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Feasibility of Applying Mixed-Reality to Enhancing Safety Risk Communication in Construction Workplaces

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Abstract: Mixed-reality technologies have proven to be valuable in many architecture, engineering and construction / facilities management (AEC/FM) applications. However, its potential of being adapted to facilitate hazard identification and risk communication in construction workplaces has yet to be fully explored. This paper makes an attempt to evaluate the feasibility of applying mixed-reality to enhancing safety risk communication in construction workplaces. Experiments have been designed in which Microsoft HoloLens® together with a developed application will be used to intervene in the practice of jobsite risk communication. A cross-sectional survey will then be followed to examine the effectiveness and acceptability of this technology through analysis on data collected from participants in the construction industry. The preliminary results show that this emerging HoloLens® technology, compared to the traditional communication methods (i.e., phone calls, walking up people and talk, and video conferencing), facilitates accurate, prompt safety communication on construction sites. Such findings signify the potential of applying mixed-reality to safety performance enhancement in the construction industry.

Key words: Survey studies, mixed-reality, construction safety, risk communication, construction industry

1. INTRODUCTION

The U.S. construction industry has long been plagued with a disproportionately high rate of work-related fatalities in comparison to other industries (BLS 2017; CPWR 2016). On construction workplaces, effective communication plays a key role in identifying hazards and preventing accidents. Unfortunately, current practices that rely on modes such as walking up to people and talk, phone calls and video conferencing do not facilitate instance access to information, context-based perception, and visual interaction that are essential for effective communication in modern construction workplaces. The mixed-reality technology has shown some potential to allow for collaborative work and remote communication with the abilities of visualizing the workplace context and performing spatial annotation. Nevertheless, its performance in ameliorating construction jobsite risk communication and hazard identification is unknown. Therefore, this research makes an attempt to evaluate the feasibility of applying the mixed-reality technology in enhancing hazards and risks communication at construction jobsites. This paper reports the ongoing work on this topic and particularly focuses on effectiveness of applying this technology. In specific, this paper answers the research questions of (1) whether the mixed-reality technology improves the effectiveness of risk communication on construction jobsites in contrast to the conventional methods, and (2) to what extent the mixed-reality technology improves such communication based on the above metric.

2. BACKGROUND

In the practice of construction safety management, one key measure to preventing accidents and protecting workers is hazard identification (Luo et al. 2017; Manuele 2005). Unfortunately, identifying hazards at construction jobsites suffer 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 of the hazards at jobsites (Perlman et al. 2014). As a consequence, the remaining unidentified hazards present the most unmanageable risks. Based on the literature (Khanzode et al.2012; Luo et al. 2017), the challenges for hazard identification management at jobsites include, but are not limited to, limited knowledge of who performs the safety inspection task, obsolete safety plan for task changes, behind-schedule pressure from those who oversee daily tasks, poor communication of hazards to the construction team, and the large-scale, dynamic and complex nature of construction.

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; Christian et al. 2009; Haslam et al. 2005; Sawacha et al. 1999) have highlighted the importance of communication in safety and health performance improvement of construction. In practices, jobsite safety is historically communicated on site and in person (e.g., during daily safety inspection). Unfortunately, these traditional communication processes, typically involve walking up to someone, picking up a phone, and video conferencing, 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). With emerging technology advancing at ever-increasing speeds, there is a need to improve the way site hazard identification and risk communication is performed. This latent opportunity will help to develop new mediums, interfaces, and paradigms to fulfill this need as well as enhance the safety delivery in the construction industry.

Among existing emerging technologies, 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. 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 with the assistance of the mixed-reality technology. 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). As in 2016, Microsoft released HoloLens®, which is 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). In spite of this, scientific investigation on its feasibility to enhance safety risk communication on construction sites is still lacking.

3. OBJECTIVE AND HYPOTHESIS

In support of the authors' long-term goal to design and implement simple, yet effective strategies for mitigating work-related injury risks to construction workers, the immediate goal in this study is to evaluate the feasibility of applying an emerging mixed-reality technology in ameliorating safety and health communication at construction jobsites. The central hypothesis is that adoption and expansion of such mixed-reality technology together with a videoconferencing application will significantly increase the ability to communicate safety and health risks among the construction workforces on the spot and remotely on jobsites. To test the central hypothesis, a holographic application that enables users turn the field view of HoloLens® into a collaborative environment was prototyped and subsequently evaluated for safety-related issues of communication, visualization, and remote collaboration through trials and feedback from potential users in the construction industry.

