According to a study conducted by Carter and Smith (2006), an average maximum hazard identification level of 76.4% was revealed based on analysis of three construction projects. In another hazard recognition and risk perception test, it was found that construction superintendents with many years of experience still were unable to identify all hazards at jobsites (Perlman et al. 2014). Consequently, the remaining unidentified hazards present the most unmanageable risks.

Timely and accurate communication has been proven to be instrumental to hazard identification and other safety management activities in construction (Abdelhamid and Everett 2000). Studies (Alsamadani et al. 2013; Haslam et al. 2005) have highlighted the importance of communication in safety and health performance improvement of construction. In practices, jobsite safety has been historically communicated on site and in person (e.g., during daily safety inspection). Unfortunately, in the communication process, the typical modes involve walking up to someone, picking up a phone, and video conferencing, which do not facilitate instant access to information, situational awareness, context-based perception, and visual interaction that are essential for effective communication on modern construction sites (Stanton 2013). In specific, walking up to someone to talk and report potential hazards is time-consuming and may hence hinder prompt action to risk control. Phone calls (i.e., audio-only) and video conference (e.g., audio-video) communication conditions possess limitations of lacking visual and spatial cues that are deemed important for effective communication (Billinghurst and Kato 1999). There is a need for improving the way that site hazard identification and risk communication is performed. With emerging technology advancing at ever-increasing speeds, there is an inherent opportunity to develop new mediums, interfaces, and paradigms to fulfill this need as well as enhance the safety delivery in the construction industry.

Mixed-reality is the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time (Ohta and Tamura 2014). It holds great potential of creating shared three-dimensional communication space that enables to generate combined audio, visual, and spatial cues. Imagine that during daily performance of a workplace's inspection, the site engineer who wears a headset can invoke a floating virtual screen to display information that s/he needs. S/he then pinpoints a hazard, and the headset will visualize and display it on the screen of the manager's computer in an offsite office. Reciprocally, the manager can finger draw diagrams on his/her screen and have them appear to the headset wearer (i.e., the engineer). This may become real, as in 2016, Microsoft released HoloLens® (Fig. 1), a holographic computer built into a headset that allows for seeing, hearing, and interacting with holograms within a real environment. Such a holographic platform holds promise to enable better education, research, collaboration, and practice in areas such as safety communication enhancements. (Hoffman 2016). Nevertheless, scientific evidence in applying this technology in construction settings for improvement of safety risk communication and hazard identification is still lacking.

Fig. 1: Microsoft HoloLens®

OBJECTIVES

The objective of this small study is to evaluate the feasibility of applying an emerging mixed-reality technology in ameliorating safety and health communication at construction jobsites. The research questions the study plans to address include:

1) whether the proposed technology improves the accuracy, efficiency, and ease-of-use on communication of construction jobsite safety and health issues in contrast to the conventional methods;
2) to what extent the proposed technology improves such communication as to the above metrics;
3) to what extent the proposed technology is accepted by the industry.

METHODS

This study answered by the above research questions and by doing so, accomplished the research objective through the following two phases.

The *first phase* was to develop a holographic application that enabled to turn a user's field view into a collaborative environment where others can see and interact with the aid of HoloLens®. The display of HoloLens® allows for superimposition of computer-generated holograms over the user's view of the real world. By presenting additional, contextual information to the user, the real world is enhanced beyond the user's normal experience. In this phase, the Visual Studio 2015, Unity HoloLens Technical Preview, and the device of HoloLens® were used for the development of this application. The HoloLens® set-up consists of holographic lenses, a depth camera, speakers above the ears, and on-board processing via an Intel 32-bit architecture, an unspecified GPU (graphics processing unit) and HPU (holographic processing unit) that runs the application development. Once initial setup and calibration are complete, the proposed application starts with a hand gesture that invokes the holographic equivalent of the Windows start menu (Furlan 2016). The pointer is controlled by the user's gaze and clicking is done with a finger gesture. Safety information such as a quick manual can be dragged into the reviewer's space using a pinching gesture. The user enters text in search of relevant information using a gaze-activated keyboard. Development of this phase materialized the abilities to move about untethered while communicating and collaborating with remote team members through Skype®, to visualize items that have yet to be real such as to superimpose elements to a 3D space, to annotate spatially and textually in the 3D space by both parties, and to support the subsequent evaluation of the developed technology.

