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An Augmented Reality System for the Construction Industry and Its Impact on Workers' Situational Awareness

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Abstract: Augmented reality (AR) technology assists construction workers by superimposing additional virtual information onto their real worksite environments. Ideally, this provides them with a better understanding of their tasks and hence boosts task performance. However, the additional information that AR places in users' field of view could limit their ability to understand what is going on in their surroundings and to predict how conditions may change in the near future. AR-assisted systems on construction sites could therefore expose their users to safety risks due to disturbance from the system. Hence, it is important to understand how AR-assisted systems can block users' understanding of their immediate environments, and in turn, how worksite safety in the construction industry could be improved through better design of such systems. This preliminary research conducted a laboratory experiment that simulated rebar inspection tasks and compared the situational awareness of AR users against that of subjects using traditional paper-based inspection methods, as measured by the Situation Awareness Rating Technique. Based on the results, we discuss the safety impact of head-mounted AR-assisted displays on situational awareness during construction tasks.

Keywords: Augmented reality-assisted systems, Rebar inspection tasks, Paper-based inspection, Situational awareness, Situation Awareness Rating Technique

1. INTRODUCTION

Augmented reality (AR) enables the superimposition of information useful to task performance onto real-world scenes via diverse display systems including head-mounted displays (HMDs), desktop screens, and tablets [1]. It offers important benefits at various stages during construction projects, such as 3D visualization during a design phase, safety/inspection assistance during construction, and information access and evaluation for maintenance and renovation [2], contributing to better task performance [3]. For example, task-related information (e.g., drawings, 3D models, assembly instructions, etc.) that are overlaid on the user's field of view in the AR environment can reduce the frequency of attention-switching between tasks and such information, allowing practitioners to remain more focused on the task itself [4].

However, inserting additional information into users' field of view has been found to reduce their head and eye movement in real worksite environments [5]. Consequently, in some circumstances, AR interfaces could limit a user's ability to fully recognize the surrounding environmental conditions and/or to predict how the conditions could change in the near future. Since a construction site is a complex and dynamic environment, failure to maintain an appropriate level of situational awareness (SA) can have serious negative effects on worksite safety [6]. However, even though previous research efforts have developed various AR applications in construction, the negative impact of AR systems on safety has not been fully considered when designing the AR system.

As a starting point for such research, we conducted an experimental study comparing workers' SA between traditional paper-based and AR-assisted rebar-inspection tasks. Specifically, participants were divided into two groups who were asked to conduct rebar inspection tasks using a traditional paper-based and an AR-assisted inspection method, respectively. For SA measurement, we simulated these tasks in a construction site-like environment in a laboratory and used the Situation Awareness Rating Technique (SART) after the tasks were completed [7]. Based on the results, we discuss two groups' awareness of their surroundings by each SART category, i.e., understanding of the surrounding situation, attention supply, and attention demand.

2. LITERATURE REVIEW

2.1. AR-assisted tasks for construction

Applications of AR in construction projects have increased considerably in recent years [8], mainly because such technology can aid understanding of work processes through visualization of construction elements or task-specific information (e.g., drawings, instructions, etc.) against the background of actual project sites [9]. For example, a tablet-based system that visualizes 2D drawings has shown its usefulness to detect dimension errors on worksites more easily [10]. Recently, due to the advancement in mobile AR devices such as HMDs (e.g., Microsoft HoloLens), users can perceive an augmented environment continuously while leaving their hands free [5, 11]. This could provide additional benefits in construction contexts, in which a given individual will commonly engage in both cognitive (e.g., checking drawing information) and physical activities (e.g., fixing, assembling, etc.). Though previous studies have tended to focus on desktop-based or tablet-based AR applications in construction [10, 12], HMD-based ones would also seem to have considerable potential for use in diverse construction tasks.

2.2. Situational awareness and AR-assisted display systems

In general terms, SA is being aware of what is happening around us. More specifically, Endsley [13] defined it as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." In the same work on SA theory, Endsley divided it into three levels, i.e., perception (level 1), integration and comprehension (level 2), and prediction (level 3).

