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Impact of information display on worker performance for wood frame wall assembly using AR HMD under different task conditions

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ABSTRACT

Augmented Reality (AR) head-mounted displays (HMDs) provide users with an immersive virtual experience in the real world. The portability of this technology affords various information display options for construction workers that are not possible otherwise. However, the impact of these different information presentation options on human performance should be carefully evaluated before such technology is deployed in the jobsite. In this paper, we describe a research effort examining how different information displays presented via AR HMD influence task performance when assembling three sized wooden wall frame assembly tasks. We asked 18 construction engineering students with framing experience to finish three wood frame assembly tasks (*large, medium, and small*) using one of the three information displays (*AR 3D conformal, AR 2D tag-along, and paper blueprints*). The task performance was measured by *time of completion* and *framing errors*, which were analyzed and compared among each factor.

1. Introduction

The rapid development in AR applications has brought this technology into various aspects of our daily lives. In addition to the use cases in education, entertainment, and manufacturing, AR also has opportunities of use in the construction industry [7]. From the studied examples of practical applications in construction education [13,3], facility management [2,6], construction inspection [25,32] and design [30], we can see that AR provides a more interactive, intuitive, and efficient experience in comparison to the traditional paper-based media. In addition to these, through the advances in software and hardware of AR technology, AR HMDs support more hands-free tasks for the users. With multiple human–computer interaction (HCI) methods, such as gestures and speech, AR HMD can support workers in complex working environments. For example, Trimble, working with Microsoft, released the first HoloLens Hard Hat as a proof of concept showing the capabilities of AR HMD as an efficient collaboration and information display tool for on-site construction tasks [18].

Previous research exploring the use of AR for on-site construction activities, such as assembly related tasks, is limited. One explanation for this deficit could be that field studies involving assembly tasks require careful planning due to high material costs and longer time commitment from the subjects [15]. Compared to other on-site construction tasks, such as quality control, assembly tasks are more labor intensive and can expose workers to situations with increased risk. Thus, it is critical to understand the impact introducing a novel technology, such as AR, has on workers' task performance. For instance, one current restriction to using AR HMDs is the limited field of view (FOV) to overlay virtual information onto users' view of the real-world, which can interfere in the comprehension of that virtual information [10]. The FOV limitation could prevent building information from being adequately displayed during assembly tasks, which could influence the worker's performance when constructing large scale building components, such as a wood wall frames. In attempt to simulate assembly tasks, previous studies utilized LEGOs [27,11] and lab-based pipe assemblies[12,16] for a construction model. However, real-world assembly tasks performed on construction sites would require AR cues to be rendered on a much larger scale that causes virtual information to exceed the FOV of AR HWDs. Additionally, studies using these small-scale assembly tasks do not account for other factors that are introduced with larger, on-site assembly tasks such as the increased labor required to manipulate larger materials (e.g. lumber), complexity of construction site setups, and bias of individual expertise in assembly, all of which can be challenging to implement an experimental study in a construction site. Thus, further research must be conducted to

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Table 1
Experimental conditions.

	Small Frame	*Medium Frame*	*Large Frame*
AR 3D conformal	small - conformal	medium - conformal	large - conformal
AR 2D tag-along	small - *tag-along*	medium - *tag-along*	large - *tag-along*
Paper blueprints	small - paper	medium - paper	large - paper

Fig. 1. Assembly scene using HoloLens.

understand how AR HMD restrictions such as FOV can affect workers' performance when constructing large scale building components, such as a wood frame wall.

To better understand the impact of different information display methods on the scale of assembled objects, this paper focused on evaluating a wood frame assembly task under several conditions. These conditions were created with a combination of 3 frame sizes (*large*, *medium*, and *small)* and 3 information display types (*AR 3D conformal*, *AR 2D tag-along*, and *paper blueprints)*. In total, 9 different conditions consisting of these factors were tested in this study (Table 1).

2. Background and literature review

2.1. AR applications in construction assembly

An early application of AR HMD in construction assemblyReiners et al. [21] proposed a door lock assembly task utilizing a see-through HMD with a camera. The feedback from the subjects pointed out that the integrated display of virtual image and the physical presence of a door gave an intuitive interpretation of the assembly process. This study showed how having an AR HMD provided an advantage by changing the way of visualizing information during a construction assembly task. In other studies, AR was shown to improve user's cognition and learning processes, specifically by enhancing the performance of engineering students in building design and construction assembly projects [26,24]. With more effective information display methods, AR is poised to improve worker task performance in construction assembly.

As we see advances in AR technology, emerging AR HMD commercial products in the market, such as Microsoft HoloLens, are showing their potential to support more complex hands-free construction tasks. Even though recent research has put the focus on the performance of AR applications in construction assembly, previous studies in this area generally adopted an abstract representation of construction tasks, such as LEGO or pipe model assembly. Tang et al. [27] conducted a Duplo block assembly task to examine the effectiveness of AR instruction. The results indicated that AR improved task performance with a lower error rate, less time to completion and reduced cognitive workload. Similar findings were reported in the studies from Hou et al. [11] and Loch et al. [17]. AR assistance in these small-scale simulation tasks of construction assembly has better task efficiency and accuracy than conventional 2D media like monitors and blueprints. Another widely used task model is pipe assembly, which requires a higher spatial cognition ability. Hou et al. [12] found that AR display helped inexperienced subjects with better productivity outcomes. Kwiatek et al. [16] showed that AR devices do not only improve task performance in pipe spool assembly, but also narrow the gap among participants' spatial skills. Given the results from these studies, AR applications are conducive to users with various proficiency levels in assembly tasks.

Recently, there have been other studies investigating the usability of AR for various construction assembly tasks. Chalhoub and Ayer [5] examined AR as a more efficient alternative instruction for conduit construction over 2D plans. The findings showed that even for experienced workers AR improved their productivity. Fazel and Izadi [9] proposed an interactive multi-marker AR tool for free-form modular surface implementation. Five brick-structure assemblies were made with integrated common accessible devices. Relatively low error rates in placement and orientation were discovered, which illustrated the usability of AR in complex modular structure assembly. Mitterberger et al. [19] also applied an AR setup for a manual bricklaying task. A camera and a mounted screen were used for tracking and visualizing the brick placement for quality inspection and schedule monitoring. The results showed a high precision in brick location, and a gradual reduction in the time consumption of each brick laid.

