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MEASURING THE IMPACTS OF AR HMD ON USERS' SITUATION AWARENESS DURING WOOD FRAME ASSEMBLY TASKS

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SUMMARY: *Advances in the development of Augmented Reality (AR) hardware and software allow for novel opportunities to positively influence the traditional construction industry. Recent research studied the feasibility of various AR devices for supporting construction assembly tasks, however, there is limited work examining the usability of AR head-mounted display (HMD) in relation to construction workers' cognitive skills such as situation awareness. This study evaluated three information display types (paper blueprint, tag-along image and conformal model) during wood frame assembly of three different scales (small, medium, and large) to investigate how AR HMDs impact user's situation awareness with respect to mental workload. Eighteen construction engineering students were recruited in a within-subjects experiment. The findings showed no significant difference in both the mental workload and the situation awareness for all three display types, suggesting that AR displays did not generate significant excessive mental burden or distractions on users in comparison to traditional paper-based information. Specifically comparing the AR displays, the results revealed that user's mental workload was affected by field of view (FOV) restriction in AR HMD, whereas situation awareness wasn't impacted.*

KEYWORDS: *Augmented Reality (AR), Head-Mounted Display (HMD), Mental Workload, Situation Awareness, Wood Frame Assembly, Field of View (FOV)*

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1. INTRODUCTION

Augmented Reality is an emerging technology in the AEC industry as a method for effectively and intuitively presenting information, and construction practitioners are exploring how to apply AR to more traditional construction activities, such as on-site assembly. As a visualization technology that connects virtual objects and the physical world, AR can meet the demands of a wide range of on-site construction tasks that require access to instructional information, collaboration, and inspection in various construction tasks. Although the number of studies about AR applications for construction are increasing, there is still an essential need to develop a comprehensive AR visualization system to enhance its usability (Qin et al., 2021; Qin and Bulbul, 2022). An intuitive natural user interface is paramount for using AR in the field (Chi et al., 2013; Rankohi and Waugh, 2013), and a portable and immersive device would be a desired AR display due to the dynamic environment of construction site. With the fast-paced development of AR technologies, there are multiple commercial HMDs (Microsoft HoloLens, Google Glasses, Vuzix Smart Glasses, etc.) that can be competently used in the field. However, the adoption of AR HMD for construction tasks is still in the research stage as several technical challenges need to be addressed before it can be used in the field.

One of the technical difficulties for the existing HMDs is the restriction of field of view (FOV), which can potentially interfere with user's task performance. Early research suggests that perceptual biases may be caused by FOV limitations and thus leads to an underperformance in task completion (Drascic and Milgram, 1996). Moreover, the incomplete perception of information from the environment will further affect the comprehension and projection based on Endsley's three-level situation awareness model (1995). It suggests that the restriction of FOV may weaken user's situation awareness. On the construction side, recent studies (Gheisari et al., 2010; Hasanzadeh et al., 2018) discussed the causal relationship between insufficient situation awareness and higher probability of construction accidents. Moreover, Jung et al. (2018) demonstrated the trade-off between immersion of an AR system and user's situation awareness, indicating that a strengthened immersive AR display may reduce the situation awareness. However, there is limited research for AR HMDs impact on user's situation awareness. Especially in the case of a large construction assembly task, the restriction of FOV prevents workers to perceive the entirety of a model, which could potentially distract the user to adjust their position and seek information out of their view. Thereby, workers may fail to perceive the potential hazards in the field and increase their risk of having an accident. Consequently, there is an essential need to study the impact of AR displays and its limited FOV on user's situation awareness when considering the usability of AR HMD in the construction field.

Situation awareness was demonstrated to be supported by working memory in a dynamic environment (Gutzwiller and Clegg, 2013), which shared the same cognitive resource with mental workload. Early research identified that mental workload is based on the intricate relations between "the requirements of a task, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the operator" (Hart and Staveland 1988). Vidulich and Tsang (2015) argued that it is important to analyze both situational awareness and mental workload for assessing the effectiveness of task and interface design, because they could either support or compete with each other. In the construction domain, Chen et al. (2016) proposed that mental workload could be an indicator for estimating worker's safety awareness. Furthermore, similar to situation awareness, the limited FOV of HMD could hinder the accessibility of information for a large-scale layout, potentially increasing the mental effort to acquire task information. By comparing AR and other information displays, measuring mental workload reflects the effectiveness of presented information, which helps in understanding how efficient and intuitive each information display type can be for situation awareness.

Through this paper, we explored how both situation awareness and mental workload were subject to changes in two factors: *information display type* (paper blueprint, tag-along image, and conformal model) and *framing scale* (small, medium, and large) during a wood frame assembly. Since assembly is one of the core tasks in construction, the wood framing experiment was used in this study because it has the proper task complexity, which involves steps such as measuring, marking, searching for information, remembering information and such. The potential benefit of AR for assembly tasks is that it mitigates searching for information by placing the information in its context, in front of the user. Although there are multiple assembly tasks in construction at different complexity levels, wood frame assembly is selected for this research because it was simple enough for recruiting test subjects and challenging enough for the test subjects to have measurable number of errors. The outcomes are expected to provide clues for evaluating AR HMD use in other construction assembly tasks by comparing different information formats. Additionally, wood frame structure is the most used in residential projects in the U.S. The nine possible combinations of assembly settings in the study can simulate different framing conditions in the real world. By involving different framing scales, the effects of restricted FOV in HMD on workers' cognitive skills were investigated. In addition to paper documentation, two AR displays were designed to help in understanding how different display types could affect workers' cognitive skills with the same restriction of FOV. Given our previous work examining the impact on framing efficiency and accuracy (Qin et al., 2021), this study explored the cognitive analysis for adopting AR HMD in various framing conditions.

2. THEORETICAL BACKGROUND

2.1 Information Processing and Mental Workload

The Information Processing Model provided by Atkinson and Shiffrin (1968) first explained the mechanism of how the brain acquires, processes, and stores information. Based on this theory, Sweller (1988) proposed the Cognitive Load Theory (CLT), further emphasizing the limited capacity of working memory to temporarily hold information during tasks. It was highlighted that task and instructional materials should be carefully designed to avoid information overloading. Three types of mental workload were believed to collectively occupy working memory, which were *intrinsic load*, *extraneous load*, and *germane load*. Among them, extraneous load reflects the effectiveness of instructional materials and is considered the key to reduce overall mental workload, while the other two are associated with inherent features: task complexity and individual's ability of constructing schemas. In this study, participant's extraneous load depended on the information provided on the displays, which revealed the discrepancy of mental workload generated by each display method.