In various complex and dynamic situations, a range of AR-assisted display systems are currently being used to support SA. In the security domain, for instance, an HMD-assisted display system is helping professionals to focus on the situation while keeping their hands free [14]. In ground transportation, AR-based systems can reduce drivers' distractions and thus increase their safety by boosting their understanding of the environment [15]. In aviation, AR-assisted head-up display systems enhance pilots' route awareness, such as through better understanding of their position within airports, distances to their next turns, and the directions of turns [16]. While these studies have found that the use of the AR system can enhance SA for the given task, one study [17] has reported that the additional information provided from the AR system and limited field of view may lead to users' failure of recognizing the surrounding conditions. This failure would have a negative impact on construction safety as construction workers should be continuously aware of safety risks at complex construction sites [18].

3. RESEARCH METHODOLOGY

To better understand how AR assistance could affect users' SA from a safety point of view, we selected rebar inspection tasks that involve intensive information processing within a short period and compared traditional paper-based and AR-assisted inspection tasks in a laboratory setting. Figure 1 represents an overview of the study procedure. First, we recruited a sample of 28 Ph.D. students (18 males, 10 females) from the Department of Building and Real Estate at the Hong Kong Polytechnic University. The participants were randomly divided into two groups of 14, one of which was assigned to paper-based inspection, and the other to AR-based inspection using a Microsoft HoloLens (A in Figure 1). Though the participants had various levels of professional experience in the construction industry, all were familiar with rebar inspection. To simulate a construction environment more realistically in the laboratory setting (B in Figure. 1), recorded sounds of construction equipment were played at accurate volumes, and a person was employed to drive a laden forklift trolley near each participant during the inspection task. The participants were asked to check for errors such as missing rebars, spacing issues, etc., in a sample of a rebar framework. While one group was given a paper-based rebar drawing during the inspection, the other was provided with 3D rebar drawing information superimposed on the actual rebar through HoloLens-based AR (C in Figure 1).

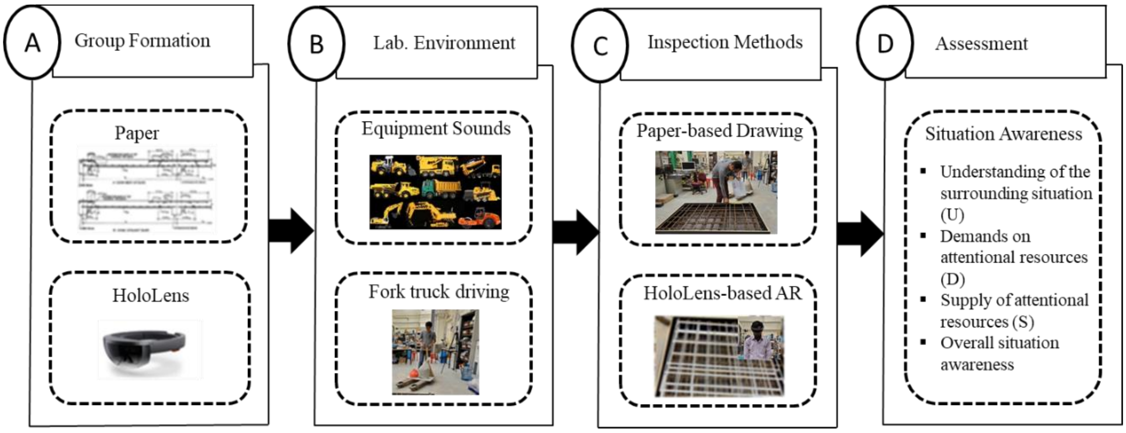
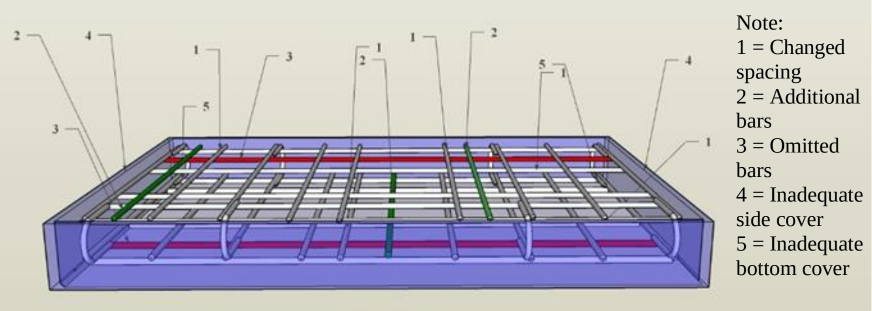


