Exploring the Construction Task Performance and Cognitive Workload of Augmented Reality-Assisted Rebar Inspection Tasks

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ABSTRACT

Augmented reality (AR) is capturing increasing attention as a way to provide cognitive assistance in many fields. Inspiring from the benefits of AR, architecture, engineering and construction industries and researchers are interested to apply AR technologies for various construction tasks such as design review, assembly, inspection or facility maintenance, etc. However, even though AR technologies are designed to support users' cognitive capability by providing superimposed information on real-world scenes, this information from AR may lead to one's cognitive overload, causing an adverse effect on task performance. As a result, it is important to understand how AR would affect one's cognitive load, and in turn, task performance for better use of AR systems in construction. As a preliminary investigation, this research compared task performance and cognitive loads during traditional paper-based and AR-assisted rebar inspection tasks at the laboratory setting. Participants' task performance and cognitive load were measured by 1) completion time and the number of rebars correctly detected, and 2) NASA Task Load Index (TLX). Based on the result, we discussed the impact of AR application on rebar inspection tasks from a cognitive perspective.

INTRODUCTION

The architecture, engineering and construction (AEC) industry has moved to embrace augmented reality (AR) technologies due to their potential application areas at different project stages such as visualization during design stage, safety/inspection during construction, and information access and evaluation for maintenance during facility management stage (Rankohi and Waugh, 2013). From a cognitive perspective, as these tasks in the AEC industry involve information-intensive processes, AR-assisted tasks that allows practitioners to reduce cognitive burden for information handling could lead to enhanced work performance. For example, in the AR environment, additional information (e.g., computer graphics, text, sound) are overlaid in the user's field of view, lowering the frequency of attention switching between tasks and information required for the tasks (e.g., manuals, drawings, etc.), and thus user' performance is expected to increase (Wang and Dunston, 2006). In addition, by integrating spatially related information to physical objects and locations in the real world, AR provides strong leverage of spatial cognition and memory (Biocca et al., 2001). As a result, performing the cognitive construction tasks with an aid of the AR system could reduce the mental workload and task completion time (Wang and Dunston, 2006).

Despite these benefits of AR, additional information provided to the users from AR systems could lead to unexpected consequences such as a cognitive overload issue (Bellucci et al., 2018). In some of the occasions, AR interfaces could overload the user with excessive information such that important cues from the actual environment could be missed, leading to the user's performance loss. However, previous studies on AR systems have not fully considered this issue when designing the systems, and no specific AR system design guideline exists to prevent from the cognitive overload (Li and Duh, 2013). As a result, in-depth understanding on how AR would affect the user's cognitive load (CL) and task performance in the context of construction tasks would be helpful for better design of AR systems in construction.

As a starting point, this study conducted an experimental study to compare CL and task performance during traditional manual (paper-based) and AR-assisted rebar inspection tasks to understand the relationship between CL and performance. In particular, two groups of participants were recruited for the experiments, and each group was given a rebar inspection task for a concrete slab using a paper-printed rebar drawing and a 3D rebar model superimposed on a slab using an AR device (i.e., Microsoft Hololens). For task performance, we measured completion time and errors identification rate while CL was measured by using the NASA Task Load Index (TLX) (Hart, 2006). Based on the result, we discussed the user' performance and each category of NASA TLX (mental demand, temporal demand, performance, effort, and frustration) for traditional paper-based and AR-assisted inspection.

LITERATURE REVIEW

AR-assisted tasks for construction

The applications of AR technology in construction projects have been significantly increased in recent years (Piroozfar et al., 2018). The main motivation towards is that it could ease to understand the work process by visualizing construction elements or task-specific information (e.g., drawings, instructions, etc.) against the background of an actual project site through various AR systems and devices (Kopsida & Brilakis, 2016). For example, a tablet-based AR system could enable construction professionals to easily detect dimension errors on the jobsite through the assistance of ARToolKit (Kwon et al., 2014). Recently, due to the advance of AR devices such as Head Mounted Displays (HMD) (e.g., Microsoft HoloLens), users can constantly perceive an augmented environment while leaving one's hands-free (Polvi et al., 2018; Tang et al., 2003). This could provide additional benefits in the construction context where both cognitive (e.g., checking drawing information) and physical (e.g., fixing, assembling, etc.) activities are very common to perform tasks. Even though previous studies have focused on the use of desktop-based or tablet-based AR applications in construction (Kim et al., 2013; Kwon et al., 2014), HMD-based AR applications would also have great potential to be used for diverse construction tasks.