Since there is a fundamental difference between how information is presented on paper, 2D AR displays, and 3D AR displays, the Multiple Resources Theory (MRT) provided by Wickens (1984) can provide insight on how these graphical presentations utilize different cognitive resources. According to MRT, the processing code is generally composed of verbal and spatial resources, which are anatomically related to left and right cerebral hemispheres. This indicates that spatial and verbal information can be separately processed in the brain at the same time. The displays used in this study required participants to use different amount of each resource for processing framing instructions. For instance, conformal model had higher demand for spatial ability while 2D displays asked for verbal calculation for dimensions. Furthermore, Parasuraman and Caggiano (2005) suggested that the MRT can be conceptualized as the amount of information that can be processed in working memory, which shows a consistent viewpoint between the MRT and CLT. This hints the causality between adoption of different information displays and possible discrepancy in mental workload.

2.2 Situation Awareness

The evaluation of situation awareness in this study was based on Endsley's (1995) model, which hierarchically defined three levels of situation assessment: *perception*, *comprehension*, and *projection*. Each level is the precursor to the next, forming a chain from perception, through interpretation, to prediction, which then supports the decision-making process. This process helps construction worker to comprehend critical factors in the environment and predict future status. Recent studies investigated the relationship between various construction accidents and failure to perceive potential risks caused by lack of situation awareness (Garrett and Teizer, 2009; Gheisari et al., 2010; Fang et al., 2018; Hasanzadeh et al., 2018). Especially, the findings revealed that users' situation awareness was impacted by factors such as task complexity, workload, stress, and visual attention. When the attentional distribution is occupied by these factors, users' need to maintain sufficient awareness to perceive and react to the environmental information, which can protect them from hazards. Therefore, evaluating the impact of AR displays has on workers' situation awareness is of paramount importance for adopting this technology in the field, especially when considering how restricted FOVs can negatively impact workers performance (Drascic and Milgram, 1996; Arthur and Brooks Jr, 2000). In this study, comparative evaluation of participants' situation awareness was conducted between all information display types with different scales of framing tasks that could result in a visualization problem.

3. LITERATURE REVIEW

3.1 AR in Construction Assembly

The attempts to utilize AR HMD in construction assembly dates back to when Reiners et al. (1999) first adopted

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a see-through HMD with a camera for a door lock assembly task. An improvement of intuitive interpretation of the assembly instruction was reported by the participants, which was credited to the immersive display spatially relating a virtual design to physical objects. In the light of this outcome, the potential applications of AR in construction assembly are further explored in the past decades. A wide range of laboratory-scale research has been conducted to understand the impact of AR on user's task efficiency and accuracy. Tang et al. (2004) proposed a directed assembly of Duplo blocks using various instructional designs, where the AR HMD showed an advantage in both efficiency and accuracy compared with printed manual and 2D monitor display. Compared with a video-based instruction, Loch et al. (2016) found a similar result in Lego block assembly. In addition to these applications for small-scale simulations, AR has also been evaluated in pipe assembly with higher demand of spatial cognition. Both Hou et al. (2013) and Kwiatek et al. (2019) concluded that AR helped users to improve spatial cognition and performance in assembling complex spatial models. These findings echoed the point of view from Biocca et al. (2001), that AR can leverage user's spatial cognition by building spatial connections between virtual and physical objects. In essence, AR applications utilized this capability to improve productivity and performance in assembly tasks. On the basis of these precursor research, AR has been applied in more practical situations, such as conduit construction (Chalhoub and Ayer, 2018), implementing free-form modular surface (Fazel and Izadi, 2018), manual bricklaying (Mitterberger et al., 2020), and wood frame assembly (Qin et al., 2021). These studies examined the usability of AR for various practical tasks and compared the performance with traditional 2D printed manuals, of which the findings supported the improvement of task efficiency and accuracy by AR displays.

In this paper, the usability of AR display was assessed from cognitive perspective, evaluating user's mental workload and situation awareness. Different from the previous attempts, this study implemented a comprehensive cognitive analysis for wood frame assembly using both paper and AR displays.

3.2 Mental Workload Measurement

Mental workload is one of the most referred metrics for assessing human-system performance, which reflects user's cognitive reaction to the technology during interaction. According to the previous literature, NASA-TLX is one of the most widely-used methods for evaluating mental workload for AR and construction related studies (Dadi et al., 2014; Hou et al., 2013; Mitropoulos and Memarian, 2013; Shin and Dunston, 2009; Wang and Dunston, 2006). The queries consist of six subscales: mental demand, physical demand, temporal demand, performance, effort and frustration, which provides an overall workload for the entire task (Hart and Staveland, 1988). Previous research indicated a wide usage of NASA-TLX for assessing mental workload in AR-based systems, including driving simulation (Medenica et al., 2011; Kim et al., 2013), construction inspection (Shin and Dunston, 2009), and model assembly (Tang et al., 2004; Wang and Dunston, 2006; Hou et al., 2013; Loch et al., 2016). On the construction side, this measure was also used by studies involved various construction assemblies, such as masonry work (Mitropoulos and Memarian, 2013), Lego block assembly (Dadi et al., 2014), and pipe assembly (Hou et al., 2013). The feasibility of NASA-TLX was validated to detect the workload difference between AR system and other media. In this study, NASA-TLX was used for evaluating participant's overall mental workload for wood frame assembly under different conditions.

3.3 Situation Awareness Measurement

Based on the three-level construct of situation awareness, Endsley (1988) developed a freeze probe technique providing objective measures of operator's situation awareness in a dynamic environment, which was called Situation Awareness Global Assessment Technique (SAGAT). It measures the situation awareness by randomly freezing the operators and querying about their perceptions of the situation at that time, which is straightforward and less affected by other factors. Stanton et al. (2004) summarized that SAGAT had been validated by numerous studies, and (Endsley, 2000) reported a high degree of reliability as well. In recent research about AR applications, SAGAT has been widely used to examine the improvement of operator's situation awareness by using AR-based systems across a variety of domains, including military identification (Mitaritonna et al., 2020), operator training (Hayden et al., 2020), and driving simulation (Lindemann et al., 2018). These findings provided evidence of the feasibility of SAGAT assessment in studies based on human-system interfaces. Given these premises, SAGAT was adopted in this work to evaluate participant's situation awareness during assembly task.

4. RESEARCH PROBLEM

As an emerging visualization technology, the impacts of AR have been investigated on various construction tasks. Among them, assembly task was mostly done in scaled-down settings, such as Duplo blocks. From a practical perspective, there is an essential need to examine the performance of this technology in a real-world scale, which will bring out some potential issues caused by restriction of FOV in HMD, including perceptual impacts and information accessibility. A comprehensive assessment on a cognitive level is necessary, which includes measures for both *mental workload* and *situation awareness* as these factors were validated to play causal roles in construction accidents (Chen et al., 2016; Hasanzadeh et al., 2018). Consequently, studying the improvement of task efficiency and accuracy is not sufficient to support the usability of AR HMD in the construction field. More evidence from a cognitive perspective is required to ensure that the technology will not cause latent mental troubles.

Therefore, this paper explored the gaps in the existing knowledge in the following points:

i) evaluation of the usability of AR HMD in a realistic wood frame assembly setting (different framing scales, nailing process, potential hazards setting, and other workers in the work area),

ii). comprehensive analysis for both mental workload and situation awareness,

iii). further comparison of the impacts of different AR displays (tag-along and conformal) on workers' cognitive skills and, the possible effects from FOV on information accessibility.