Briefly, AR applications have showed promise in improving performance in various construction assembly tasks. Both time, efficiency, and accuracy have been examined in previous studies. This paper will discuss the task performance of wood frame wall assembly in multiple conditions of frame sizes and information displays using an AR HMD.

2.2. Information display

The documentation of building information has been greatly changed in the past few years. From hand-drawn blueprints to digital documents, the display and transmission of building information becomes more paperless and accessible. Despite that, there is still room for innovative technologies, such as BIM (building information modelling), to have a better integrated information management approach. Applications using VR/AR technology provide construction personnel with a more intuitive and perceptual graphic language for better comprehension of the design. Different from VR, which creates a completely virtual environment, AR augments the physical workspace with digital graphic information, which can be either 3D models or 2D images. Presenting a design in the context of existing conditions is a more immersive information display experience for users [31].

Moreover, users can acquire better spatial cognition from AR, which cannot be given solely by a paper media. Kwiatek et al. [16] confirmed the view that a hand-held AR device brought more benefits to users who had weaker spatial cognition during a pipe assembly task. With the spatial cognition being well supported, users' task performance improved with a shorter task time and reduced need of rework. Wang's study Wang [29] for using AR HMD for virtual construction worksite planning also improved the efficiency and provided error prevention. Overall, according to past research, AR display shows an advantage in spatial cognition improvement.

Although AR displays bring benefits of a better spatial perception to users, the restriction of FOV is a technical challenge for most current types of AR HMD. Consequently, the recent hardware development of AR HMD has put strong efforts into widening the FOV to improve user experience with a more complete and accurate display. Compared with the first generation, Microsoft's HoloLens 2nd generation has expanded the FOV from 34 to 52 degrees. However, AR see-through HMD generally provides a horizontal FOV in the range of 20–60 degrees [4], which is quite limited when compared with the 200-degree FOV of human

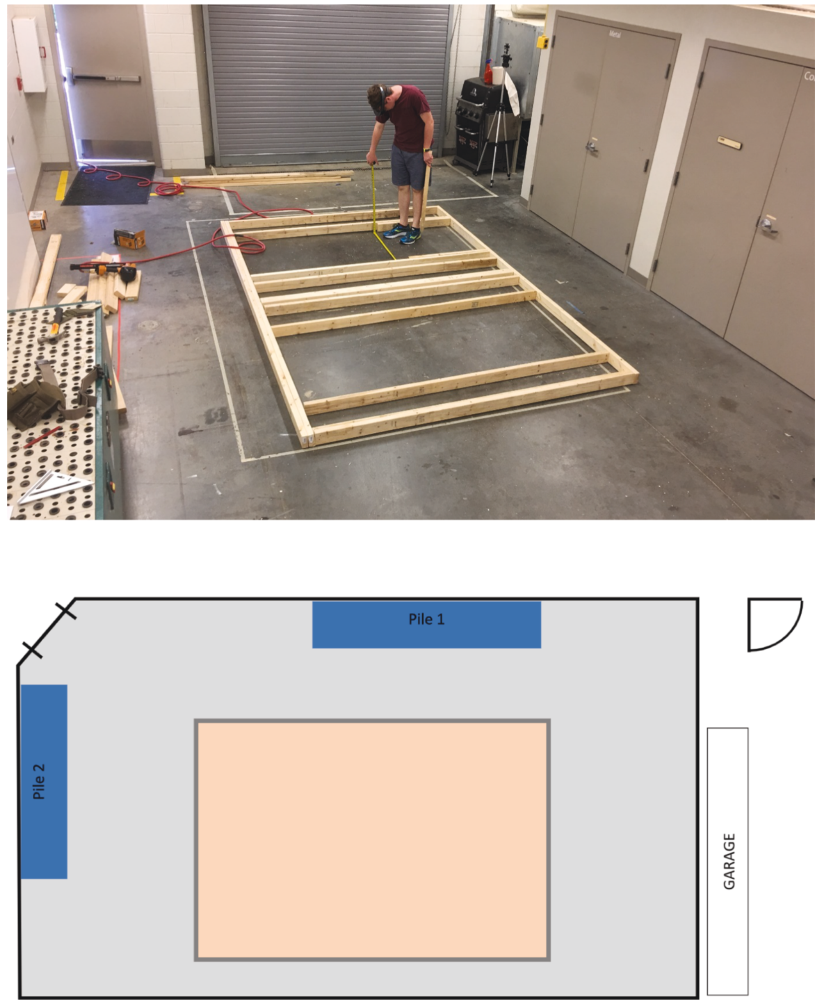


Fig. 2. Framing scenario for large wall (top); Experiment site layout (bottom).

eyes. Drascic and Milgram [8] pointed out that the weakness of restricted FOV may result in a perceptual bias, which can interfere with task performance. Using VR HMD in a similar situation provides valuable hints according to the previous research. Degraded performance was also found in Arthur and Brooks Jr's study Arthur and Brooks [1] indicating that even using HMD with high FOV of 112 degrees could lead to the performance of searching, walking, distance estimation, and spatial memory being affected. Ragan et al. [20] found a better training performance with higher FOVs during a visual scanning task in a virtual environment. Looking back to AR, the study for the impact of FOV is still in a limited scope. Researchers have customized wide FOV displays to explore how FOV and information display method influence task performance. Comparing the in-view and in-situ annotation methods, Kishishita et al. [14] figured out that annotations with leader lines inside of FOV could decrease user's searching ability. Additionally, Ren et al. [22] utilized an AR display with full-surround FOV in a task for artifact tracking. The result indicated that the full FOV shortens the task time compared with a constrained one. These studies discussed the impact of both information display and FOV on the performance of tracking objects. With a more complex working environment and task objective, there is little research studying how information display and FOV affect construction worker's performance using an AR HMD.