Figure 1. The framework of this research

In total, 14 errors were intentionally placed in the rebar framework, as shown in Figure 2. These fell into five general categories, i.e., 1) incorrect spacing between rebars (n=5), 2) extra rebars (n=3), 3) missing rebars (n=2), 4) insufficient rebar cover at the side face (n=2), and 5) insufficient rebar cover at the bottom face (n=2).



Note:
1 = Changed spacing
2 = Additional bars
3 = Omitted bars
4 = Inadequate side cover
5 = Inadequate bottom cover

Figure 2. A conceptual diagram showing errors in a rebar framework

During the paper-based inspection session, participants were asked to find one error from each of the five above-mentioned classes by comparing the rebar drawing to the rebars actually placed in the slab formwork, as shown in Figure 3 (left). They were also allowed to use a tape measure, if necessary. Rather than being provided with a drawing, each member of the second group wore a Microsoft HoloLens showing a 3D rebar model superimposed on the actual rebars, as shown in Figure 3 (right). The 3D rebar model was initially drawn in SketchUp and then integrated with the HoloLens app Trimble Connect (https://mixedreality.trimble.com/) for registration. Participants in both groups were instructed to perform the inspection task as fast and accurately as possible while remaining aware of changes in the surrounding environment.

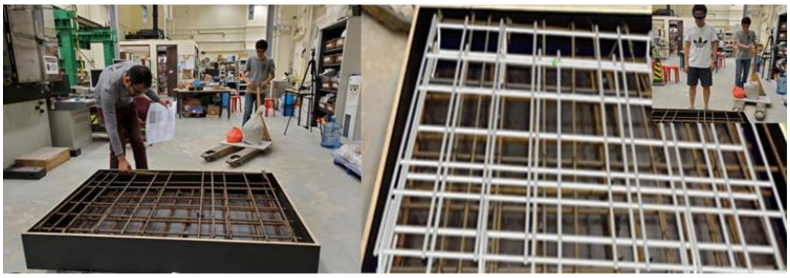


Figure 3. Paper-based and HoloLens-based AR inspection

For each session, we measured the participants' SA using SART [7] (D in Figure 1). The SART is a well-known post-trial subjective rating technique for the assessment of the participant's situation awareness. In this instrument, respondents self-report their SA based on 10 items, covering the surrounding environment's 1) information quantity, 2) information quality, 3) familiarity, 4) instability, 5) variability, and 6) complexity, and their own 7) arousal, 8) spare mental capacity, 9) concentration of attention and 10) division of attention. All items are answered using the same five-point Likert scale, ranging from 1 = Low to 5 = High. The 10 items are further grouped into three dimensions, i.e., understanding of the surrounding situation (U, items 1-3), demand on attention resources (D, items 4-6), and supply of attention resources (S, items 7-10); and a person's overall SART score is calculated as SA = U-(D-S). Here "Understanding" (U) referring to understanding of the surrounding situation; "Demand" (D), represents the amount of attentional demand placed on surrounding environment; and "Supply" (S) referring to applied cognitive resources on surrounding situation.

4. RESULTS

Rebar-inspection accuracy for each experimental session was measured using one-way analysis of variance (ANOVA), the results of which are shown in Table 1, along with the mean number of errors identified by error type with their standard deviations (SDs); F statistics; and significance levels (*p*). On average, the non-AR-using participants identified more errors than the AR users did, with significant differences observed between the two participant groups when it came to identifying spacing, side-cover, and bottom-cover errors ($p<0.05$). Also, a one-way ANOVA conducted on the data as a whole revealed statistically significant accuracy differences between the two inspection techniques ($p<0.05$).