The *second phase* to evaluate the developed holographic application for safety-related issue visualization, communication, and remote collaboration for solutions. To this end, construction sites were identified in Morgantown, WV and its neighboring area. Through collaborating with industry partners such as Contractor Association of West Virginia and AECOM, forty-nine (49) males and four (4) females with work experience ranging between two (2) to thirty-eight (38) years participated in the study. These participants were practitioners in the construction industry, including project managers, site managers, project engineers, safety manager, safety officer, superintendents, supervisors, and laborers, who were available on site and were willing to participate in the experiment. They were invited to experience the developed technology in which they were instructed to mimic a scenario on safety risk communication that the research team has designed – one at jobsite and one in office and communication was performed with the aid of the three-dimensional holographic and collaborative environment. This study did not control a specific activity that would be observed on jobsites considering the implementation feasibility of being not interfering with the ongoing work in a construction site. It was the participants' choice to walk about the work environment and observe their area of interest (e.g., foundation pit, wall erection, and scaffolding) that would involve safety issues. The information that was communicated included potential hazards and violations of the current workplace, and spatial annotations and verbalized comments of the hazards, violations, and their suggested preventive and protective measures associated with the video stream. Upon completion, immediate feedback was sought from these participants on the feasibility, benefits and limitations of the developed technology through a questionnaire that has been administered by the research team. The performance metrics were designed to include accuracy, efficiency, ease-of-use, and acceptability of the proposed technology that were benchmarked against the current communication techniques at jobsites. The current communication techniques consisted of phone calls, walking to people and talk, and video conferencing. In addition, the questionnaire provided an option for participants to specify other techniques they employ and seek for their feedback on the performance comparison between the proposed technology and the techniques they specified. Feedback on potential limitations of applying the proposed technology was also collected in the questionnaire, including whether the technology leads to work distraction, whether wearing HoloLens is comfortable, whether barriers to industrial implementation exist, and if any, what those barriers could be.

Design of the survey questionnaire was based on the performance metrics and queries set forth above and guided by a communication evaluation guide by Asibey et al. (2008). The reason that this guide was chosen was because it focuses on communication effectiveness and provides a well-defined evaluation strategy tool. Following this evaluation strategy tool, a communication evaluation scheme was developed and presented in Table 1.

Table 1: Developed Communication Evaluation Scheme for the Proposed Technology

Step 1: Determine what to evaluate	*Applying the mixed-reality technology of HoloLens® to enhancing safety risk communication in construction workplaces*
Step 2: Define the goal	*To reduce workplace accidents and injuries*
Step 3: Define the objective	*To improve hazard identification capabilities among the project team; to make more hazards identifiable*
Step 4: Identify the audience	*Construction practitioners who inspect, oversee, record, and report jobsite safety risks*
Step 5: Establish the baseline	*List conventional safety communication channels including phone calls, walking up to people and talk, video conferencing, and others, if any*
Step 6: Pose the	*Ask participants to compare hololens with conventional safety*

evaluation questions	*communications channels for criteria in Step 7* *How do participants respond to the choice of the proposed communication channel (i.e., communication in a collaborative mixed-reality environment)?*
Step 7: Develop the measures	*Accuracy [i.e., participants feel hololens makes it easier to deliver messages; to comprehend messages; to locate the described hazards on sites; participants interested in the unique features of HoloLens (i.e., shared field of view, visual annotation/marking).]* *Efficiency (i.e., participants feel that they may complete their hazard identification and risk discussion faster.)* *Ease-of-use (i.e., participants feel the HoloLens interface is user-friendly and easy to operate .)* *Acceptability (i.e., audience feels comfortable wearing HoloLens; audience feels no distraction wearing HoloLens; audience is willing to use this technology in their future work; audience is willing to invest this technology for their future work; audience feels no barriers to industrial implementation.)*
Step 8: Select the evaluation techniques	*The developed mixed-reality communication tool including HoloLens® and a tablet computer with needed software installed; in-person surveys using questionnaire*