Cognitive load and AR-assisted tasks

While a number of definitions of CL exist, this study considers CL as the amount of mental efforts during one's information processing (Brunken et al., 2003). According to the cognitive load theory by (Doswell and Skinner, 2014) that describes one's limited cognitive capability, human working memory can only handle seven (plus or minus two) disconnected items in average simultaneously, and thus cognitive overload could occur when human working memory is forced to process excessive information too quickly. As a result, the amount of information that needs to be handled could significantly affect one's task performance.

Various studies have studied the relationship between CL and performance, which can be illustrated in Figure 1. Paas et al. (2004) and Lindblom and Thorvald (2014) have found that either too low CL (underload) or too high CL (overload) could lead to performance issues. For example, cognitive underload could occur when the user heavily relies on the system for the tasks and thus may cause the loss of interest by the user, leading to more task-related errors. Instead, if the amount of information from the system and the interaction between the system and the user surpasses human processing capacity, the user could not process all the information properly. So, Mendel and Pak (2009) argued that user performance could be increased by reducing CL during information-intensive tasks. In conclusion, these studies indicate that the amount of information provided to users can influence their performance. During AR-assisted tasks, the users could be exposed to cognitive underload, and overload conditions depend on how AR systems are designed to support tasks. As the optimal performance of AR-based system can be achieved only when appropriate amount of information is provided, understanding the user's cognitive load in the AR environment and the corresponding performance is of importance for better use of AR systems.

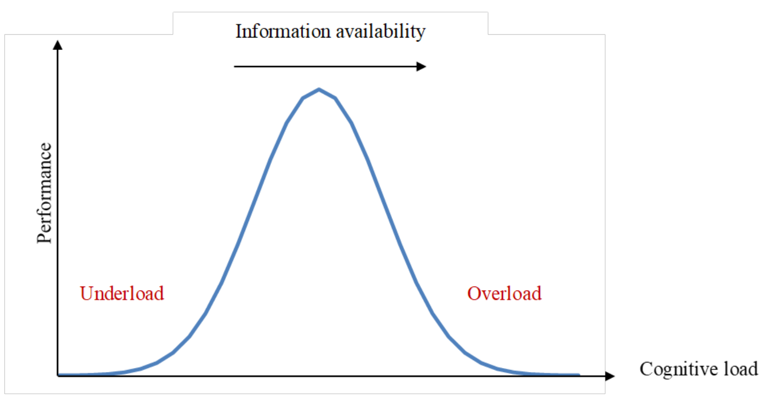

Figure 1. Relationship between CL and performance (Lindblom and Thorvald, 2014; Lyell et al., 2018; Paas et al., 2004)

RESEARCH METHODOLOGY

To understand how AR assisted tasks would affect CL and performance to users, we selected rebar inspection tasks that involve intensive information processing in a short period and compared traditional paper-based and AR-assisted tasks by simulating them at the laboratory setting. Figure 2 represents an overview of the procedure developed in this study. First, a sample size of 30 male and female Ph.D. students in the department of building and real estate at the Hong Kong Polytechnic University, were recruited for the experiment. The participants were randomly divided into two groups of each sample size of 15 students for paper-based, and HoloLens-based AR assisted inspection tasks (A in Figure 2). The participants have varying level of professional construction industry experience and thus were well-known about rebar inspection. The participants were asked to perform the rebar inspection task to check errors (e.g., missing rebars, spacing issues, etc.) in the small sample of the concrete slab. One group was given a paper-based rebar drawing during the inspection, while the other group was given 3D rebar drawing information superimposed on the actual rebar placement through HoloLens-based AR (B in Figure 2).