4. METHODOLOGY

Two thrusts were developed. The first thrust was to prototype a holographic application that 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. The prototyping of this thrust is to materialize 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. Once initial setup and calibration are complete, the 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 second thrust focused on evaluation of the prototyped holographic application for safety-related issue visualization, communication, and remote collaboration for solutions. Ten construction sites were chosen on account of the viability of the evaluation activity in regard to cost, time, site availability, and soundness of assessment. The participants were practitioners in the construction industry, including, but are not limited to, project managers, site managers, project engineers, safety manager, safety officer, superintendents, foremen, and laborers, who are available on site and willing to voluntary participate in the experiment. Upon completion of trial with HoloLens® mixed reality, immediate feedback was sought from these participants on the feasibility, benefits and limitations of the developed technology through a questionnaire administered by the researchers. The questionnaire was designed to measure the performance metrics including of effectiveness, cost-effectiveness, acceptability, ease-of-use of the proposed technology in comparison with the current communication techniques (i.e. phone calls, walking up to people and talk, and video conferencing) at jobsites. Additionally, 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. Note: as an ongoing study, this paper only focused on measurement of effectiveness instead of other metrics.

4.1. Key variables of effective communication

An important step in determining effectiveness of communication is identification and measurement of the critical communication variables. Based on existing models (Thomas et al. 1998), six (6) key variables were identified for the measurement of effectiveness in this study, including ease of conveying messages, ease of understanding messages, ease of pinpointing a site hazard being talked, usability of shared field of view to assist in remote communication, usability of visual annotation during communication, and sense of communication efficiency.

4.2. Survey design and administration

The design of the survey questionnaire was based on the performance metrics as described above and guided by the communication evaluation guide by Asibey et al. (2008). The reason that this guide was chosen is that it focuses on communication effectiveness and provides a well-defined evaluation strategy tool. As a result, the questionnaire was developed to contain a number of items, which were categorized into personal/demographic information, occupational information, business information, performance feedback (Likert scale questions) on strengths, and weaknesses of examined communication strategy (i.e., communication with the aid of the proposed technology), barrier to industrial implementation, and comments/suggestions. To increase reliability, improvement of the questionnaire was made with the assistance of one of the authors' collaborators, whose work is associated with jobsite safety supervision. In addition, 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. Suggestions from these two participants was then incorporated into the final version of the questionnaire. An extraction sample from the questionnaire is displayed in **Fig. 1** below.

Section D: HoloLens® Communication vs. Phone Calls

If your answer to Question 9 includes "01 – Phone calls", please answer the following questions 10 through 13. We would like to know about your feedback on jobsite risk communication effects with HoloLens® relative to using phone calls.

In comparison to phone calls, with HoloLens®:

10. It is easier for me to convey a message during communication: CMSGVSTEL

01 – Strongly Agree 02 – Agree 03 – Neutral 04 – Disagree 05 – Strongly Disagree

11. It is easier for me to understand a message during communication: UMSGVSTEL

01 – Strongly Agree 02 – Agree 03 – Neutral 04 – Disagree 05 – Strongly Disagree

12. It is easier for me to pinpoint a site hazard that I am talking: LCVSTEL

01 – Strongly Agree 02 – Agree 03 – Neutral 04 – Disagree 05 – Strongly Disagree

Fig. 1. Part of questionnaire for feedback after trial with HoloLens®

4.3. Participants

At the time of this study, thirteen participants were invited from construction companies for trial. Although there is an ongoing effort to recruit more participants, this number is based on convenience and their interests in the study. There were twelve males and one female with work experience ranging between six (6) to thirty-eight (38) years. Participants' selection was not based on race, gender, religion, education or social economic status and no identifiable information such as names date of birth, social security numbers etc. was required in the study. However, respondent's sex, highest level of education achieved and years of work experience were requested for better understanding of possible correlation. The research protocol has been approved by the Institutional Review Board (IRB) of West Virginia University.