Based on the scheme in Table 1, the questionnaire was developed to contain a number of items, which can be categorized into personal/demographic information, occupational information, business information, performance feedback (Likert scale questions) on strengths, weaknesses, and acceptability of the examined communication strategy (i.e., communication with the aid of the proposed technology), barriers to industrial implementation, and comments/suggestions. Improvement of this questionnaire was made with the assistance of one of the PI's collaborators, whose work is associated with jobsite safety supervision. During the phase of implementation, the questionnaire was further piloted with two industrial participants (one project manager and one field worker) to check its adequacy and minor modifications. Suggestions from the two participants were incorporated into the final version of the questionnaire. The study protocol was approved by the West Virginia University's Institutional Review Board (IRB).

Upon completion of the data collection, descriptive statistics and inferential statistics were applied to answer the research questions. It started with the analysis of descriptive characteristics of the data. As this study used the Likert scale for survey and the data does not follow a normal distribution, the non-parametric Kruskal-Wallis H test was then applied to determine whether there was a statistically significant difference in application of mixed reality compared to different existing communication methods. Last, t-statistic was employed to construct 95% conference interval of item means for each construct. This provided insights about where the average opinion stood based on a scale ranging from strongly disagree (0) to strongly agree (4).

ACCOMPLISHMENTS AND RESULTS

Descriptive Analysis Results

As seen in Fig 2, the medians of different categories increase from left to right indicating that responses with "agree" has a higher median value (11) than responses with "neutral" (6) and "disagree" (0). This implies that most participants agreed that MR has potential to improve risk communication on construction jobsites.

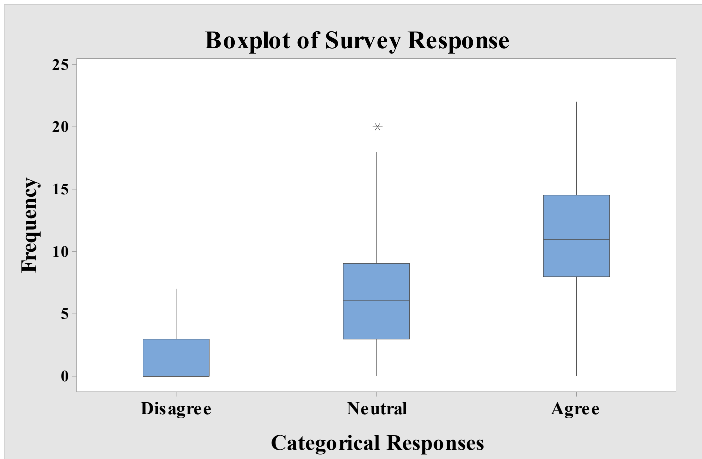

Fig. 2: Total Responses to Each Category by All Participants

Tables 2 to 5 show the frequencies of responses from participants regarding their opinions on accuracy of the mixed reality HoloLens® compared to phone calls, walking up to people and talk, video conferencing, and emails after trials. For the headings in these tables, "Con. MSG" denotes the variable of "ease of conveying messages", "Und. MSG" denotes "ease of understanding messages", "Pin. Haz." denotes "ease of pinpointing a site hazard being described", "Shr. FOV" denotes "usability of shared field of view to assist in remote communication", "Vis. Annot." denotes "usability of visual annotation during communication", and "Comm. Eff." denotes "sense of communication efficiency".