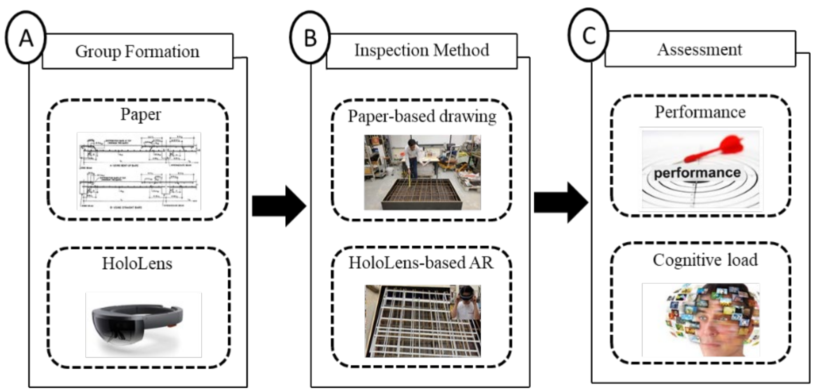

Figure 2. The framework of this research

The main task is to check the five reinforcement items errors: 1) spacing between rebars, 2) missing rebars, 3) extra rebars, 4) insufficient rebar cover at the side face, and 5) insufficient rebar cover at the bottom face. In total, fourteen errors were intentionally placed in the rebar framework, as shown in Figure 3.

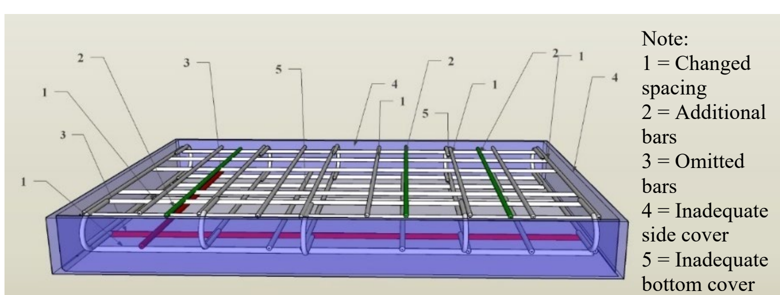

Figure 3. A conceptual diagram showing errors in the rebar framework

Specifically, during the paper-based inspection session, participants were asked to find the five items of rebar errors by comparing the rebar drawing and the rebars placed in the slab formwork as shown in figure 4 (left). Also, they were allowed to use a tape measure, if needed. The second group of participants performed the same task wearing Microsoft HoloLens that shows a 3D rebar model superimposed on the rebars placed, as shown in figure 4 (right). The 3D rebar model was drawn first in SketchUp and then was integrated with Trimble Connect that is a HoloLens App for AR application (https://mixedreality.trimble.com/) for registration. Participant in both groups were instructed to perform the inspection task as fast and accurately as possible.

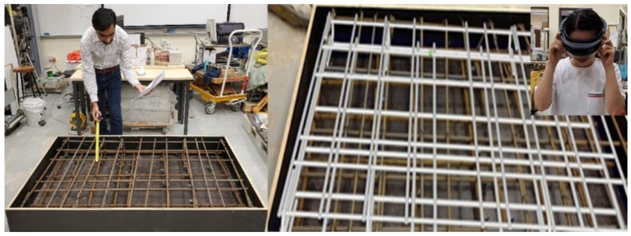

Figure 4. Paper-based and HoloLens-based AR inspection

For each session, task performance was measured using objective measures such as completion time and the total number of rebar errors correctly identified. CL perceived by participants was measured using the NASA task load index (Hart, 2006). Originally, NASA task load index contains six items (mental demand, physical demand, performance, temporal demand, effort and frustration level). However, one item "physical demand" would not be relevant to rebar inspection tasks, and thus it was not included in this study. Even though 'performance' can be observed directly using objective measures suggested above, it was included because it could imply other factors such as the level of satisfaction, self-esteem, and motivation. So, based on the five items (mental demand, performance, temporal demand, effort and frustration level), participants rated their CLs after the session using a five-point Likert scale (1 = Low, 5 = High).