The outcomes would be informative and guide the future development of AR applications in the construction field.

5. METHODOLOGY

5.1 Experimental Design

This study recruited eighteen engineering students (17 men, mean age = 23.8, SD = 4.5; 1 woman, age = 18) who had qualified skills and adequate experience in wood frame assembly. A pre-task power analysis was conducted using G power for F test – repeated measures ANOVA (f = 0.325, $\eta^2 = 0.1$) with a 54-trial within-subjects setting. The result indicated that 17 would be the minimal size guaranteed 80% power. Participants were randomly assigned to accomplish three assembly tasks under different conditions which were composed of two main factors: frame size (small, medium, large) and information display type (paper, tag-along, conformal) (see Table 1).

Table 1. Task Conditions

Participant	Task 1	Task 2	Task 3
P1, P7, P13	Small Frame	Medium Frame	Large Frame
	Conformal Display	*Paper Display*	*Tag-along Display*
	Inspection	Drop Lumber	Measure
P2, P8, P14	Large Frame	Medium Frame	Small Frame
	Conformal Display	*Tag-along Display*	*Paper Display*
	Drop Lumber	Inspection	Measure
P3, P9, P15	Large Frame	Small Frame	Medium Frame
	Paper Display	*Tag-along Display*	*Conformal Display*
	Measure	Inspection	Drop Lumber
P4, P10, P16	Medium Frame	Large Frame	Small Frame
	Tag-along Display	*Conformal Display*	*Paper Display*
	Measure	Inspection	Drop Lumber
P5, P11, P17	Small Frame	Large Frame	Medium Frame
	Tag-along Display	*Paper Display*	*Conformal Display*
	Drop Lumber	Inspection	Measure
P6, P12, P18	Medium Frame	Small Frame	Large Frame
	Paper Display	*Conformal Display*	*Tag-along Display*
	Inspection	Measure	Drop Lumber

The different framing sizes simulated specific practical use for each frame. The large frame ($12'L \times 8'H$) with a door and a window opening was designed for an exterior wall, while the medium frame ($6'L \times 4'H$) could be used as interior isolation wall. The small frames included four individual pieces ($1'8''L \times 1'4''H$, $2'4''L \times 1'4''H \times 2$, and $2'6''L \times 1'4''H$), which were used to assemble a box. Specifically, for the AR users, the differences on the framing size were also associated with how they can view the conformal models through the HMD. The size of the large frame would not let users to see the whole model due to the limitation of FOV, while the entire medium size model could be observed when the user is in a standing position and one step away from the frame. For the small frames, participants could always see the whole model even they kneel down during the nailing process. Overall, the setting of three-level framing sizes aimed to reflect the impact of FOV on users' perception of model information.

The task for each participant was building three wood frames from scratch using a nail gun with precut materials and included sub-tasks of measuring, assembling, and nailing, same as a real-world wood framing case. The experiment adopted a within-subjects design, which eliminated the individual differences in professional knowledge and skills. Enough resting time was provided between each task and pausing was allowed during the task to prevent the fatigue effect.

The workspace (Fig. 1) was a closed indoor environment isolated from unexpected external factors. Participants were required to accomplish framing in the green area using lumber from two wood piles, where material for each frame were randomly placed. Specifically, additional lumber was added to avoid the order effect in the last task. Standard 2x4 was used for framing.

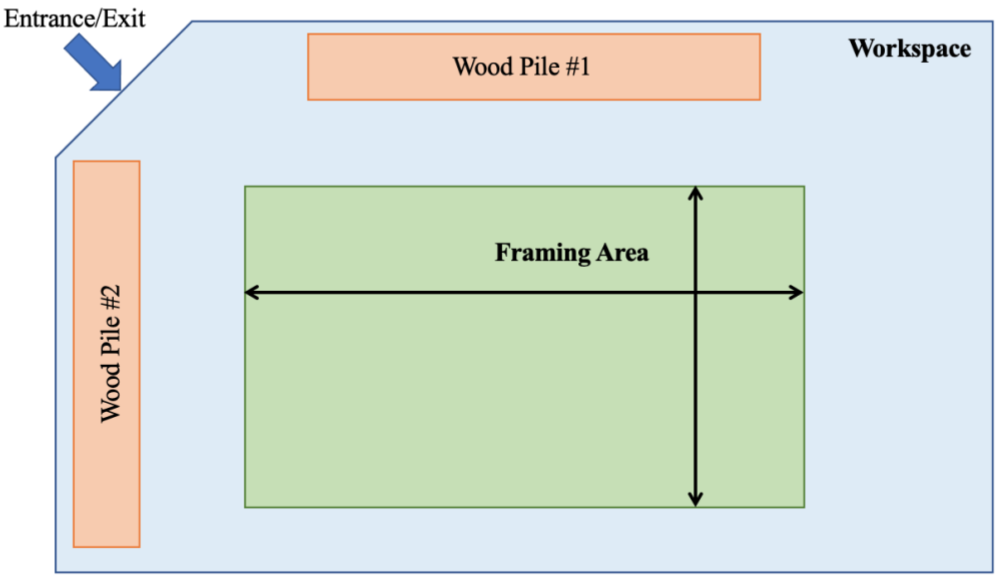

FIG. 1: Workspace Layout

To evaluate participants' situation awareness, SAGAT, a freeze on-line probe technique, was adopted. There were three different questionnaires for each task condition (See Appendix A), which all consisted of six questions associated with corresponding levels of situation awareness (2 questions for perception, 2 questions for comprehension, and 2 questions for projection). These three questionnaires were randomly assigned to each task. To fill out the individual questionnaires, participants were asked to stop mid task (freeze probe), walk away from the framing area and answer the questions to the best of their knowledge without looking at the workspace. The test did not only query the information about assembly, but also included participants' observation of surroundings. Therefore, an additional worker event (inspection, measure, drop-lumber) and several foam hazards were added in the workspace. A worker wearing a high visibility safety vest would enter the workspace every 3 - 5 minutes after the task began and conduct one of the inspection, measure, or drop-lumber tasks during the assembly (see Table 2). The worker made sure that the event would not interfere participants' assembly. Fig. 2 shows worker's path in the workspace for each task. These tasks were also randomly assigned to each task for every participant (Table 1). Information related to the worker and corresponding tasks were asked in the SAGAT questionnaires. In

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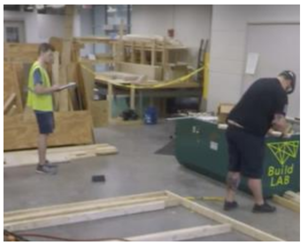
addition to that, there were three foam hazards placed in the workspace (Fig. 3). Participants were required to avoid these hazards during the experiment. Questions about the foam hazards were also included in the questionnaires.