Accuracy compared to phone calls: According to Table 2, eighty (80) percent of responses were in favor of HoloLens®, implying that application of MR has potential to increase accuracy during risk communication on jobsites compared to phone calls. The remaining eighteen (18) percent were undecided while two (2) percent disagreed that MR would improve the accuracy of risk communication. By further observation of the data, users' ability to pinpoint hazards, to share field of view, and to visually annotate in 3D space during remote communication accounts for eighty-eight (88) percent of the responses. This revealed a positive relationship between spatial cue capabilities of HoloLens® and users' ability to understand each other during communication.

Table 2: Response Counts of Accuracy on HoloLens® vs. Phone Calls

ACCURACY: HOLOLENS® VS. PHONE CALLS					
Response	Con. MSG	Und. MSG	Pin. Haz.	Shr. FOV	Vis. Annot.
0 = Disagree	2	2	1	0	1
1 = Neutral	15	13	5	6	6

2 = Agree	34	36	45	45	44
Total (N)	51	51	51	51	51

Accuracy compared to walking up to people and talk: As indicated in Table 3, an average of sixty-six (66) percent of responses supports that MR performs more accurately during communication while twenty-five (25) percent that were undecided and nine (9) percent that disagreed.

Table 3: Response Counts of Accuracy on HoloLens® vs. Walking Up to People and Talk

ACCURACY : HOLOLENS® VS. WALK UP AND TALK					
Response	Con. MSG	Und. MSG	Pin. Haz.	Shr. FOV	Vis. Annot.
0 = Disagree	7	8	6	0	1
1 = Neutral	17	15	14	7	6
2 = Agree	24	25	28	40	41
Total (N)	48	48	48	47	48

Accuracy compared to video conferencing: According to Table 4, there was a marginal difference of opinions between HoloLens® and video conferencing in term of their potential to convey messages between users in remote settings. However, it was observed that messages communicated with MR has greater chances of being clearly understood by others compared to by video conferencing, as shown in column "Und. MSG". Overall, an average of seventy-five (75) percent of responses favored that MR provides higher accurate performance during risk communication in comparison to twenty-three (23) percent of responses being neutral and two (2) percent that disagreed.

Table 4: Response Counts of Accuracy on HoloLens® vs. Video Conferencing

ACCURACY : HOLOLENS® VS. VIDEO CONFERENCING					
Response	Con. MSG	Und. MSG	Pin. Haz.	Shr. FOV	Vis. Annot.
0 = Disagree	1	1	0	0	1
1 = Neutral	13	10	6	4	3
2 = Agree	17	20	25	27	27
Total (N)	31	31	31	31	31

Accuracy compared to emails: In Table 5, accuracy was found to be greatly influenced by the capabilities of HoloLens® in pinpointing hazards in remote settings. It was also observed that an average of sixty-seven (67) percent of responses were in favor that MR improves communication accuracy while thirty-two (32) percent were neutral and one (1) percent disagreed.

Table 5: Response Counts of Accuracy on HoloLens® vs. Emails

ACCURACY : HOLOLENS® VS. EMAILS					
Response	Con. MSG	Und. MSG	Pin. Haz.	Shr. FOV	Vis. Annot.
0 = Disagree	0	0	0	0	1
1 = Neutral	15	13	11	4	4
2 = Agree	14	16	18	25	24
Total (N)	29	29	29	29	29

Tables 6 to 9 show the participants' consensus on the efficiency of the HoloLens® benchmarked with the conventional methods of phone calls, walking up to people and talk, video conferencing, and emails. For the headings in these tables, "Comm. Eff." denotes "communication efficiency".

Efficiency compared to phone calls: As shown in Table 6, fifty-nine (59) percent of responses agreed that MR was more efficient by reducing communication duration during remote collaboration than phone calls while thirty-one (31) percent were neutral and ten percent (10) disagreed.