4.4. Experimental procedures

During each experiment on site, collection of data needed for the subsequent statistical analysis started with the research team entering the construction workplace and ended with the participants providing their feedback to the questionnaire. The procedures comprised the following steps. The research team first entered the construction site and set up the communication hardware and software needed for the experiment. Before the actual trial with mixed reality, the research team introduced and demonstrated how to use the technology, with the purpose of getting the participants familiar with the functions and operations of the technology. During this session, the research team also answered any question that the participants might have. When complete, the research team then presented the IRB approved consent form to participants and allowed them to read and digest the content and ask for clarification where necessary. The participants signed off the form with applicable date. A copy of the signed form was subsequently emailed or mailed back to participants. Following this, the participants were paired for trial with the technology. For each paired group, one operated a computer tablet remotely and the other wore the HoloLens® on site. The test employed the current site scene (i.e., where the HoloLens® wearer saw) as the context for communication. During the communication, functions such as shared field of view, remote conferencing, and spatial and visual annotation were experienced. Testing of HoloLens® was placed on a site spot where both the participants and the research team deemed safe. Once complete, these two participants swapped their roles and locations and repeated the above trial procedure. All the participants were last asked to fill out the questionnaire separately based on their trial experience and opinions toward the technology.

4.5. Data processing

The questionnaire contained five scale Likert items from Strongly Agree to Strongly Disagree (where strongly agree = 01, Agree = 02, Strongly, Neutral = 03, Disagree = 04, and Strongly Disagree = 05) that were used to measure respondents attitude to a particular question. By binning the respondents' answers, this research converted the 5 Likert scales to nominal 3 scales (where Neutral = 1, Strongly disagree or Disagree = 0, and Strongly agree or Agree = 2). This transformation is needed to provide flexibility and adaptability in the resolution at which information from the data could be extracted and represented.

4.6. Statistical analysis

Fig. 2 shows that the data is not normally distributed and hence a non-parametric statistical method of Kruskal–Wallis H test was used for the analysis.

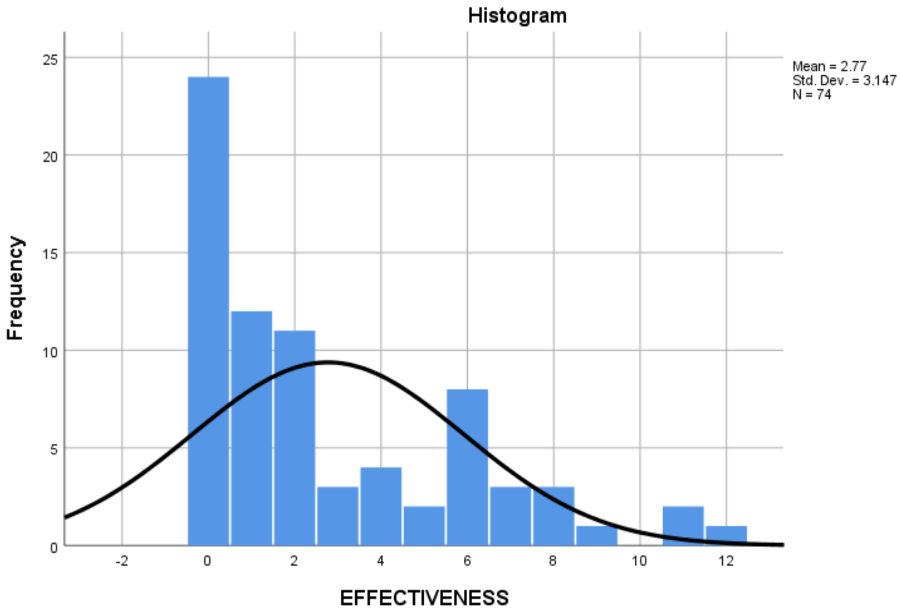

Fig. 2. Normality test to determine statistical analysis techniques

5. RESULTS AND ANALYSES

5.1. Test of homogeneity of variance

To apply the non-parametric analytical method namely Kruskal Wallis H test in this case, one critical assumption is the homogeneity of variance of the independent variables. To verify this assumption, this study applied Brown-Forsyth of homogeneity of variance. The reason for selecting this method was skewness of the distribution as shown in **Fig. 2** and the emphasis of the test on median rather than the mean of distribution due to the ordinal nature of survey data (Olejnik and Algina 1987). With the result of p-value of 0.3, which was greater than the 0.05 alpha level, we therefore failed to reject the hypothesis and concluded that the variables were homogenous.