Table 2. Worker Events

Worker's Task	Task Description
Inspection	The worker walked around the workspace in the red path in Fig. 2 and stopped for 30 seconds at each spot (I.1,2,3) to inspect the assembly. 
Measure	The worker used the purple route to measure the lumber in two wood piles with tape measure. It was required to stay at each spot for 30 – 60 seconds. 
Drop Lumber	The worker dropped additional wood pieces (2 – 3 pc.) in each pile using the black path. The wood pieces were randomly selected and would not affect the assembly task. 

During each task, participants were asked to freeze from framing to finish the SAGAT questionnaire at randomly selected times (worker event and sufficient assembly process were ensured). They were not allowed to see the framing site while answering the questions.

For workload assessment, overall scores of the assembly tasks were measured by using NASA TLX. After finishing each assembly, participants would complete the questionnaire immediately.

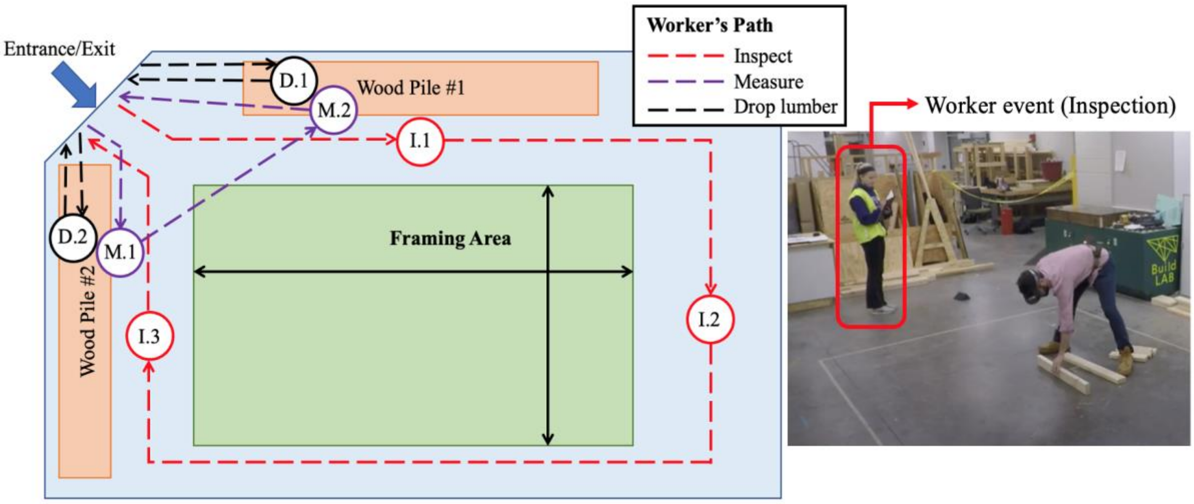


FIG 2: Worker's Path in the Workspace

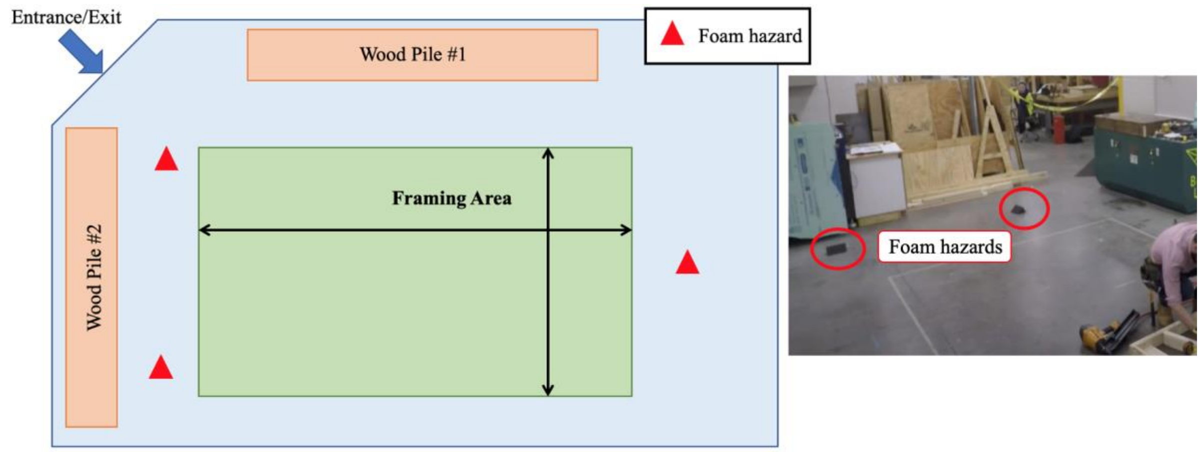


FIG 3: Foam Hazards in the Workspace

5.2 Information Displays

There were three types of information displays designed in this study, *paper blueprint*, *tag-along image* and *conformal model*. Tag-along and conformal were two different display methods in AR HMD, which presented instructional materials in 2D and 3D forms. Both displays were developed with Unity3D game engine. In this study, tag-along image displayed the frame layout in a fixed floating 2D window (Fig. 4 right). It mimicked a standard blueprint and provided identical information that would be on a paper blueprint. Participants were able to see the tag-along at a fixed position (1.5 meters away from and 0.3 meters above the HMD), which could follow one's movement in the workspace. The image was tested not to block user's view while conducting different activities. Different from tag-along, conformal display used a real-size virtual 3D model that was rendered and positioned on the top of the framing area (Fig. 4 left). A printed 2D image was used as a marker to locate the spatial reference in the workspace so that the conformal model could be placed in the correct position. Once registered, the model would remain fixed while participants built the frames. Fig. 4 (left) shows the framing scene in the middle of assembly, when the participant was placing the lumber according to the registered conformal model.

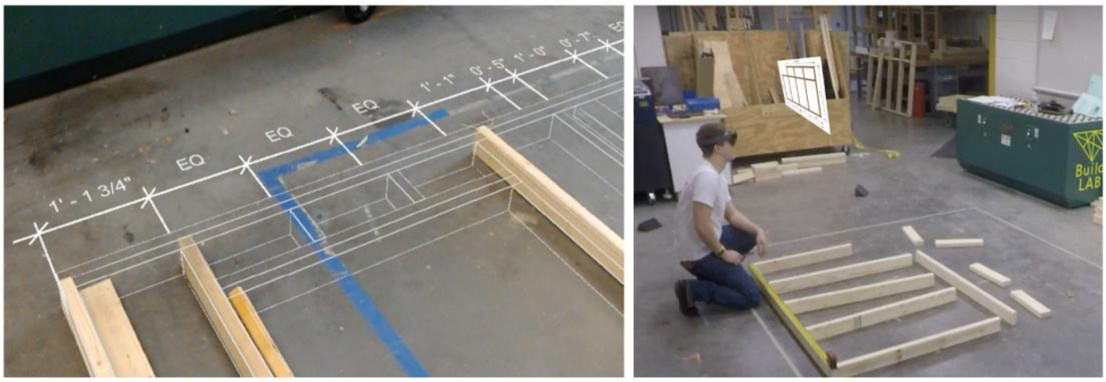


FIG. 4: Framing Scenario with Conformal Display for Large Frame (left) and Tag-along Display for Medium Frame (right)

The HMD used in this study was Microsoft HoloLens 1st generation. The technical specifications of the device provided a 1280x720 display resolution for each eye and 34 degrees FOV. In this study, the view range could constrain the visibility of entire conformal models due to the frame scale or participant's position and posture during assembly. Therefore, participants needed to move around the framing site to obtain required information.