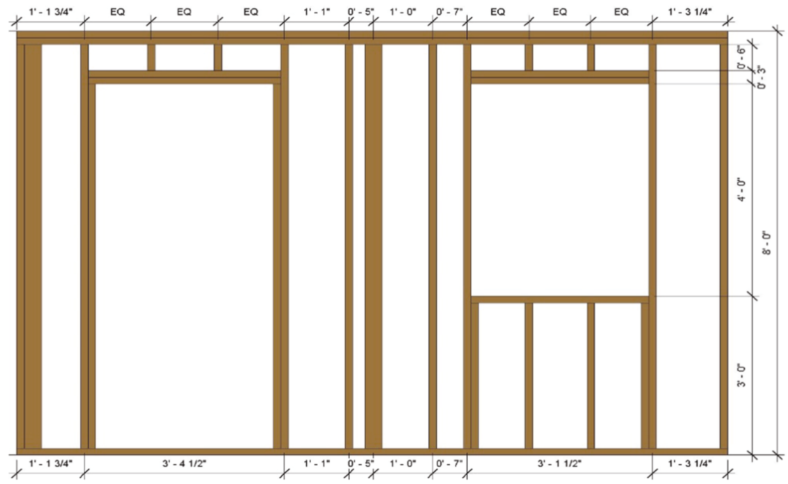
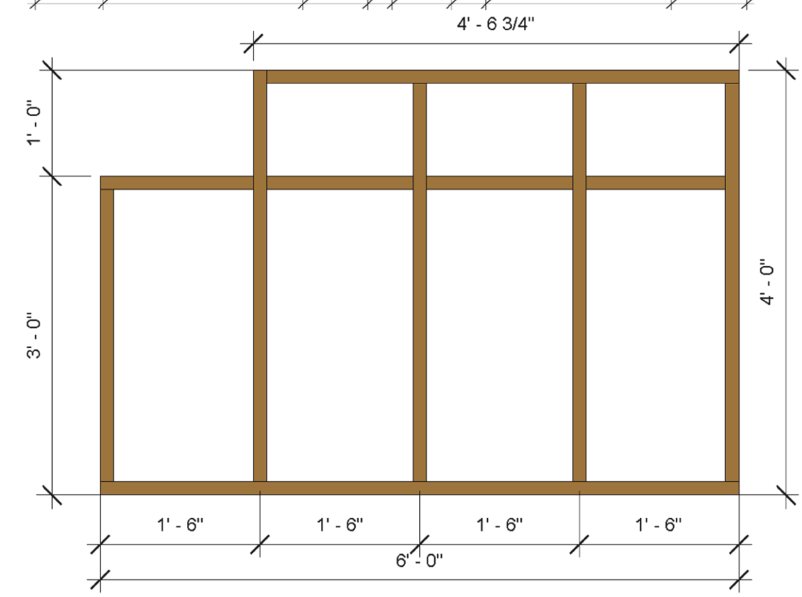
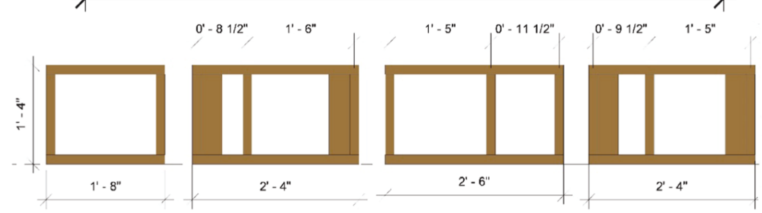
In this context, this research investigates the impact of different information displays on the assembly task performance of different sized wood frame walls. For each condition, both the information display and the frame size factors were considered, which created complex but practical assembly situations. The comparison for information displays was not just limited to 3D AR model and paper media; a 2D image display through AR headset was also studied, which avoided the potential effects from the narrow FOV. Time to completion and framing accuracy were used as two measures to evaluate the impact these factors assembly task performance.

3. Research problem

Currently, there have been various studies conducted to test the performance of using AR applications in assembly tasks. As mentioned previously, lab-scale experiment setups such as LEGO and pipe models were preferred in early studies due to technical and practical limitations. The impact of various features of a real-world construction assembly task on AR HMD use is yet to be studied. Instead of sitting or moving in a narrow range, the real-world case involves intensive labor, complex site setup and various physical scales. The performance of using AR in large-scale assembly has not been well explored.

In addition, the comparison of different information displays is usually between AR and 2D media such as paper and desktop monitor. It

Table 2
Frame Layouts and material take off.

Frame Size	Cut Length	Count	Blueprint
Large	2′-9″	4	
	3′	3	
	3′-3″	2	
	6″	4	
	6′-10.5″	2	
	7′-7.5″	11	
Total: 26			
Medium	1′-3.75″	1	
	1′-4.5″	2	
	1′-5.25″	1	
	2′-9″	1	
	3′-10.5″	1	
	3′-9″	3	
	4′-5.25″	1	
	6′	1	
Total: 11			
Small	1′-1″	15	
	1′-8″	2	
	2′-4″	4	
	2′-6″	2	
Total: 23			

is necessary to consider various visual stimuli in AR HMD due to the possible constraint of FOV. That said, the FOV restriction in HMD can lead to performance degradation, which can possibly happen during a large assembly. Consequently, compacting the large-scale model into user's sight can be a solution to this problem.

This research studies the AR HMD use in a real-world wood assembly task with different framing scales and complex task conditions. Besides the traditional paper documentation, two display methods in AR HMD have been tested to explore a potential strategy of information display to solve the conflict between physical assembly scale and limited FOV. The task performance is evaluated in both sides of time efficiency and framing accuracy. Overall, this is an exploratory study on the impact of utilizing various information displays in a real-world wood frame wall assembly task with different physical scales.

4. Methodology

4.1. Experimental design

4.1.1. Experimental setup

In this study, Microsoft HoloLens 1st generation was used as an AR HMD for the conformal and tag-along displays. The HoloLens has a 1280x720 display resolution for each eye, and the FOV is 34 degrees. Fig. 1 shows the assembly scene of the experiment with a participant wearing HoloLens.

As depicted in Fig. 2, a closed indoor environment was used for the experiment site. The middle square area in tan color was the designated assembly area for the participants along with two piles of lumber setup in the site. The lumber for all tasks were mixed and randomly distributed

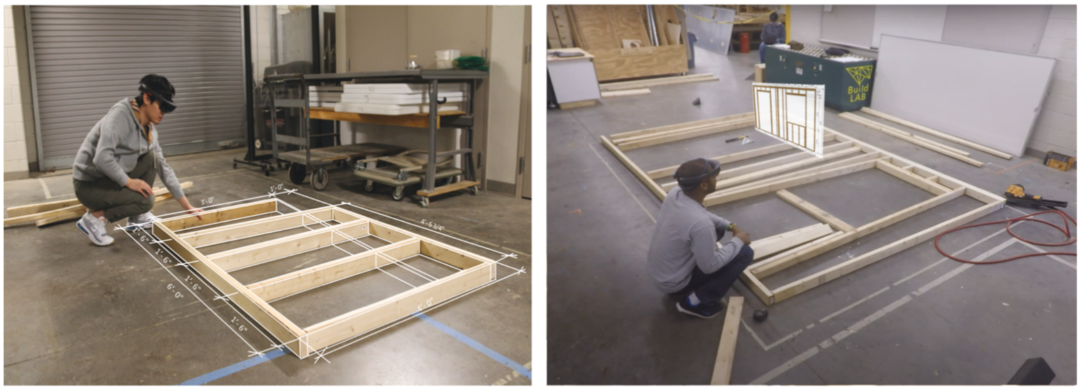


Fig. 3. Framing Scenario with Conformal Display (left); Framing Scenario with Tag-along Display (right).