5.2. Descriptive statistics

Figs. 3 to **6** show the participants' consensus on the effectiveness of the HoloLens® benchmarked with the conventional methods of phone calls, walking up to people and talk, video conferencing, and emails. For the chart titles in these figures, "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 talked", "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". In **Fig. 3**, it exhibits the effectiveness of HoloLens® relative to phone calls, revealing that seventy percent of the responses agreed that the mixed reality technology facilitates more effective communication, twenty-seven percent remained neutral, and three percent presented disagreement. In **Fig 4**, where we examined the effectiveness of HoloLens® versus walking up to people and talk, we found that seventy-five percent of the responses agreed that the mixed-reality technology is more effective, twenty-three percent were neutral and two percent disagreed. Similarly, **Fig 5**, where we compared the mixed reality versus video conferencing, revealed that fifty-six percent of the responses favored that HoloLens® is more effective during communication in comparison to forty-four percent that were neutral and zero percent of disagreement. Lastly, in **Fig 6**, we compared the mixed reality technology against emails and observed that sixty-seven percent of the responses were in favor that the mixed reality improves communication while thirty-three percent were neutral and zero percent were disagreeing. At this point, we assumed that the "neutrals" were at odds that the mixed reality has no any real impact on the effectiveness improvement during communication. This assumption increased our confidence level in determining whether the mixed reality technology can actually improve effectiveness during construction risk communication.