Table 6: Response Counts of Efficiency on HoloLens® vs. Phone Calls

EFFICIENCY: HOLOLENS® VS. PHONE CALL	
Response	Comm. Eff.
0 = Disagree	5
1 = Neutral	16
2 = Agree	30
Total (N)	51

Efficiency compared to walking up and talk: In Table 7, fifty-nine (59) percent of responses were in favor that MR would reduce discussion time during safety communication in comparison to twenty-five (25) percent being neutral and sixteen (16) percent of disagreement.

Table 7: Response Counts of Efficiency on HoloLens® vs. Walking Up and Talk

EFFICIENCY: HOLOLENS® VS. WALKING UP AND TALK	
Response	Comm. Eff.
0 = Disagree	8
1 = Neutral	12
2 = Agree	29
Total (N)	49

Efficiency compared to video conferencing: In Table 8, fifty-two (52) percent of respondents subscribed that MR produces better efficiency during risk communication than video conferencing while thirty-nine (39) percent were neutral and nine (9) percent disagreed.

Table 8: Response Counts of Efficiency on HoloLens® vs. Video Conferencing

EFFICIENCY: HOLOLENS® VS. VIDEO CONFERENCING	
Response	Comm. Eff.
0 = Disagree	3
1 = Neutral	12
2 = Agree	16
Total (N)	31

Efficiency compared to emails: Based on Table 9, fifty-seven (57) percent of responses believed that using the mixed reality intervention reduces duration of communication compared to forty-three (43) percent that were neutral and zero (0) that disagreed on the potential of mixed reality to improve communication efficiency.

Table 9: Response Counts of Efficiency on HoloLens® vs. Emails

EFFICIENCY: HOLOLENS® VS. EMAILS	
Response	Comm. Eff.
0 = Disagree	0
1 = Neutral	13
2 = Agree	17
Total (N)	30

Table 10 shows the frequencies of responses from participants regarding ease-of-use of mixed reality HoloLens®. In its headings, the variables of "Usr. Int." denotes "friendliness of the user interface of HoloLens®", and "Oper." denotes "ease of operation of HoloLens®".

Ease-of-use: In Table 10, forty-six (46) percent of responses agreed that user interface of the mixed reality HoloLens® is easy to navigate. Forty-nine (49) percent were neutral on the ease-of-use of mixed reality during communication. The remaining five (5) percent of responses indicated that the mixed reality interface is not user-friendly.

Table 10: Response Counts of Ease of Use

EASE OF USE OF HOLOLENS®		
Response	Usr. Int.	Oper.
0 = Disagree	4	1
1 = Neutral	24	26
2 = Agree	24	23
Total (N)	52	50

Table 11 shows the frequencies of responses from participants regarding acceptability of mixed reality HoloLens®. In its headings, the variables of "Cmft." denotes "comfortability of wearing HoloLens®", "No Dstr." Denotes "no distraction to work wearing HoloLens®", and "Reuse" denotes "willingness to use HoloLens® for work again".

Acceptability: In Table 11, thirty-two (32) percent of responses were willing to accept mixed reality for risk communication given the technology in its current state while fifty-one (51) percent of responses were neutral and seventeen (17) percent of responses did not agree that it is the best time to adopt the mixed reality for their site risk communication.

Table 11: Response Counts of Acceptability of HoloLens®

ACCEPTABILITY OF HOLOLENS®			
Response	Cmft.	No Dstr.	Reuse
0 = Disagree	7	12	6
1 = Neutral	20	31	27
2 = Agree	24	8	17
Total (N)	51	51	50

Inferential Analysis Results

Kruskal-Wallis H test of significance: The median differences between participants' responses for each of the constructs were statistically assessed by applying Kruskal-Wallis H test. The test results indicated that for accuracy, efficiency, ease-of-use, and acceptability, there are significant differences ($p<0.05$) when MR is used for risk communication compared to other methods in terms of phone calls, walking up to people and talk, video conferencing, and emails.