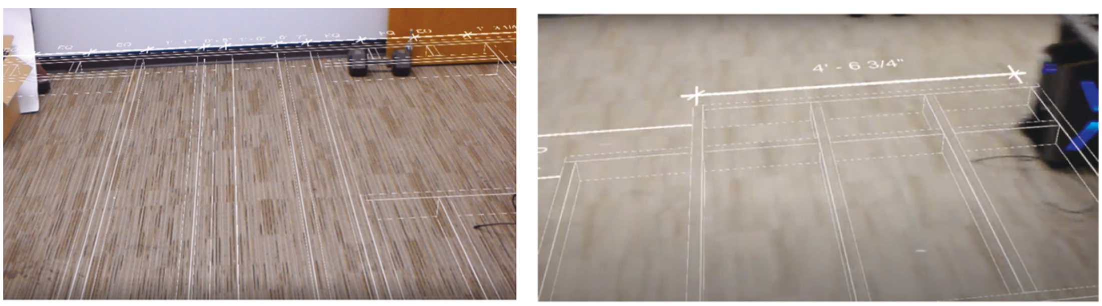


Fig. 4. See-through view for the Conformal Display of Large Frame (left) and Medium Frame (right).

Table 3
Task allocation for the participants.

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

in these piles for each participant. Specifically, selecting the correct lumber requires precise measuring skills, which is an important metric in this study for the evaluation of the framing performance. Therefore, as some distracters, additional lumber were added into the piles to avoid the order effect and to make sure participants needed to measure and select the correct lumber in all tasks.

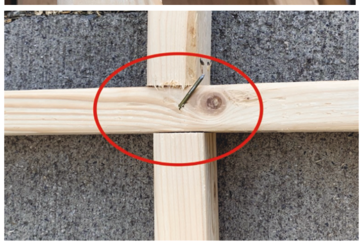
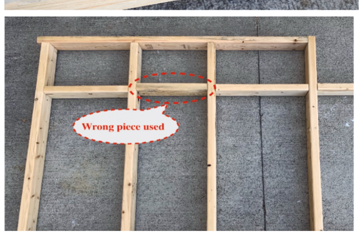
4.1.2. Framing scale

The frames used for the experiment were designed in three different scales, large, medium, and small. Table 2 shows the layouts and material take off for all three frames. While the small and medium frames were designed to fit in the FOV of HoloLens, the large frame does not allow this. Standard 2x4 is used for the construction of frames. In a real-world assembly task, it is difficult to quantify the differences in complexity and workload related to size of the tasks. Besides the number of studs and nails, measuring and nailing pattern are also two common factors impacting the task difficulty. We tried to balance the complexity and workload of each frame size by adding more complex design in the calculation for measuring and nailing pattern for the medium and small frames. For instance, the medium frame included the greatest amount of studs differing in length, which requires more complex calculation process during assembly. In addition to that, the small frame condition consisted of assembling a group of 4 small frames to balance the workload differences.

4.1.3. Information display

The frame assembly information was displayed in two mediums. Microsoft HoloLens was used for conformal and tag along displays, while paper was used for traditional printed blueprints. Fig. 3 shows the participant view for the medium assembly task using the conformal and tag-along display. Both the conformal and tag along display were developed using Unity3D game engine. The conformal display presents a 3D blueprint onto the workspace such that the virtual representations of frame layout accurately match the actual scale of the lumber used for assembly. Using a tracking marker that can be detected by the Microsoft HoloLens, the 3D model was rendered and positioned within the assembly area. The tracking marker was a printed 2D picture that was placed on the ground just outside the assembly area and was used as the reference point to anchor the conformal model in the real-world environment. Once the model was anchored, the marker was removed. During the assembly, the conformal model remained fixed while participants gradually built the wood frame. Participants could directly check the layout and dimensions of the frame in real time by comparing the wireframe model and the physical position of lumber. The tag-along display presented a virtual 2D image of the frame blueprint that fit within the FOV of the HMD. The virtual 2D blueprint image included the same blueprint image presented on the paper condition. The virtual 2D image was positioned 1.5 m from and 0.3 m above the Microsoft

Table 4
Error types for task performance evaluation.

Error Type	Interpretation	Example
Wrong stud space	An incorrect placement of a stud, which results in the layout of the frame being different from the design.	
Toenailing	Misuse of toenailing may cause an unstable connection between studs.	
Nail blow-out	A nail which blows out of a stud may cause injury	
Missing nails	A connection without proper nailing.	
Wrong pieces	Placing a stud with incorrect dimension, which causes the wrong shape or deformation of the frame	
Missing pieces	Subject misses placing a stud. This will make whole frame unstable.	

HoloLens so that it would not block participants' view of the assembly task. To refer to the virtual 2D image, participants had to slightly glance upwards.

As seen in Fig. 4, one drawback of the conformal display was due to the limited FOV of current AR HMDs, such as the Microsoft HoloLens 1st generation. These pictures were direct screenshots from the HoloLens when the user was in a standing position. It is obvious that the FOV for the large frame is not large enough to display the whole 3D model blueprint, whereas the user can see the complete model for small and medium frames. During the assembly, participants were more likely to be in a squatting or kneeling position, which could further constrain their view of the 3D model. Conversely, using a tag-along display could avoid this problem as participants were able to see the floating window from any position, however, as a trade-off, it cannot provide an overlaid 3D model in the environment.