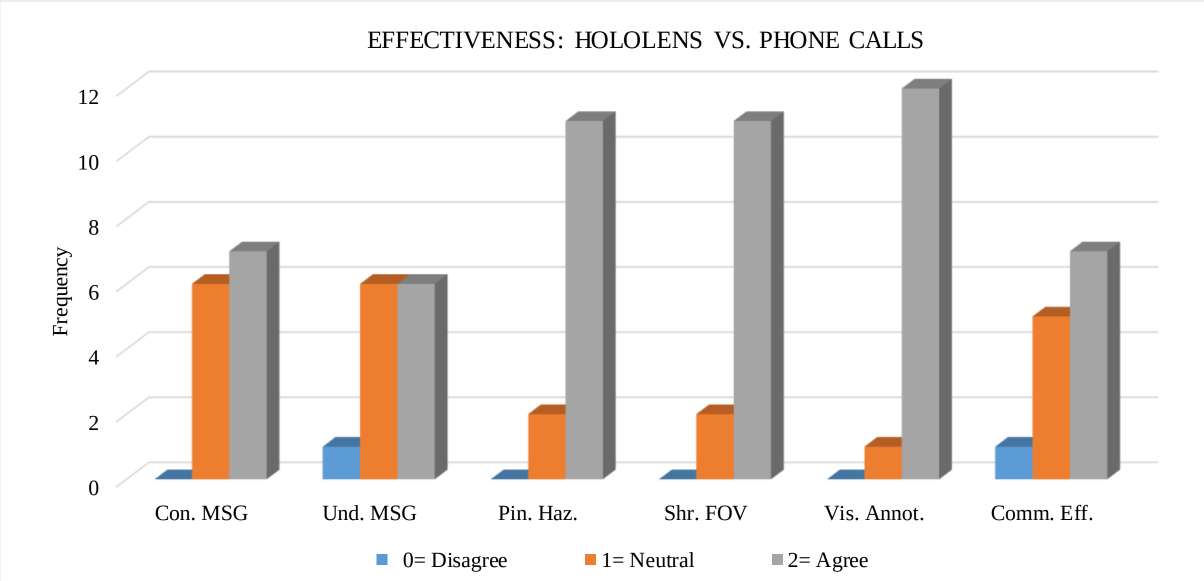

Fig. 3. Response counts of effectiveness on HoloLens® vs. phone calls

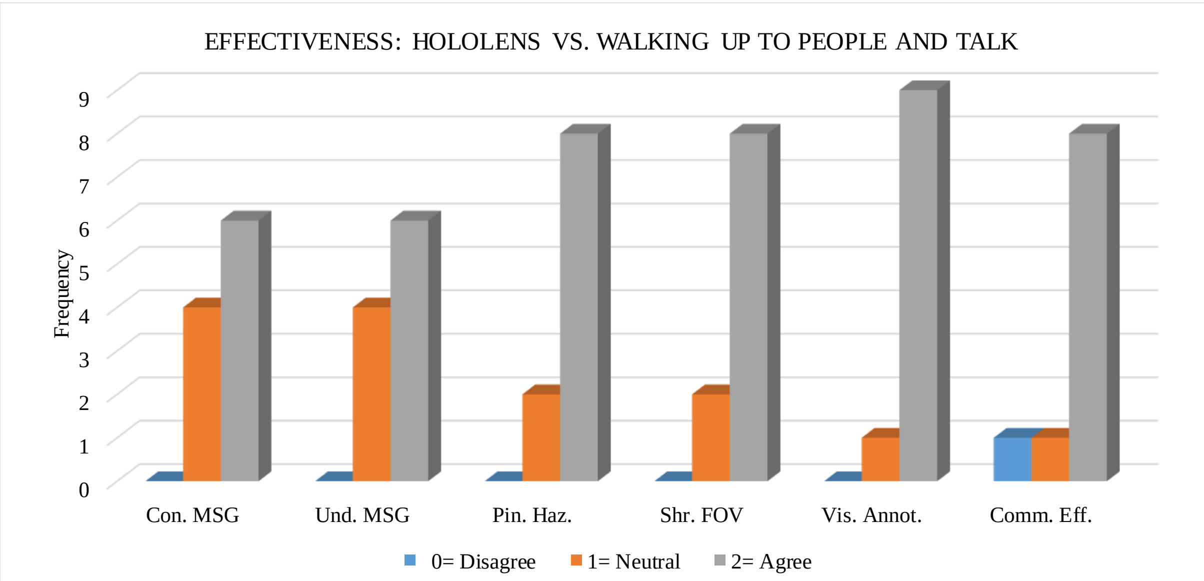

Fig. 4. Response counts of effectiveness on HoloLens® vs. walking up to people and talk