5.3 Framing Scales

In addition to information display, framing scale was another critical factor impacting participants' performance in assembly due to restriction of FOV, measuring and calculating workload, physical task load, etc. Considering that individual differences was an intrinsic factor leading to significant bias, which could be impacted by participants' framing skills, demographic factors, and original cognitive status, we utilized a within-subjects test. Three levels of framing scales were designed to simulate different framing conditions in a real-world case. Fig. 5 depicted the layout for each framing scale. To balance the task difficulty of each frame size, a trade-off between material quantity and measuring complexity was considered. Table 3 listed the material take off for all frame sizes. Compared with the larger frame, the small scale increased the number of frames and measuring complexity in the layout to make up for the difference, while the medium one included more complicated measuring and calculating workload with more fractional length design. Although the large frame required more nailing at connections, the medium and small frames needed more sophisticated operations like toenailing. This was again a trade-off between quantity and complexity. Since there was no standardization for difficulty assessment of wood framing, a pilot study was conducted before the experiment and feedbacks were considered with the finalized layouts.

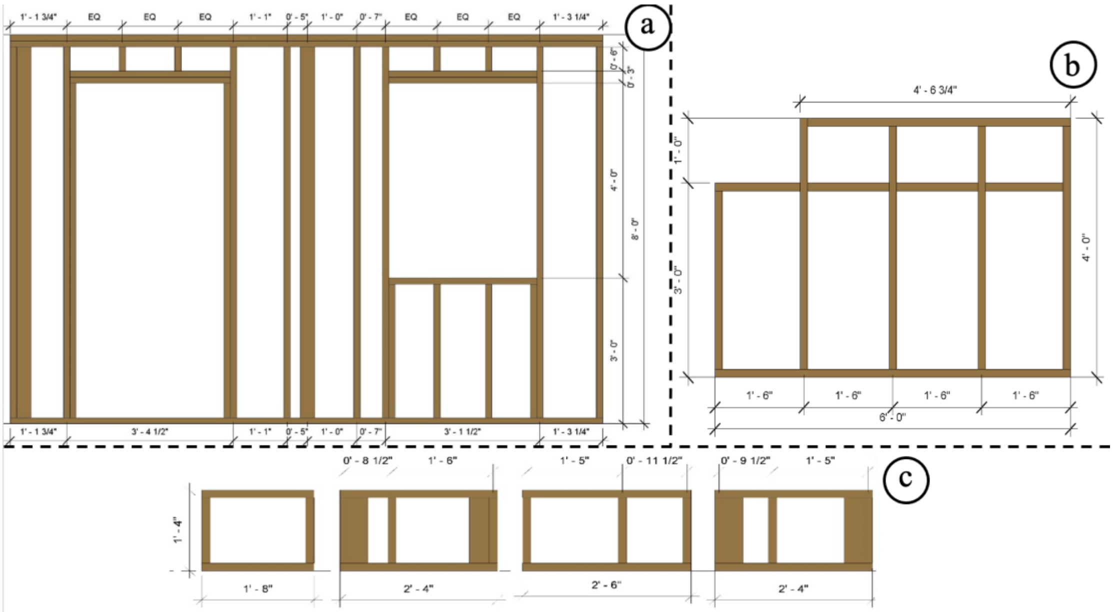


FIG. 5: Frame Layouts (a. large, b. medium, c. small)

Table 3. Material Take Off

Large Frame		**Medium Frame**		**Small Frame**	
length	*quantity*	*length*	*quantity*	*length*	*quantity*
2'-9"	4	1'-3.75"	1	1'-1"	15
3'	3	1'-4.5"	2	1'-8"	2
3'-3"	2	1'-5.25"	1	2'-4"	4
6"	4	2'-9"	1	2'-6"	2
6'-10.5"	2	3'-10.5"	1		
7'-7.5"	11	3'-9"	3		
		4'-5.25"	1		
		6'	1		
Total:	26		11		23

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6. RESULTS AND ANALYSIS

6.1 SAGAT Results

The SAGAT questionnaire consisted of six questions evaluating three levels of SA during the task (perception, comprehension, and projection), where each level had two questions. Participants got one credit for each question and their answers were rated based on the absolute error for numeric questions and correct information provided for open-ended questions. Table 4 listed the average score for SAGAT in each level under different conditions. According to the Shapiro-Wilk Test, the overall SAGAT scores were normally distributed for both conditions: *frame size* ($p_{small} = 0.674, p_{med} = 0.306, p_{large} = 0.711$) and *information display* ($p_{pap} = 0.125, p_{tag} = 0.6, p_{con} = 0.511$). Hence, repeated measures ANOVA was adopted to compare the mean difference in the factors. The result indicated no statistically significant difference in the mean scores for groups under conditions *frame size* (F (2, 34) = 0.012, p = 0.988) and *information display* (F (2, 34) = 0.637, p = 0.555).

Table 4. Mean Scores and Mean Comparison Results for SAGAT

		Perception (out of 2)	**Comprehension (out of 2)**	**Projection (out of 2)**	**Overall Score (out of 6)**
Frame Size	Small	1.662	1.227	1.267	4.156
	Medium	1.572	1.307	1.320	4.199
	Large	1.513	1.548	1.143	4.204
	Sig.	*0.594*	*0.937*	*0.724*	*0.988*
Information Display	Paper	1.472	1.394	1.309	4.174
	Tag-along	1.654	1.326	1.400	4.380
	Conformal	1.621	1.363	1.021	4.004
	Sig.	*0.066*	*0.632*	*0.660*	*0.555*

To understand the situation awareness performance at a more detailed level, scores of three levels were also compared with the same method. Since the Shapiro-Wilk Test rejected the normality hypothesis for data in each group, the Friedman Test was used as a nonparametric method to analyze the mean rank differences. As listed in Table 4, the results showed no significant difference in all three levels for the groups under conditions *frame size* ($\chi^2_{per}(2)$ = 1.042, p_{per} = 0.594; $\chi^2_{com}(2)$ = 0.131, p_{com} = 0.937; $\chi^2_{pro}(2)$= 0.646, p_{pro}= 0.724) and *information display* ($\chi^2_{per}(2)$ = 5.437, p_{per} = 0.066; $\chi^2_{com}(2)$ = 0.918, p_{com} = 0.632; $\chi^2_{pro}(2)$= 0.831, p_{pro}= 0.660).