RESULTS

Figure 5 and 6 illustrates the time for completion of each individual participant during the paper-based and AR-assisted sessions, respectively. The results show that AR-assisted rebar inspection took shorter completion time than paper-based inspection, indicating that AR assistance for rebar inspection significantly increased task performance.

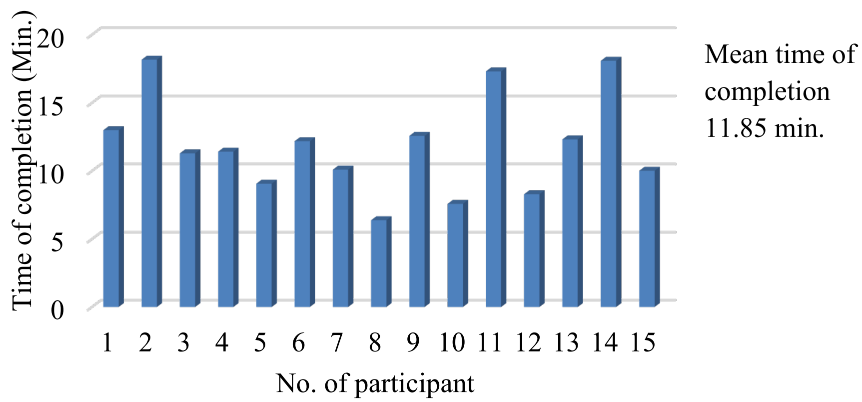

Figure 5. Time of completion in paper-based inspection

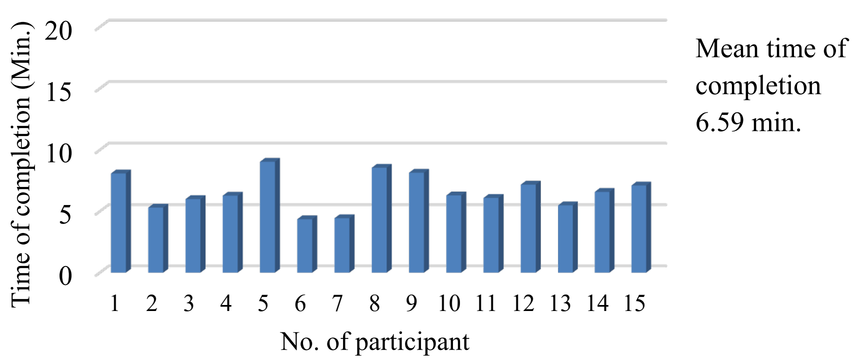

Figure 6. Time of completion in AR-assisted inspection

In terms of accuracy of rebar inspection, the one-way ANOVA procedure examines error identification rates in each experimental session, as shown in Table 1. Table 1 shows rebar errors (e.g., mean and standard deviation (SD), F statistics with degree of freedom and significance level (p)). The one-way ANOVA reveals there is no statistically significant difference between the paper-based inspection and AR-assisted inspection groups for identifying spacing, number of less and additional bar errors (p values are greater than 0.05). However, one-way ANOVA revealed a significant difference between paper-based and AR-assisted participants to identify side cover errors, $F(1,28) = 30.82$, $p < 0.05$ and bottoms cover spacing errors $F(1,28) = 5.67$, $p < 0.05$.

Table 1. Total Number of Errors Correctly Identified in Each Treatment. The Symbol * Indicates Significance Difference (*p* < 0.05)

Rebar errors	Instruction medium	No. of errors placed	No. of errors identified Mean (SD)	F {1,28}	*p*
Spacing between bars	Paper-based drawing	5	2.73 (1.43)	0.40	0.53
	HoloLens		3.0 (0.75)		
Missing rebars	Paper-based drawing	2	1.60 (0.63)	0.33	0.57
	HoloLens		1.46 (0.63)		
Extra rebars	Paper-based drawing	3	1.66 (0.48)	1.75	0.19
	HoloLens		2.0 (0.84)		
Side cover spacing	Paper-based drawing	2	1.66 (0.61)	30.82	0.00*
	HoloLens		0.4 (0.63)		
Bottom cover spacing	Paper-based drawing	2	0.6 (0.82)	5.67	0.02*
	HoloLens		0.06 (0.70)		