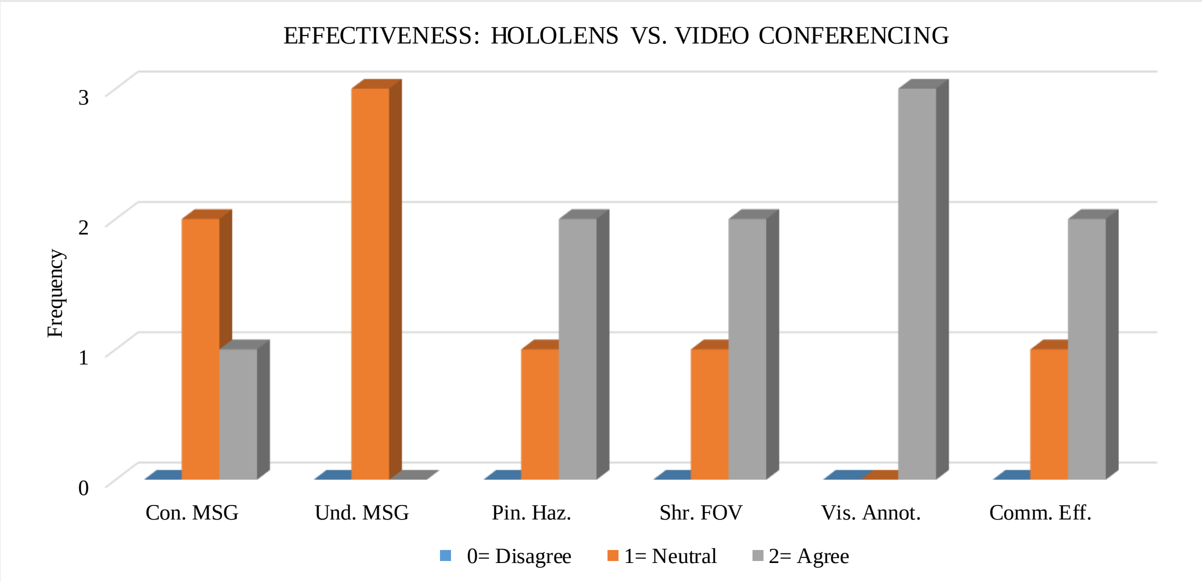

Fig. 5. Response counts of effectiveness on HoloLens® vs. video conferencing

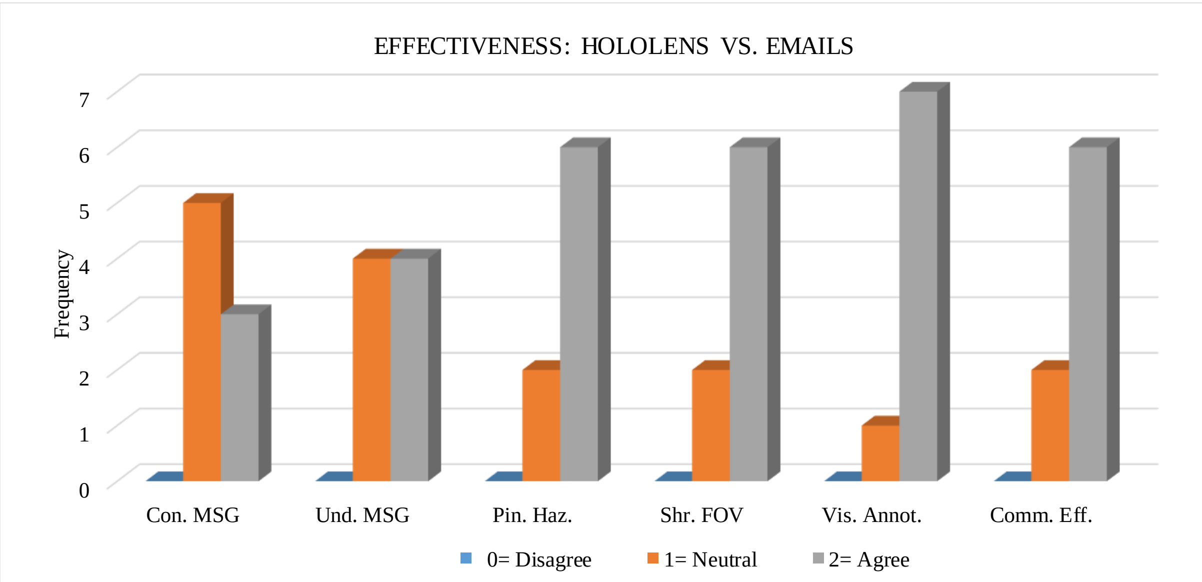

Fig. 6. Response counts of effectiveness on HoloLens® vs. emails

Median Scores. In non-parametric methods, the median of individual differences is used as the metric to express the size of group differences. This is because it provides an additional metric to facilitate the interpretation of results and give an express validation of the subjects' agreement. From **Table 1** below, the median scores of participants show that HoloLens® mixed reality outperforms phone calls, walking up to people and talk, video conferencing, and emails in terms of effectiveness when compared the observed median scores in "Agree" to "Disagree" and "Neutral". The median score for "Agree" when comparion made on HoloLens® versus phone calls is eleven (11) as against two (2) in "Neutral" and zero (0) in "Disagree". Similar comparison of HoloLens® versus video conferencing shows two (2) for "Agree", one (1) for "Neutral" and zero (0) for "Disagree" while HoloLens® versus walking up to people and talk indicates eight (8) for "Agree", two (2) for "Neutral" and zero (0) for "Disagree". In HoloLens® versus emails, the median score for "Agree" is six (6) compared to the two (2) for "Neutral" and zero (0) for "Disagree". Since the median score of the population of "Agree" returned significantly higher values in support of effectiveness of mixed reality versus other communications methods, we inferred that the mixed reality technology facilitates overall greater effectiveness than others during communication.