Fig. 6 depicted the distribution of scores under each condition with box plots. According to the plots, a similar distribution of three levels could be found in two condition groups. Specifically, perception scores were more concentratedly distributed in a high-score interval (1.25 – 2), where conformal display was negatively skewed and tag-along display had the highest Q1 (lower quantile) score at 1.58. The result suggested that AR displays outperformed in perception level compared with paper blueprint. In contrast, comprehension and projection scores distributed more dispersedly in the interval. Noticeably, paper display was negatively skewed, which guaranteed a relatively more stable performance in comprehension. Besides, large frame was negatively skewed and had a relatively higher Q1 score at 1, which suggested a better performance in comprehension. For projection level, conformal display had a low Q1 score at 0, which implied an underperformance in this aspect. Based on the lower median and Q3 (higher quantile) score, large frame underperformed compared with the other framing scales.

Comparing the mean SAGAT score for each combined condition did not show any correlation between factors (frame size and information display), except for tag-along display (Fig. 7). The score for tag-along condition decreased when the framing scale got larger, however, the pattern was not significant which had a rate of descent between two size factors at 6.4% and 16.9%. For both paper and conformal displays, it showed no clear pattern with the framing scale.

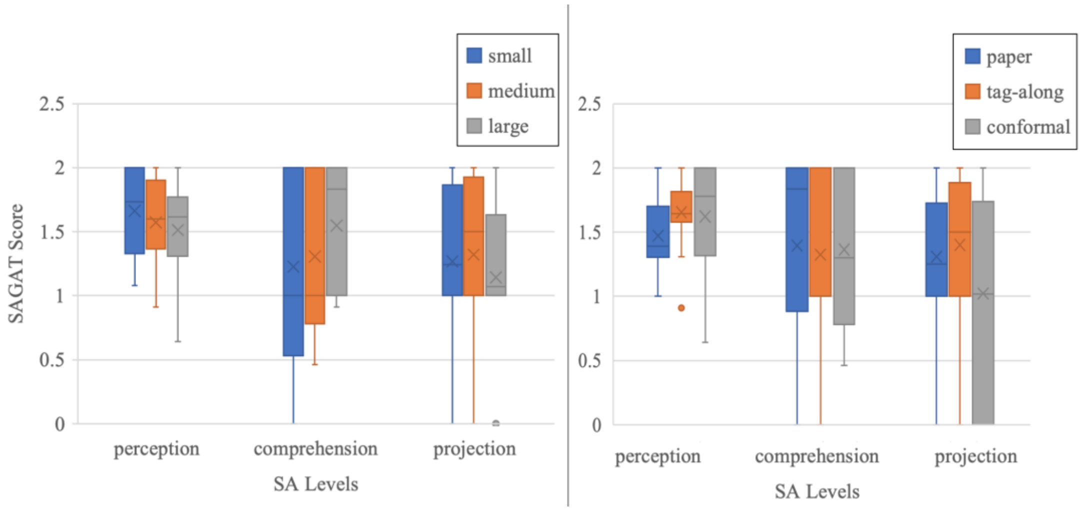

FIG. 6: Box Plots of Situation Awareness Level Scores for Frame Sizes (left) and Information Displays (right)

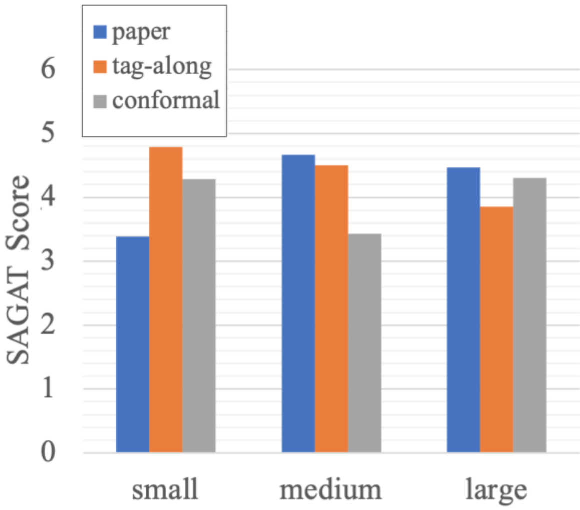

FIG. 7: SAGAT Scores for Combined Conditions

6.2 NASA TLX Results

To understand participants' cognitive load during the tasks, an overall weighted NASA TLX score was analyzed. The normality was validated with the Shapiro-Wilk Test (p_{small} = 0.415, p_{med} = 0.106, p_{large} = 0.096; p_{pap} = 0.379, p_{tag} = 0.398, p_{con} = 0.274). A repeated measures ANOVA was used to compare the mean difference between the groups. Table 5 showed the results from ANOVA and corresponding post hoc test. The ANOVA determined that mean TLX score differed statistically significantly between frame sizes (F (2, 34) = 5.589, p = 0.008). Post hoc analysis with Bonferroni adjustment revealed that TLX score for small frame was statistically significantly lower than large frame (15.33 (95% CI, 5.41 to 25.26), p = 0.002), while neither significant mean difference was detected between small and medium frame (8.57 (95% CI, - 4.18 to 21.33), p = 0.276), nor medium and large (6.76 (95% CI, - 6.87 to 20.39), p = 0.616). Additionally, the ANOVA determined no statistically significant mean difference between information displays (F (2, 34) = 1.611, p = 0.215).

Comparing the TLX scores under frame size conditions, large frame had a more concentrated distribution with positive skewness, while medium and small frames were more dispersed and negatively skewed (see Fig. 8). Participants were more consistent in the feedback of large frame assembly that required more mental workload. Similar results were found in the display groups, participants reported commonly higher mental workload using conformal display. Although Q3 scores were approximately closed to 60 between three displays, paper and tag-along had lower Q1 scores under 40. Specifically, paper condition was negatively skewed which indicated participants' evaluation were closer together above 54.67 (median score).

Table 5. Analysis of NASA TLX Score

Descriptive statistics

		Mean TLX Score	Std. deviation	N
Frame size	*Small*	44.37	12.994	18
	Medium	52.94	17.345	18
	Large	59.70	15.966	18
Information display	*Paper*	52.09	17.744	18
	Tag-along	47.99	15.06	18
	Conformal	56.94	16.29	18

Repeated measure ANOVA

Frame size		Information display	
F (2, 34)	Sig.	*F* (2, 34)	Sig.
5.589	0.008	1.611	0.215

Post hoc analysis (with Bonferroni adjustment)

	Mean difference	95% CI for difference		Sig.[b]
		Lower bound	Upper bound	
medium - small	8.57	- 4.18	21.33	0.276
large - medium	6.76	- 6.87	20.39	0.161
large - small	15.33	5.41	25.26	0.002