Finally, the one-way ANOVA procedure examines the CL in each treatment (Table 2). Table 2 shows self-rating results using NASA TLX (e.g., mean and standard deviation (SD), F statistics with degree of freedom and significance level (*p*)). These results show no statistically significant difference exists between the two sessions (all *p* values are greater than 0.05). However, on average, it seems that participants in AR-assisted rebar inspection sessions had less amount of CL. Especially, the largest difference between paper-based and AR-assisted inspection was observed in the frustration level.

Table 2. ANOVA Results: NASA TLX Scores for Each Item for Evaluating CL

NASA TLX items	Instruction medium	Mean (SD)	F {1,28}	*p*
Mental Demand	Paper-based drawing	3.20 (0.77)	1.12	0.29
	HoloLens	2.93 (0.59)		
Temporal Demand	Paper-based drawing	3.0 (0.75)	0.21	0.65
	HoloLens	2.86 (0.83)		
Effort	Paper-based drawing	3.06 (0.70)	1.12	0.29
	HoloLens	2.80 (0.67)		
Performance	Paper-based drawing	3.46 (0.74)	0.06	0.80
	HoloLens	3.40 (0.73)		
Frustration Level	Paper-based drawing	2.40 (0.91)	2.46	0.12
	HoloLens	1.93 (0.70)		
Total CL workload	Paper-based drawing	3.02 (0.44)	3.00	0.09
	HoloLens	2.78 (0.29)		

DISCUSSION

This study compared participants' CL and performance in paper-based and AR-assisted rebar inspection tasks, and the results indicated AR-assisted rebar inspection had better performance and also less CL. In terms of performance, participants with AR assistance found side cover and bottom cover spacing errors less accurately compared with participants in paper-based sessions. The superimposed 3D rebar model during AR-assisted sessions may help the participants to easily detect errors in terms of the numbers of rebars or spacing issues but would not provide clear depth information on rebar placement. Even though no significant difference was observed, AR assistance tends to reduce participants' CL in all NASA TLX items investigated, which may contribute to better performance. Rebar inspectors perform several cognitive activities simultaneously such as looking, comprehending, searching, remembering, and deciding. This often makes it difficult for inspectors to check rebar errors in a short time (Yabuki and Li, 2007). Our experimental results confirmed that the AR system is likely to be particularly helpful in such situations, as it can allow participants to reduce their mental demand to examine all distances and spaces of reinforcing bars by directly comparing the 3D rebar model and rebars placed in the form. The temporal stress would not discourage the participants in AR-assisted sessions because the 3D information is superimposed on the real environment and the participants did not require time-consuming gaze shifts between the screen of the HMD and the real environment. Also, AR-assisted inspection required low effort (mentally and physically). However, participants in AR-assisted sessions were a little bit less satisfied with their performance in accomplishing the task goal. This could be explained by the unfamiliarity of this new technology and the discomfort due to a small field of view of HoloLens. Whereas, low frustration level in using AR-assisted sessions indicates that participants did not require to use a tape measure to check each rebar distances because the superimposed 3D rebar model may help participants to easily detect errors.

CONCLUSIONS

The findings of our study exposed that the type of information format presented to the construction practitioners can influence their cognitive demands and performance. Especially, the rebar drawing information that was provided by a superimposed rebar model in AR-assisted inspection would help to decrease the users' CL to find required information (e.g., the number of rebars required, proper spacing, etc.) and to process the information (e.g., identifying missing rebars or additional rebars placed). Also, the decreased CL during rebar inspection would contribute to better performance. Despite the useful findings in this study, however, there are some limitations in this study, suggesting the future research direction. First, it should be further studied that how different ways of information visualization (e.g., superimposed 3D models with additional information such as dimensions or rebar inspection instructions) in AR systems would affect both performance and CL. Also, as the limited field of view of HoloLens could be a significant factor that may affect performance and CL, other types of AR systems with a better field of view such as table-based AR needs to be examined.

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