Table 1. Median scores for effectivenss

Group	HoloLens vs. Phone Calls	HoloLens vs. Video Conferencing	HoloLens vs. Walking Up to People and Talk	HoloLens vs. Emails
Disagree	0.00	0.00	0.00	0.00
Neutral	2.00	1.00	2.00	2.00
Agree	11.00	2.00	8.00	6.00

5.3. Kruskal Wallis H test of significance

To answer the first research question on whether the mixed-reality technology improves the effectiveness of risk communication on construction jobsites in contrast to the conventional methods, the Kruskal Wallis H test of significance was applied. **Table 2** shows the results, based on which there is a statistically significant p-value in effectiveness (all p-values less than the alpha level of 0.05: phone calls = 0.014, video conference = 0.023, walking up to people and talk = 0.001, and emails = 0.002), when HoloLens® is compared with these communication media. We can therefore reject null hypothesis that there is no difference in the mean scores of the variables and conclude that the mixed reality intervention significantly increases the effectiveness of construction risk communication compared to phone calls, video conference, walking up to people and talk, or emails.

Table 2. Kruskal Wallis H Test of Significance, α= 0.05

	HoloLens vs. Phone Calls	HoloLens vs. Video Conferencing	HoloLens vs. Walking Up to People and Talk	HoloLens vs. Emails
p-value	0.014	0.023	0.001	0.002

5.4. Cramer's V effect size test

To answer the second research question as to what extent the mixed-reality technology improves such communication based on the above metric. We conducted a Cramer's V effect size test. The test is to quantify the size of the difference between groups of variables. Using (Cohen 1988, p. 25 and 79) guideline, the magnitude of effect increases from 00-0.19 being very weak to 0.80-1.0 very strong (00-0.19 = very weak, 0.20-0.39 = weak, 0.40-0.59 = moderate, 0.60-0.79 = strong, 80-1.0 = very strong). As seen in **Table 3**, the effect size of the mixed reality in comparison to phone calls, walking up to people and talk, and emails are all in the strong or large zone (0.723, 0.742 and 0.742 respectively) indicating a large impact of mixed reality on communication effectiveness. The effect size of the mixed reality in comparision to video conferencing is not as strong as other comparisions. The reason might be the limited number of responses collected thus far in regard to experience with video conferencing that allows Hololens trails to be benchmarked with. Among all thirtheen participants, only three used to have experience of risk communication using video conferencing. It is expected that in the future study, as the number of responses increases with respect to experience with communication by using video conferencing, the relevant effect size will increase. The effect size test is particularly useful because it allows the analysis to move beyond the simplistic of the probability of statistical significance to the far more sophistication of the standard deviations of such significance. Moreover, by placing the emphasis on the most important aspect of an intervention - the size of the effect - rather than its statistical significance (which conflates effect size and sample size), and by doing so it promotes a more scientific approach to the accumulation of knowledge.

Table 3. Cramer's V effect size test

	HoloLens vs. Phone Calls	HoloLens vs. Video Conferencing	HoloLens vs. Walking Up to People and Talk	HoloLens vs. Emails
Effect Size	0.727	0.300	0.742	0.742

5. CONCLUSIONS AND FUTURE WORK

This paper presented the work of assessing effectiveness of applying the mixed-reality HoloLens® in enhancing risk communication at construction jobsites. The result from this study showed that the mixed reality technology possesses great potential for improving the risk communication on sites by evidence of the significant p-values and phenomenal effect sizes. The technology has the advantages for use in a dynamic construction environment because it allows users viewing the same space during remote collaboration and enables seamless and instance access to information needed for hazard understanding and communication. However, the current work suffers from limitations. The number of participants is limited, which might have impacts on the results; and the fact that people have never used the mixed reality intervention except for the few minute trials during the experiments might constitute a bias and threat to validity. Future work will collect more data to consolidate the findings in a statistically significant manner as well as seek to assess the remaining metrics including cost-effectiveness, ease-of-use, and acceptability of the mixed reality technology.

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