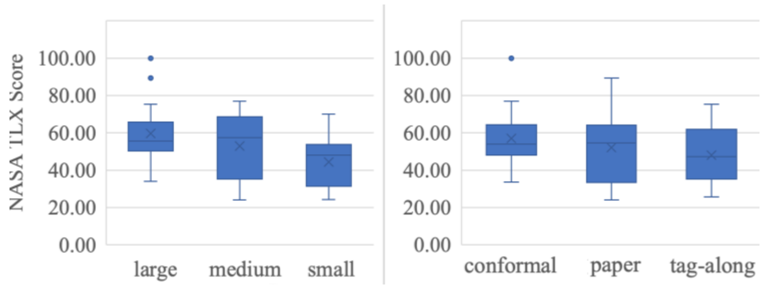

FIG. 8: Box Plots of NASA TLX Scores for Frame Sizes (left) and Information Displays (right)

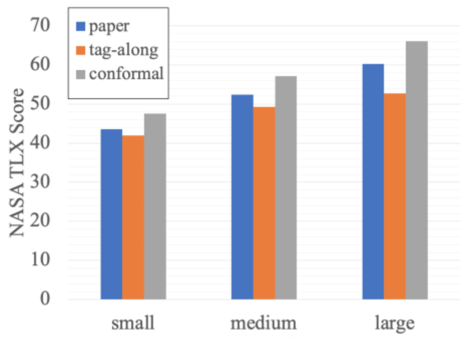

FIG. 9: TLX Scores for Combined Conditions

Fig. 9 illustrated the average TLX scores for each combined condition, where a similar distribution has been found that tag-along and conformal were the lowest and highest scores across all framing scales. Scores were also positively correlated to the frame size in all three displays. What's more, tag-along display had the lowest increment between two frame sizes, suggesting a more reliable performance under different framing scales. In contrast, the score in conformal display was comparably affected more by the increase of frame size.

7. CONCLUSIONS

This study explored the impact of information displays under different framing scales on user's cognitive skills, which included the evaluation of situation awareness and mental workload. Framing scale was an additional factor to make the experiment more realistic, where the usability of AR HMD under various framing conditions were more comprehensively considered. Additionally, it also examined the potential impacts brought by the restriction of FOV using different AR display types. It was investigated (Fazel and Izadi 2018) that restriction of limited FOV in AR HMD could lead to disadvantage in assembly efficiency and accuracy when the information was displayed as an actual-size conformal model. Similarly, a significant difference was noticed comparing the TLX score between small and large frames in this study ($p = 0.002$). Participants reported higher demand of mental workload because they had to adjust their positions during the assembly to acquire information outside of FOV. On the contrary, tag-along display avoided the restriction of FOV and provided user with an option whether to see the instruction or not during tasks. It didn't occupy any physical resources as a paper instruction did and only required a simple head movement to see the information, which simplified the process of managing resources. According to the individual analysis, this was a clear advantage making the tag-along a more reliable display type generating the lowest mental workload for assembly task across all conditions. The result echoes to the previous research (Fazel and Izadi 2018) and gives an explanation for the lower efficiency and accuracy from the cognitive perspective. The FOV limited the accessibility of information from the model, which increased workers' mental effort to seek effective information out of view.

However, compared with other research utilizing a scaled-down assembling setting and reporting a lower mental workload with AR assistance (Yang et al. 2019; Dadi et al. 2014; Hou et al. 2013; Wang and Dunston 2006), the results did not show significant advantage of AR displays compared with paper documentation. To justify this discrepancy, there are multiple factors that need to be considered. First, the assembly setting utilized in this study ranged from small to large, which presented different situations of information accessibility limited by the FOV. However, in the previous research, scaled-down models were not affected by this restriction. Then, the task complexity was increased by assembling real frames, involving subtasks such as measuring, assembling, and nailing. Specifically, nailing was not assisted by AR, but wearing AR device could be a distraction during the process, which may indirectly increase the mental burden. Although there was no significant difference in the mean TLX score between each display type, the result still indicated that AR displays would not generate significant excessive mental workload compared with paper documentation. The mean difference comparison among three display methods showed approximate results, indicating that no significant increment or reduction was identified in AR displays. Specifically, the tag-along display generated relatively least mental workload, while the conformal model had the most. This may be explained by the limited FOV and information accessibility issue discussed in the previous paragraph. However, the findings still pointed out that AR displays had similar mental burden compared with paper layout. At the same time, the previous research (Qin et al. 2021) indicated that AR display can be a good fit for improving assembly efficiency and accuracy. Considering these premises, AR displays still have the potential to be a usable information presentation method for wood frame assembly task.

The SAGAT was adopted to quantitatively assess participants' situation awareness in three levels: perception of data, comprehension of meaning and projection of the near future. Even though there was no significant mean score difference between conditions, the descriptive statistics of the scores revealed a latent influence of the framing scale and information display factors. Given the discrepancy of data dispersion in each condition, tag-along display performed most stably with a smaller deviation and higher mean, whereas the scores varied from each other using conformal display. This result supports the outcome from mental workload evaluation and explains the relation between the increased workload and decreased situation awareness in conformal condition. Analogously, a similar trade-off was found in the tag-along display, which had lower mental workload and higher situation awareness. Additionally, although there is no significant difference found in both tests for frame size and information display factors, the result is still worthwhile because it suggests that AR HMD does not affect workers' situation awareness during assembly. Especially, the tag-along display outperformed in perception and projection questions, while the conformal display got higher scores in perception questions compared with the paper layout. The findings suggest that AR display may help users to perceive effective information in their surroundings. In addition, the similar distribution of SA scores found in the comprehension questions indicate that users' perception-based decision-making process is not affected by different display methods. Thereby, AR displays would not be considered to generate notable distractions to workers and the visual cues in the surrounding could still be perceived by them.

In addition to mental workload and situation awareness, restriction of FOV was a latent factor affecting the usability of AR displays in assembly. The individual analysis under all combined conditions revealed a difference in the impact of FOV on participants' performance. For the AR displays, the TLX scores had consistently positive correlation with the framing scale, suggesting that mental workload was affected by the restriction of FOV. When frame size increased, participants had to move around to switch between a partial and an entire view of the frame layout, which could increase the task load. However, no pattern was found in the SAGAT scores other than a weak negative correlation for tag-along display. It further implied that the impact from FOV on situation awareness was limited.

8. LIMITATIONS AND FUTURE WORK

The following limitations need to be acknowledged in this study: Even though this research aimed to evaluate the AR HMD use in a realistic setting the experiments were still completed in a controlled environment and do not fully reflect the real-world setting. In addition, due to the experimental design, the assembly tasks required long durations of time (three to four hours per subject), limiting the potential number of participants. Therefore, further study of this topic is suggested with similar experiments and a larger sample size. It should also be noted that the gender distribution of the sample group was imbalanced. The participants were randomly selected from the qualified group of subjects. Due to the proficiency requirement, we had only one female participant in this study. Although it is reported that women framers comprise much less population compared with men in the industry (male: 88.2%, female: 11.8%), we acknowledge that there could be gender differences related to task performance, which should be explored in future research by recruiting a more gender balanced sample.