Post hoc analysis for pairwise comparisons: Post hoc analysis was to examine which groups of responses (i.e., Disagree vs. Neutral, Disagree vs. Agree, and Neutral vs. Agree) are significantly different from each other. In this study, Kruskal-Wallis pairwise comparison was used to determine where significant difference occurs in the medians of the three response groups and presented the results in Table 12 below.

Table 12: Post Hoc Analysis, α= 0.05

Construct	Category	p-value	Remarks	Comments
Accuracy				
HoloLens® vs. Phone Calls	Disagree vs. Neutral	0.017	< 0.05	Significance
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.001	< 0.05	Significance
HoloLens® vs. Walking Up and Talk	Disagree vs. Neutral	0.021	< 0.05	Significance
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.001	< 0.05	Significance
HoloLens® vs. Video Conferencing	Disagree vs. Neutral	0.034	< 0.05	Significance
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.001	< 0.05	Significance
HoloLens® vs. Emails	Disagree vs. Neutral	0.001	< 0.05	Significance
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.011	< 0.05	Significance
Efficiency				
HoloLens® vs. Phone Calls	Disagree vs. Neutral	**0.059**	**> 0.05**	**Not significance**
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.001	< 0.05	Significance
HoloLens® vs. Walking Up and Talk	Disagree vs. Neutral	**0.199**	**> 0.05**	**Not significance**
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	0.001	< 0.05	Significance
HoloLens® vs. Video Conferencing	Disagree vs. Neutral	0.034	< 0.05	Significance
	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	**0.213**	**> 0.05**	**Not significance**
HoloLens® vs. Emails	Disagree vs. Neutral	0.003	< 0.05	Significance

	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	**0.549**	**> 0.05**	**Not significance**
	Disagree vs. Neutral	0.001	< 0.05	Significance
Ease-of-Use	Disagree vs. Agree	0.001	< 0.05	Significance
	Neutral vs. Agree	**1.000**	**> 0.05**	**Not significance**
	Disagree vs. Neutral	0.001	< 0.05	Significance
Acceptability	Disagree vs. Agree	**0.051**	**> 0.05**	**Not significance**
	Neutral vs. Agree	0.009	< 0.05	Significance

Pairwise comparisons of the accuracy: In all pairwise comparisons of the accuracy of HoloLens® against other methods, results revealed statistically significant agreements ($p<0.05$) that the mixed reality HoloLens® has potential to increase the accuracy of communication than the other four traditional methods.

Pairwise comparisons of the efficiency: Similar significant results were also obtained in the pairwise comparison of the efficiency of HoloLens® with phone calls and walking up to talk, respectively. The pattern in these comparisons showed that respondents rated the efficiency of HoloLens® to reduce the time spent in delivering succinct messages that others can easily understand higher than the other methods. Although we found the pairwise comparisons between the "Neutral" and "Disagree" not significant ($p > 0.05$) for the same constructs, they do not have any significant adverse effect on the overall efficiency rating of the mixed reality. For the pairwise comparisons of efficiency of HoloLens® with video conferencing and emails, there was no significance difference between "Agree" and "Neutral". This showed that respondents do not believe there was a significant communication time saved between when they used HoloLens® and video conferencing or emails.

Pairwise comparisons of the Ease-of-Use: The comparison between "Neutral" and "Agree" responses showed an evidence of insignificance ($p>0.05$); but the comparison between "Disagree" and "Agree" and "Disagree" and "Neutral" responses were significant.

Pairwise comparisons of the Acceptability: The "Disagree" and "Agree" comparison for acceptability was insignificant based on the result. However, "Disagree" and "Neutral" and "Neutral" and "Agree" comparisons were significant.

The insignificance differences from the ease-of-use and acceptability of HoloLens® may indicate that some amendments to features and adequate training of practitioners for use of the technology are required to maximize the full potential of its use in the construction industry.