Table 1. Total number of errors correctly identified in each treatment

Rebar error type	**Inspection medium**	**No. of errors placed**	**Mean no. of errors identified (SD)**	**F**	***p***
Spacing between bars	Paper HoloLens	5	3.64 (1.15) 2.35 (1.33)	7.44	0.01*
Extra rebars	Paper HoloLens	3	2.35 (0.74) 2.21 (0.57)	0.32	0.57
Missing rebars	Paper HoloLens	2	1.21 (0.80) 1.28 (0.61)	0.07	0.79
Side cover spacing	Paper HoloLens	2	1.92 (0.26) 0.85 (0.77)	24.17	0.00*
Bottom cover spacing	Paper HoloLens	2	1.07 (0.82) 0.00 (0.00)	19.11	0.00*
Total no. of errors identified	Paper HoloLens	14 14	10.19 (3.77) 6.69 (3.28)	11.91	0.00*

Note. * = significant difference ($p < 0.05$).

Next, we used one-way ANOVA to examine the SART three main dimensions and overall SART scores within each treatment. As well as these overall scores with their cumulative mean values and SDs, Table 2 presents F statistics, and significance levels (*p*). For this purpose, first, we grouped SART 10 items into three main dimensions namely: (1) understanding of the surrounding situation or U (information quality, information quantity, familiarity); (2) the amount of attentional demand placed on surrounding environment or D (complexity, variability, instability); and (3) supply of cognitive resources on surrounding situation or S (arousal, concentration, division of attention, mental capacity). Then, by conducting one-way ANOVA test, we noticed significant inter-group differences in the three main SART categories ($p<0.05$). The higher cumulative average score of (U) in the non-AR group (9.99) expresses that participants were more understanding of the surrounding situation than the AR users (8.76). The cumulative average values of (D) in the non-AR group (10.19) represent that the non-AR group was putting more attention to observe any changes in the surrounding environment than the AR users (9.48). And the cumulative average values of (S) in the non-AR group (13.40) indicates that participants of this group were used more cognitive resources on surrounding situation than AR users (11.37). After analysing cumulative mean group scores of SART three dimensions, a total SART score is calculated by using the formula, SA = Understanding – (Demand – Supply). The overall cumulative mean SART score was found higher in the non-AR group (13.20) than for the AR-assisted group (10.55) which indicates that the non-AR group had higher SA; however, this difference was not statistically significant ($p>0.05$). The following three subsections provide detailed discussions of each SART category in turn.

Table 2. Situation Awareness Rating Technique scores

SART category	Inspection medium	Mean (SD)	F	*p*
Understanding of the surrounding situation (U)	Paper HoloLens	9.99 (2.69) 8.76 (2.38)	4.85	0.03*
Attention demand (D)	Paper HoloLens	10.19 (2.13) 9.48 (2.27)	6.89	0.01*
Attention supply (S)	Paper HoloLens	13.40 (3.72) 11.37 (3.22)	10.61	0.00*
Overall situation awareness (SA)= U-(D-S)	Paper HoloLens	13.20 (4.28) 10.55 (3.33)	0.41	0.52

Note. * = significant difference ($p < 0.05$).

4.1. Understanding of the surrounding situation

Table 3 presents the SART scores for each subfactor of category U. There are no statistically significant differences between the two sessions, with all *p* values >0.05. However, a statistically significant difference was observed between two sessions for total understanding of the surrounding situation (information quality, information quantity, and familiarity). The cumulative mean values of total understanding of the surrounding situation were also observed higher in the non-AR group (9.99) than the AR users (8.76), which clearly indicates that non-AR group participants were more understanding of the surrounding situation.

Table 3. Situation Awareness Rating Technique scores for items on understanding of the surrounding situation

Subfactors of U	Inspection medium	Mean (SD)	F	*p*
Information quantity of the surrounding situation (U1)	Paper HoloLens	3.42 (0.93) 2.92 (0.82)	2.35	0.14
Information quality of the surrounding situation (U2)	Paper HoloLens	3.07 (0.82) 2.92 (0.73)	0.23	0.63
Familiarity with the surrounding situation (U3)	Paper HoloLens	3.50 (0.94) 2.92 (0.83)	2.90	0.10
Total understanding of the surrounding situation = U = U1+U2+U3	Paper HoloLens	9.99 (2.69) 8.76 (2.38)	4.85	0.03*

Note. * = significant difference ($p < 0.05$).