9. CONTRIBUTIONS

The outcomes of this study have significant implications for the practice of evaluating usability of AR HMD in construction assembly from a cognitive perspective. This is also one of the first attempts to assess the performance of various instructional displays in various physical frame sizes. Different from the other laboratory settings using scaled-down models, this work measured the mental workload and situation awareness within a real-world working process and environment, which requires participants to measure, layout and nail the frames. Therefore, the results are more comprehensive and practical to the evaluation of AR HMD. The findings indicated no statistically significant difference in mental workload or situation awareness between the displays, which suggests that AR displays would not affect the cognitive status compared with traditional paper instruction.

Furthermore, the technical restriction of AR HMD is a longtime concern for blocking user's view in tasks. This study revealed the relationship between cognitive performance and AR displays under different framing scales that can be constrained by the FOV. The findings imply that mental workload was affected by the restriction, while situation awareness wasn't. Limited FOV results in extra efforts for acquiring effective information in conformal model, which increases the mental workload along with the frame size. However, the restriction of FOV did not block workers' view to observe the surrounding so that they still can receive visual cues from the workspace. This may explain the insignificant difference between the situation awareness among the frame scales. Interestingly, tag-along reduces task load by a compressed and accessible display method, which is even lower than using the paper blueprint. Considering the impact of AR displays on assembly efficiency and accuracy that studied in the previous work (Qin et al., 2021), tag-along display can be a desired solution to the FOV restriction and improve productivity as well. This can be a cornerstone for future research about the usability of AR HMD in various construction activities but not limited to wood frame assembly.

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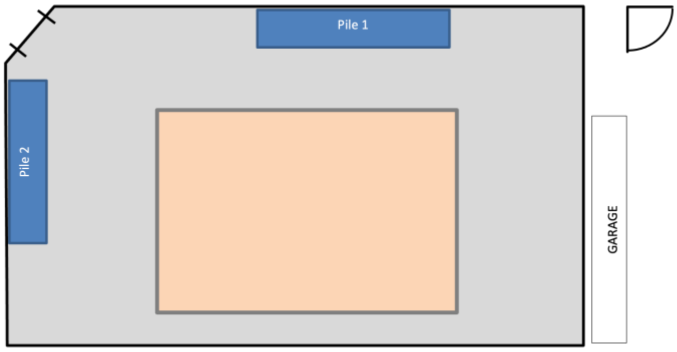
APPENDIX A

SAGAT Questionnaire 1:

Q1: What was the last step you performed before the freeze? Be as specific as possible.

Q2: On the provided layout, draw the position and layout of the wood frame you are trying to construct. Please try to be as detailed as possible and draw to scale to the best of your ability.



Q3: What is the total surface area of the frame you are currently assembling?

Q4: What is the longest piece of wood required for the current frame being assembled?

Q5: How many more pieces of wood will you need to finish the frame?

Q6: How much more time will you need to complete the task?

SAGAT Questionnaire 2:

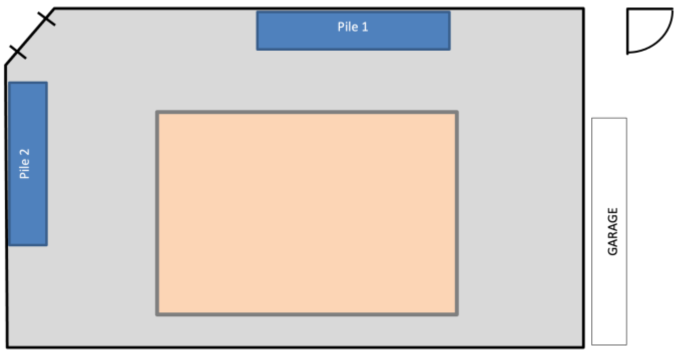
Q1: What was the green worker holding when they entered the workspace?

Q2: How much time did the green worker spend in the workspace?

Q3: Did the green worker's task have an impact on you or your task?

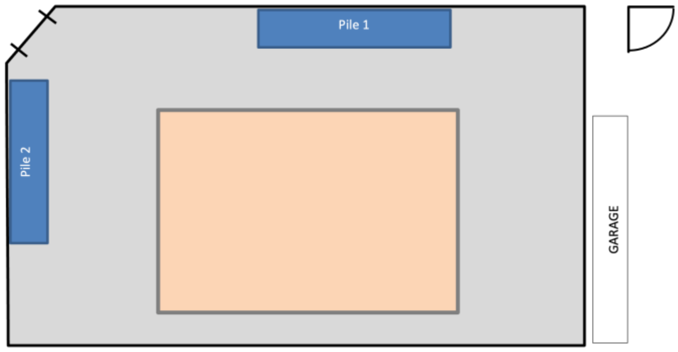
Q4: What was purpose of the green worker's task?

Q5: On the diagram below, circle the pile of wood that the green worker will visit first the next time they enter the workspace.



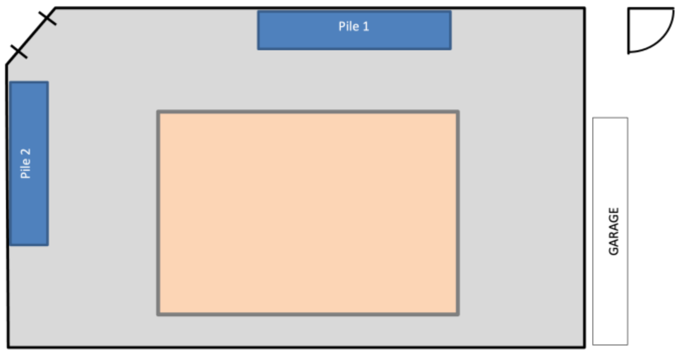
Q6: On the diagram below, circle the pile of wood that will have the least amount of material remaining at the end of the task.

CC BY



SAGAT Questionnaire 3:

Q1: Draw the locations of the hazardous objects on the diagram below (try to be as accurate as possible).

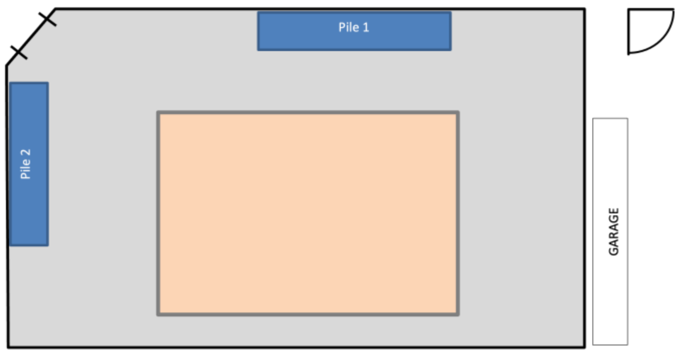


Q2: How many pieces of wood have you assembled (nailed together) so far?

Q3: Are there any pieces of lumber in Pile 1 that are bowed to the point that they are unusable?

Q4: How many times have you been within 1 foot of the hazardous object?

Q5: On the diagram below, draw the path the green worker will take the next time they enter the worksite, perform their task, and exit the work site (try to be as accurate as possible).



Q6: Which pile will have the most amount of material remaining at the end of the task (Pile 1 or Pile 2)?