Mean of Responses at 95% Confidence Interval: To answer the research questions as to the extent to which the mixed-reality technology improves communication based on the metrics of performance. Student's t-test was employed to determine where most of agreements fall given the 5-Likert scales of opinions (i.e., strongly disagree = 0, disagree = 1, neutral = 2, agree = 3, and strongly agree = 4). Table 13 displayed the result of 95% confidence interval for the extent of agreement of the respondents. Using this interval, we obtained a range of means by which we could determine the magnitude of responses to each construct at 95% confidence level.

Table 13: Mean of Responses at 95% CI, α= 0.05

Construct	Mean	Standard Deviation	Mean Range @ 95% Confidence Interval
Accuracy			
HoloLens® vs. Phone Calls	3.00	0.70	2.91 - 3.09
HoloLens® vs. Walking Up and Talk	2.72	0.89	2.61 - 2.83
HoloLens® vs. Video Conferencing	2.86	0.65	2.76 - 2.96
HoloLens® vs. Emails	2.86	0.73	2.74 - 2.97
Efficiency			
HoloLens® vs. Phone Calls	2.69	0.91	2.43 - 2.94
HoloLens® vs. Walking Up and Talk	2.53	0.96	2.26 - 2.81
HoloLens® vs. Video Conferencing	2.45	0.72	2.19 - 2.72
HoloLens® vs. Emails	2.73	0.74	2.46 - 3.01
Ease of Use	2.38	0.79	2.22 - 2.53
Acceptability	2.21	0.78	2.09 - 2.34

From Table 13, the means in all cases range between neutral to agree, meaning that the extent of agreement on the scale of 0-4 is between 2 and 3. However, accuracy of mixed reality versus phone calls produced the highest mean range of 2.91-3.09, signifying that the upper bound of the extent agreement fell between agree and strongly agree region of the rating. With this range, there is a 95% confidence interval that the lower range of value for the potential of HoloLens® to improve accuracy of communication would not be below 2.91. This is in the "agree" region of the scale. With this value, we therefore concluded that HoloLens® increased the accuracy communication. Next, we examined the comparisons of HoloLens® with walking up and talk, video conferencing and emails, respectively. It was observed that the mean range for accuracy in these cases are between 2.61 and 2.83 for walking up and talk, 2.76 and 2.96 for video conferencing, and 2.74 and 2.97 for emails. These ranges for the accuracy of HoloLens® equally fell between "neutral" and "agree" but were closer to "agree" than "neutral", which means that the HoloLens® has superiority performance in accuracy when compared to walking up and talk, video conferencing, and emails. In assessing the mean range at 95% confidence interval for the efficiency of HoloLens® in comparison to phone calls, walking up and talk, video conferencing, and emails respectively, the mean values equally lied between "neutral" and "agree" but this time with lower range values that were closer to "neutral". Ease of use and acceptability both possessed the least low and least upper range values. This means that respondents are more likely closer to "neutral" end of the spectrum than "agree" in their opinions when comparing the ease of use and acceptability of mixed reality with other methods.

Discussion

This study established a positive and quantifiable relationship between communication effectiveness and the MR technology. The statistical analysis showed that MR has potential to improve risk communication and thereby better off safety management that may lead to accident reduction on construction sites. Based on comments provided in the open section, participants showed a great degree of immediate willingness to adopt the technology.

At the time of undertaking this project, Microsoft provides a Development Edition of HoloLens that exists in the U.S. market which currently costs $3,000. This price, together with the cost of a tablet, would approximately lead to $3,500 for implementation of the proposed technology. Nevertheless, as the mixed-reality devices and sensor technology advance, it can be foreseen that the cost of implementing such technology will become cheaper and more affordable.

However, there are several caveats that were observed in this study. One is that the cross-sectional method was used for data collection. The method offers a quick way to gather sufficient sample considering the time allotted for execution of the study. However, the fact that trials and participation are only limited to participants from the construction industry brought about extensive delay in consent approvals, which dragged the duration of data collection beyond the targeted summer window (May-August) when outdoor construction activities was at its peak. To achieve the set objectives, complementary indoor data collection procedure was implemented where outdoor field trials were not feasible. By designating participants into separate remote areas of existing facilities where routine collaboration is essential to complete tasks, the participants could have the needed mixed reality experience to provide opinions for the survey.