4.1.4. *User task*

Eighteen engineering students with relevant construction background and wood frame assembly experience participated in the experiment (17 men, mean age = 23.8, SD = 4.5; 1 woman, age = 18). All the participants had training and experience with nail gun use. The male and female ratio reflected the actual situation in industry, which is reportedly that women comprise much less population of all the people working in construction compared with men USBLS [28]. Given the distribution of men and women in the industry, our resulting sample was more so reflective of this skewed population. However, we acknowledge there could be gender differences related to task performance, which should be explored in future research by recruiting a more gender balanced sample.

The study involved nine possible conditions occurred equally, each of which consisted of two factors (*frame size* and *information display*). Table 3 listed the task allocation for the participants. During the experiment, each participant performed three assembly tasks with different information displays, in the order given in the able. All the tasks were required to be completed in the designated area (Fig. 2).

Our study design considered the elimination of fatigue effect by adding enough break time between each task condition. If necessary, subjects were allowed to take breaks during the task, which was not included in the time of completion. In addition, three display conditions were completely different in both information presentation and interactions with the AR model, which did not provide participants with practice or learning experience from using previous conditions. All recruited participants had experience with wood frame assembly, which should be considered as a method that also reduced the likelihood of learning effects from occurring.

4.1.5. *Measures*

The experimental design included two measures, time to completion and quality of work. For each trial, the time to completion, which was the time spent assembling a frame, was recorded and analyzed to examine the impact of frame size and information display on the assembly task. The quality of work was used to measure the worker performance and assessed by the accuracy of the frame layout and the occurrence of errors. Six error types were identified and listed in Table 4. From measuring and framing accuracy to nailing pattern, different aspects were considered for performance evaluation with these error types. The number error occurrence was recorded after each trial for further analysis.

4.2. *Data analysis*

The time of completion for each trial was recorded and used for a time analysis between different conditions. To evaluate the framing accuracy, we investigated the task performance based on the different error types in 3.1.5 from three perspectives. First, Friedman Test was utilized to study the impact of each factor (frame size and information display) on the occurrence of each type of error. Next, a further pairwise Wilcoxon Signed-Rank Test was applied to compare effect of conditions within each pair under the two factors. Then third, a more detailed individual analysis was conducted. Different from the pairwise comparison, the individual analysis visualized the errors under all nine conditions, allowing us to assess the distribution of each error type. Specifically, the error types were categorized into different classes for a hierarchical management during the individual analysis.

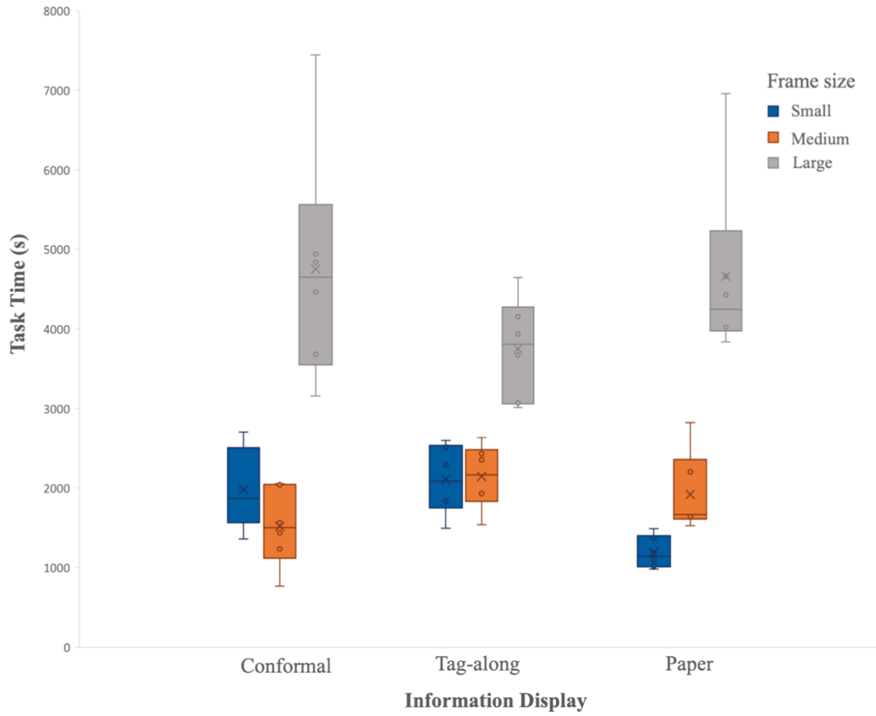


Fig. 5. Boxplot for Task Time in different conditions.

Table 5
Results from Friedman test.

Error types	Frame size		Information display	
	$\chi^2(2)$	*p value*	$\chi^2(2)$	*p value*
Wrong stud space	3.600	0.165	1.200	0.549
Toenailing	4.000	0.135	4.000	0.135
Nail blow-out	0.125	0.939	0.500	0.779
Missing nails	0.143	0.931	0.884	0.643
Wrong pieces	6.300	0.043	2.100	0.350
Missing pieces	26.000	0	3.846	0.146

Table 6
Pairwise comparison for different frame size conditions.

Error type	Paired groups	Z	Sig. (2-tailed)
Wrong stud space	large - medium	−0.813	0.416
	large - small	−1.994	0.046
	medium - small	−0.770	0.441
Toenailing	large - medium	−1.414	0.157
	large - small	−1.414	0.157
	medium - small	0	1
Nails blow out	large - medium	0	1
	large - small	−0.184	0.854
	medium - small	0	1
Missing nails	large - medium	0	1
	large - small	−0.552	0.581
	medium - small	−0.577	0.564
Wrong pieces	large - medium	−1.382	0.167
	large - small	−0.816	0.414
	medium - small	−2.041	0.041
Missing pieces	large - medium	−3.235	0.001
	large - small	−3.235	0.001
	medium - small	0	1

Table 7
Pairwise comparisons for different information display conditions.

Error type	Paired groups	Z	Sig. (2-tailed)
Wrong stud space	conformal - tag	−1.163	0.245
	conformal - paper	−0.045	0.964
	tag - paper	−1.109	0.268
Toenailing	conformal - tag	−1.414	0.157
	conformal - paper	−1.414	0.157
	tag - paper	0	1
Nails blow out	conformal - tag	−0.577	0.564
	conformal - paper	−0.535	0.593
	tag - paper	−0.707	0.480
Missing nails	conformal - tag	−0.796	0.426
	conformal - paper	−0.081	0.935
	tag - paper	−0.513	0.608
Wrong pieces	conformal - tag	−1.382	0.167
	conformal - paper	−1.633	0.102
	tag - paper	−0.272	0.785
Missing pieces	conformal - tag	−1.983	0.047
	conformal - paper	−2.058	0.040
	tag - paper	−0.159	0.873

5. Results and analysis

5.1. Time of completion

To evaluate the worker performance in each condition, task time was recorded for each trial and compared among factors. According to Fig. 5, the frame size had an impact on the average time of completion, where a larger frame size required more time to build. For the comparison among information display conditions, paper condition had a relatively lower task time during small frame assembly, while no significant difference was found in the other two displays. In medium and large frame assembly, conformal and tag-along had correspondingly lower time of completion.