4.2. Demands on attentional resources

As Table 4 indicates, with regard to each subfactor of D, there was no statistically significant difference between the two sessions, with all *p* values >0.05. However, a statistically significant difference was observed between two sessions for total demand on attentional resources (instability, variability, and complexity). The cumulative mean value of total attention demand was also noticed higher in the non-AR participants (10.19) which denotes that non-AR participants were putting more attention to observe any changes in the surrounding environment than the AR users (9.48).

Table 4. Situation Awareness Rating Technique scores for items on attention demand

Subfactors of D	Inspection medium	Mean (SD)	F	*p*
Instability of the surrounding situation (D1)	Paper HoloLens	3.42 (0.75) 3.21(0.69)	0.60	0.44
Variability of the surrounding situation (D2)	Paper HoloLens	3.35 (0.74) 2.78 (0.80)	3.81	0.06
Complexity of the surrounding situation (D3)	Paper HoloLens	3.42 (0.64) 3.00 (0.78)	2.48	0.12
Total attention demand = D = D1+D2+D3	Paper HoloLens	10.19 (2.13) 9.48 (2.27)	6.39	0.01*

Note. * = significant difference ($p < 0.05$).

4.3. Supply of attentional resources

Table 5, which presents the SART scores for each of the four subfactors of S, shows that two of them – division of attention (S3) and spare mental capacity (S4) – differed significantly between two sessions ($p<0.05$). There was also a statistically significant difference was observed between the two sessions for total supply of attentional resources (arousal, concentration, division of attention, and mental capacity). The higher cumulative mean value in the non-AR group (13.40) also indicates that participants of this group were used more cognitive resources on the surrounding situation than AR users (11.37).

Table 5. Situation Awareness Rating Technique scores for items on attentional supply

Subfactors of S	Inspection medium	Mean (SD)	F	*p*
Arousal (S1)	Paper HoloLens	3.35 (0.74) 2.85 (0.95)	2.40	0.13
Concentration of attention (S2)	Paper HoloLens	3.21(0.97) 3.07 (0.82)	0.17	0.68
Division of attention (S3)	Paper HoloLens	3.42 (1.08) 2.64 (0.63)	5.44	0.02*
Spare mental capacity (S4)	Paper HoloLens	3.42 (0.93) 2.71 (0.82)	4.57	0.04*
Total Attention Supply = S = S1+S2+S3+S4	Paper HoloLens	13.40 (3.72) 11.37 (3.22)	10.61	0.00*

Note. * = significant difference ($p < 0.05$).

5. DISCUSSION

This study of SA across paper-based and AR-assisted rebar-inspection tasks has revealed that using the focal AR-assisted system led participants to understand their surroundings less well than a similar group that used traditional paper methods to complete the same task under the same conditions. The superimposed 3D rebar model shown in the head-mounted AR display system worn by the members of the former group appeared to help them to detect a certain kind of error, missing rebars. However, its disadvantage in terms of SA was observed across all three categories of the SART (U, D, and S); and the system could therefore be reasonably expected to increase potential worksite safety issues. Considering that inspectors on construction worksites perform several activities simultaneously – looking, comprehending, searching, remembering, and deciding – they are generally required to achieve full understandings of their surroundings over a very short period. Our experimental results confirm that equipping inspectors with head-mounted AR-assisted systems is likely to be unhelpful in such situations, as participants in the paper-based condition were more fully aware of small changes in the background environment than their AR-assisted counterparts were. In part, this could be explained by HoloLens' relatively small field of view, which would have tended to focus its wearers' attention more narrowly on their tasks than natural human vision would, and thus rendered them less alert to potential changes in their immediate environment.

6. CONCLUSIONS

Our findings have revealed that both the information provided in the display of an AR-assisted system, and that system's relatively restricted field of view, can negatively influence construction practitioners' SA, and thus would likely increase potential safety issues if used during worksite inspection tasks. However, a key limitation of this study that should be borne in mind before generalizing from its results is that it only looked at one type of AR-assisted system. Therefore, future research should examine the impacts on users' SA of others (e.g., tablet-based) AR-assisted display systems, especially those with better fields of view.

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