Secondly, it was noted that the learning curve in the experiments might differ from person to person. The fact that the participants only had a few minutes to experience the mixed reality and form opinions may either lead to certain biases or unwillingness to express extreme opinions due to the lack of adequate knowledge of the technology. Although this study could not directly account for the factors that lead to satisficing on the part of respondents, analysis of post hoc test in Table 12 would help understand and quantify the impacts of lack of opinions of participants on each performance metric.

Third, the participants selected in this study varied in terms background in years of experience (2-38 years) and roles (e.g., managers, engineers, laborers). This might have impacts on their perception and responses to the questions. However, this study did not consider this factor, which leaves room for future extension.

Finally, this study being the first evaluation of the feasibility of applying mixed reality in on-site construction settings requires adequate training and education of participants to adequately master the functionality and the deployment of mixed reality in applicable scenarios. Unfortunately, the limited time and resources at our disposal meant that we can only give short but uniform trainings across board, and to all participants such that would reduce variations as much as possible. Residual biases may however still exist because of the tendency of respondents to satisfice due to insufficient training or inadequate education. Estimation of variations due to these types of biases and their specific implication on the results is beyond the scope of this study.

Future work will address issues relating to barriers for adoption that will focus on improvement of function operations and user interface by designing more convenient experience to adequately cater for industry needs. Future work will assess the extent and implication of error due to biases on the performance metrics. Future work will also seek to understand the impact of the adoption this technology on the industry by assessing the cost-effectiveness of the mixed reality technology. This will enable us to quantify the expected return value on investment based on injuries avoidance and time saved as a direct result of using the mixed reality intervention during construction risk communication.

CHANGES/PROBLEMS

There are no changes or problems encountered during the study.

FUTURE FUNDING PLANS

Based on the findings of this small study, the research team plans to seek additional funding from NASA West Virginia Space Grant Consortium, Reginal 3 University Transportation Center, National Institute for Occupational Safety and Health (NIOSH), and construction companies to improve the present technology and further its applicability for safety management.

LIST OF PRESENTATIONS/PUBLICATIONS

Presentation:

- "Feasibility of applying mixed-reality to enhancing safety risk communication in construction workplaces." Presented by Fei Dai at the *7th International Conference on Construction Engineering and Project Management (ICCEPM 2017)*, Chengdu, China, Oct. 30, 2017.
- "Three-dimensional visual and collaborative environment for jobsite risk communication." Presented by Fei Dai at the *ASCE 2018 Construction Research Congress (CRC 2018)*, New Orleans, LA, April 4, 2018.

Publication:

- Abiodun Olorunfemi. (2018). *Assessing the Feasibility of Applying Mixed Reality in Enhancing Construction Site Safety Communication*. Master Thesis, West Virginia University.
- Abiodun Olorunfemi, Fei Dai, Liyaning Tang and Yoojung Yoon. (2018). "Three-Dimensional Visual and Collaborative Environment for Jobsite Risk Communication." *Construction Research Congress*, pp. 345-355, April 2-5, New Orleans, Louisiana, USA.
- Abiodun Olorunfemi, Fei Dai and Weibing Peng. (2017). "Feasibility of Applying Mixed-Reality to Enhancing Safety Risk Communication in Construction Workplaces." *The 7th International Conference on Construction Engineering and Project Management (ICCEPM 2017)*, Oct. 28-30, 2017, Chengdu, China.

DISSEMINATION PLAN

The research team plans to disseminate findings revealed from this project and its follow-up research, if any, via:

- Journal publications in top journals such as ASCE Construction Engineering and Management, Automation in Construction, and Safety Science;

- Conference papers/posters and presentations in construction, transportation, or civil engineering (e.g., CRC, IC3E, TRB, and ICCCBE);
- Industry seminars and workshops through WV Construction & Design Exposition.

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