Table 8
Measuring and Framing Problem for each condition.

Frame Size	Info. Display	Measuring Problem	Framing Problem		Sum
		Wrong stud space	Wrong pieces	Missing pieces	
Small	**Conformal**	–	1	–	1
		2	–	–	2
		2	–	–	2
		3	–	–	3
		1	–	–	1
		–	–	–	0
Cumulative total		**8**	**1**	**0**	**9**
Small	**Paper**	1	–	–	1
		2	–	–	2
		–	–	–	0
		–	–	–	0
		3	–	–	3
		1	–	–	1
Cumulative total		**7**	**0**	**0**	**7**
Small	**Tag**	2	–	–	2
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
Cumulative total		**2**	**0**	**0**	**2**
Medium	**Conformal**	2	2	–	4
		–	–	–	0
		–	–	–	0
		3	3	–	6
		–	–	–	0
		–	–	–	0
Cumulative total		**5**	**5**	**0**	**10**
Medium	**Paper**	4	2	–	6
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
Cumulative total		**4**	**2**	**0**	**6**
Medium	**Tag**	–	–	–	0
		–	–	–	0
		–	1	–	1
		–	–	–	0
		–	–	–	0
		2	2	–	4
Cumulative total		**2**	**3**	**0**	**5**
Large	**Conformal**	–	2	–	2
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	1	1
		–	1	–	1
Cumulative total		**0**	**3**	**1**	**4**
Large	**Paper**	3	–	2	5
		–	–	2	2
		–	–	1	1
		–	–	1	1
		–	–	3	3
		–	–	2	2
Cumulative total		**3**	**0**	**11**	**14**
Large	**Tag**	–	–	2	2
		3	–	1	4
		–	–	2	2
		–	–	1	1
		–	–	5	5
		–	–	1	1
Cumulative total		**3**	**0**	**12**	**15**

5.2. Framing error analysis

5.2.1. Friedman test

Since the error evaluation consists of count data, which was not normally distributed, Friedman Test, a nonparametric method was used to compare the difference in the mean ranks of each factor. Table 5 shows the results from Friedman Test for the effects of two factors: *frame size* and *information display* on each error type. According to the results from the frame size group, there were statistically significant differences in *wrong pieces* and *missing pieces* errors, where $\chi^2(2) = 6.3, p = 0.043$ and $\chi^2(2) = 26.000, p = 0$.

In the group of information display, we saw no significant difference for all error types. Hence, pairwise analysis was required to figure out whether there was a mean difference between each two conditions.

5.2.2. Pairwise comparison

As a post-hoc test of Friedman Test, we evaluated the relationship between the conditions under each factor (frame size and information display) associated with all error types, using Wilcoxon Signed-Rank Test. To avoid Type I error, the Bonferroni adjustment was conducted, which had a new significant level of 0.05/3 = 0.017. Tables 6 and 7 show a further pairwise analysis for each paired group. We found significant differences in the *large-medium* (Z = -3.235, p = 0.001) and *large-small* (Z = -3.235, p = 0.001) comparisons for the *missing pieces* error, while *medium-small* groups have similar results (Z = 0, p = 1). Since there was no other statistically significant results for other groups, an individual analysis on each condition was conducted to compare further details (see Table 8).

5.2.3. Individual analysis

Further data analysis was conducted to visualize the distribution of error types in each condition, which helps to explore possible patterns from a more intuitive perspective. In order to get a better understanding of worker performance, all six error types were categorized into three groups based on what caused the error: measuring problem, frame problem and nailing problem. The *wrong stud space* error usually was caused by a calculation mistake or misuse of tape measure, which was classified into the measuring problem. The framing problem included the *wrong pieces* and *missing pieces* errors, which were most likely caused by misunderstanding of the frame design. The other three error types were all about nailing problems, which is directly coordinated with a participant's proficiency nail gun use and nailing skills. Since participants' construction experience varied from each other, their performance in nailing tasks could be biased. Consequently, we compared measuring problem with framing problems, and nailing problems was evaluated separately.

The stacked bar graph in Fig. 6 shows the distribution of measuring and framing problems in all conditions. According to this plot, the tag-along display had the lowest number of errors during small and medium assembly, while the conformal display performed the best in large framing conditions. There is also an obvious pattern that as the frame size increased, the percentage of framing problems increased and the percentage of measuring problems decreased. This can also be observed in the left part of Fig. 7. In the comparison among different information displays, the tag-along display had the least measuring problems and the most framing problems. On the other hand, the conformal display had the least framing problems, and the paper display had the most measuring problems.

Table 9 shows the evaluation for nailing problems. According to the stacked bar graph (Fig. 8), *missing nails* was the most common error in all conditions and *toenailing* error only occurred in the large-conformal condition. Fig. 9 shows the average number of errors for single factors. The *missing nails* error had significantly more occurrence in the large frame condition, however, there was a slight difference in the error occurrence for all information displays. For the *nail blow-out* error, the small frame condition and the paper display condition had the highest error number. According to the raw data, Participant 6 and 13 had significantly more nailing problems than others, which can be considered as a bias due to their nailing skills. Besides, the video recording the task process shows that the framing sequence in the large frame condition directly led to the toenailing errors. Hence, the difference in

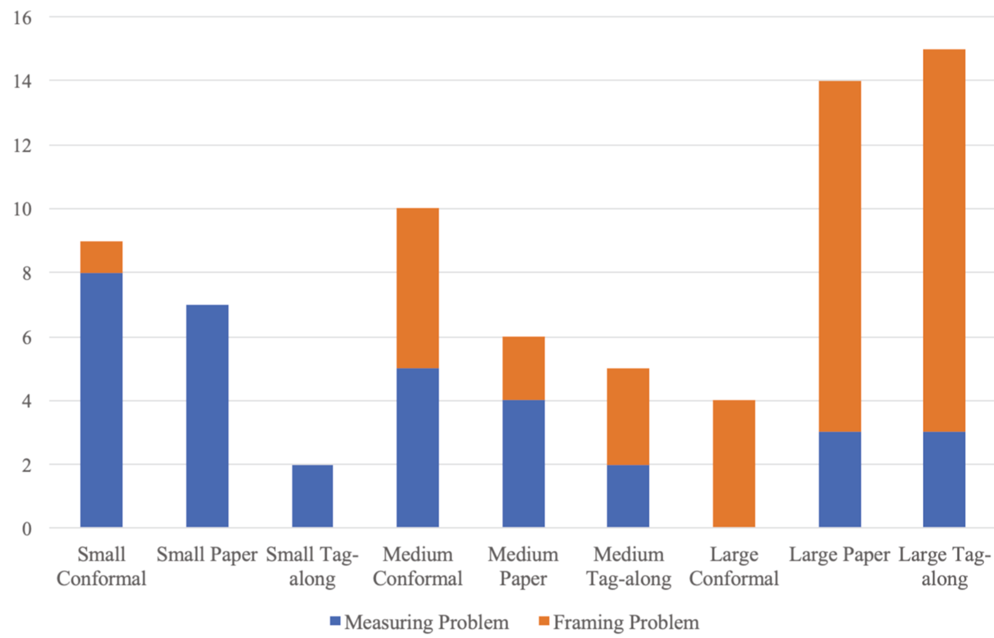


Fig. 6. Measuring and Framing Problems of each condition.

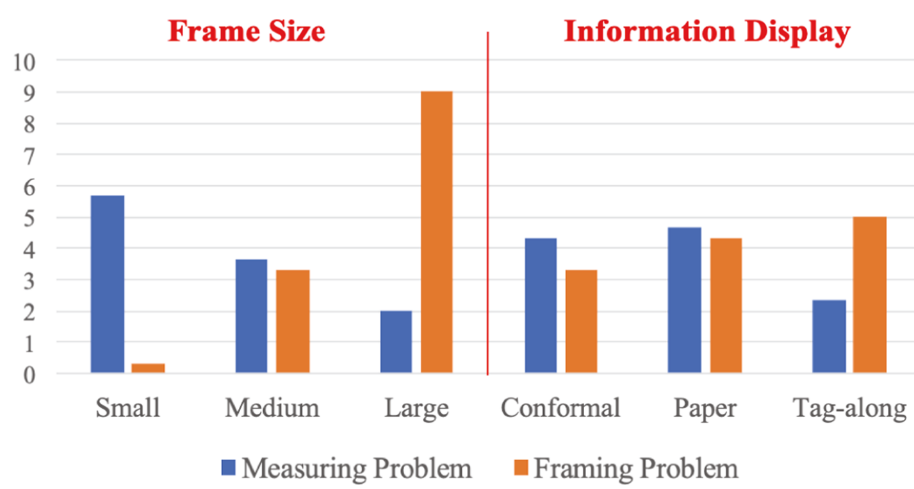


Fig. 7. Average number of measuring and framing errors for single factors.

individual's nailing proficiency is an inevitable influence on the nailing performance.

Overall, the detailed individual analysis was conducted because the statistical tests did not show significant results for the group comparison. The results show that there are differences among each condition of the nine possible combinations. However, when we only look at the comparison for displays, there is no evidence for a significant difference either. This suggests that the selection of display type needs to be based on the task condition. For different frame sizes, there may be different options for best displaying the instruction. In another word, there is no universality in selecting the best display for all framing scales. We cannot consider the impact of display methods without the framing scale factor.

6. Conclusion

This research effort evaluates the assembly performance based on the time it took to complete wood frame walls and the accuracy of the frame while using various information displays. Different from previous studies, both the physical scale and the information display have been taken into consideration in attempts to conduct a more realistic evaluation of the complex factors affecting workers' performance during assembly tasks. Although AR HMDs has been shown to improve the presentation of 2D graphical information [27,11,17,5,16], the limited FOV of AR HMDs drastically restricts the amount of information that can be overlaid onto users' view of large assembly tasks. The findings from this research effort show that the conformal display requires more time

Table 9
Nailing problem for each condition.

Frame Size	Info. Display	Nailing Problem			Sum
		Toenailing	Nail blow-out	Missing nails	
Small	**Conformal**	–	–	–	0
		–	1	–	1
		–	–	–	0
		–	–	–	0
		–	–	4	4
		–	–	3	3
Cumulative total		**0**	**1**	**7**	**8**
Small	**Paper**	–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	3	–	3
		–	–	–	0
Cumulative total		**0**	**3**	**0**	**3**
Small	**Tag**	–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
Cumulative total		**0**	**0**	**0**	**0**
Medium	**Conformal**	–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
		–	–	–	0
Cumulative total		**0**	**0**	**0**	**0**
Medium	**Paper**	–	–	–	0
		–	1	3	4
		–	–	–	0
		–	–	–	0
		–	–	1	1
		–	–	–	0
Cumulative total		**0**	**1**	**4**	**5**
Medium	**Tag**	–	–	–	0
		–	1	–	1
		–	–	–	0
		–	1	–	1
		–	–	–	0
		–	–	–	0
Cumulative total		**0**	**2**	**0**	**2**
Large	**Conformal**	1	–	1	2
		1	2	1	4
		–	–	1	1
		–	–	1	1
		–	–	–	0
		–	–	–	0
Cumulative total		**2**	**2**	**4**	**8**
Large	**Paper**	–	1	1	2
		–	–	1	1
		–	–	1	1
		–	–	–	–
		–	–	1	1
		–	–	2	2
Cumulative total		**0**	**1**	**6**	**7**
Large	**Tag**	–	–	1	1
		–	–	5	5
		–	–	1	1
		–	–	–	–
		–	–	1	1
		–	–	–	–
Cumulative total		**0**	**0**	**8**	**8**

for completion for large scale framing tasks. However, the tag-along display, which avoids the limitation of FOV by presenting the virtual 2D image of the blueprints within the HoloLen's FOV, was shown to decrease task time. This result could be due to the tag-along display improving workers' efficiency by reducing efforts associated with workers switching attention between paper instructions and on-hand work during the task. This result echoes those from Tang et al. [27] that suggest a reduction in attention switching and head movements due to using AR improves the time efficiency for the task. Overall, the findings suggest that HMD helps to obtain information more efficiently than paper documentation in medium and large assemblies, and the strategy of selecting a proper information display strongly depends on the physical scale of the assembled object.

The framing accuracy is another important quality control metric when evaluating the performance. This research analyzes the framing error in three classes: *measuring, framing and nailing problems*. The measuring and framing problems are usually caused by misunderstanding blueprints or incorrect calculations, while the nailing problems are related to the framing sequence and nail gun proficiency. The findings showed reduced measuring and framing problems while using the HMD. The conformal display enables users to check the layout of lumber with the overlaid 3D blueprint model, which reduced errors in the large assembly. This was most clearly observed in the large-conformal condition having the least number of errors. Even though the FOV limitation of AR HMDs restricted users' view of the conformal display, the ability to view the overlaid 3D blueprint model helped users check the layout of their work in the large frame and detect any incorrections, which may have reduced the frequency of measuring and framing problems. However, tag-along display works better in medium and small assemblies. Additionally, there is no evidence for information display having a significant impact on the nailing problems. The nailing performance is more likely related to the physical scale and the worker's proficiency.

Although the restriction of FOV is a technical limitation for current AR HMD, this research still shows advantages in time efficiency, and reducing measuring and framing problems in medium and large assemblies. Specifically, the strategy of selecting an appropriate display method according to the physical scale would help to avoid the FOV limitation and produce the biggest benefit of using AR HMD. Another concern from the users is that the HMD is too cumbersome to wear when conducting such a time-consuming and labor-intensive task as sweating and head movements to view presented information are adding extra burden to the task. Even though the devices are designed to be more wearable and minimalistic, a less weight product can help to reduce the burden on workers during a labor-intensive and time-consuming task.

Besides the limitations above, the attention switch problem is another interesting finding. By placing the graphical information inside of user's FOV, AR HMD saves time for attention switch between the paper documentation and on-hand work. However, there is research suggesting the inattentional blindness may be caused by using an inappropriate display method in HMD [23]. Consequently, further studies examining users' attention and situation awareness is a necessity considering the feasibility of using AR HMD in a real-world construction task.

This work contributes to previously published literature exploring the use of AR HMDs for industrial assembly tasks specifically by investigating the usability of AR HMDs across varying scales of wood frame assembly tasks. Additionally, this research effort attempts to move the use of AR HMDs from the lab into the real-world by examining assembly tasks frequently performed on real-world construction sites. By evaluating how information displays impact workers' performance, these findings can be used to inform the development of best practices for designing AR HMD technologies for large scale assembly tasks and other related on-site construction tasks. The outcome of this work can also inform efforts to develop guidelines for the construction industry in the AR HMD technology adoption. Another contribution of this study is introducing physical scale as a parameter for evaluating the usability of AR HMD. Even though this work only focused on assembly tasks, similar research can be designed for other construction tasks such as inspections, excavations and others.

Declaration of Competing Interest

The authors declare that they have no known competing financial

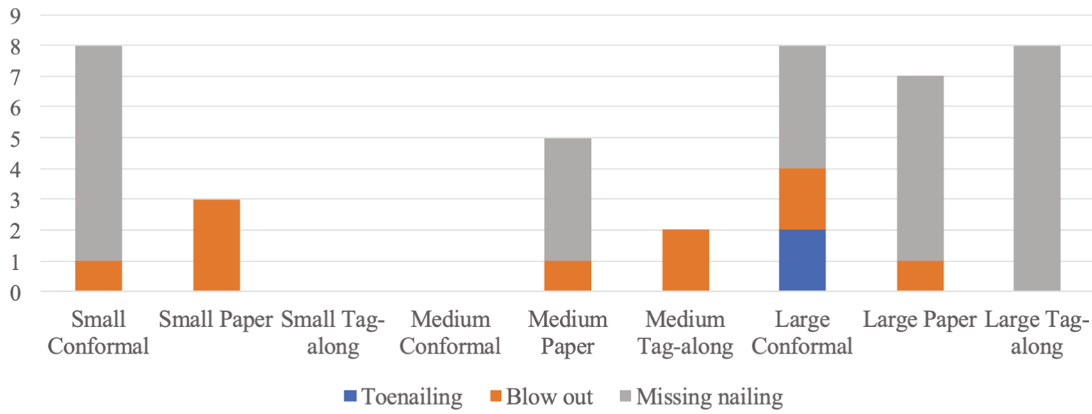


Fig. 8. Nailing Problem of each condition.

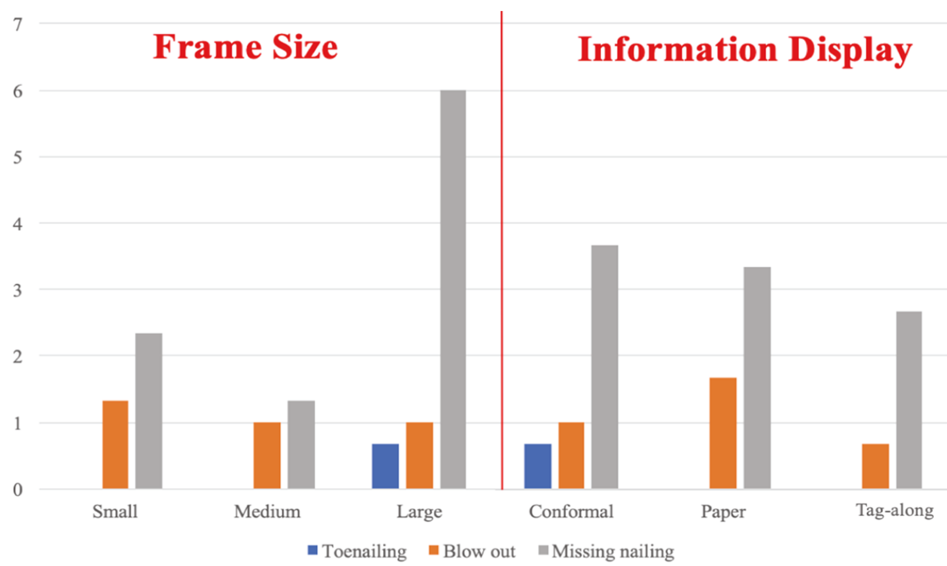


Fig. 9. Average number of nailing errors for single factors.

interests or personal relationships that could have appeared to influence the work reported in this paper.

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