

Investigating the Impact of Augmented Reality and BIM on Retrofitting Training for Non-experts

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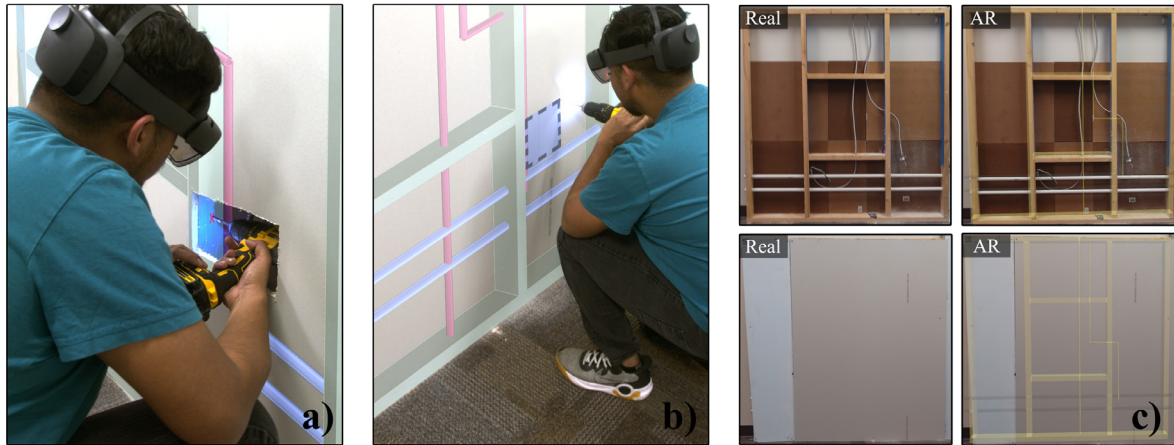


Fig. 1: Using a head-mounted AR system for retrofitting (a), obscured building information data (b) can be displayed to improve decision-making and reduce the time required to complete complex and demanding retrofitting tasks. Spatially oriented models derived from existing building documentation can be further augmented using task-relevant visuals to indicate to wearers where and how to interact with building components (alb).

Abstract—Augmented Reality (AR) tools have shown significant potential in providing on-site visualization of Building Information Modeling (BIM) data and models for supporting construction evaluation, inspection, and guidance. Retrofitting existing buildings, however, remains a challenging task requiring more innovative solutions to successfully integrate AR and BIM. This study aims to investigate the impact of AR+BIM technology on the retrofitting training process and assess the potential for future on-site usage. We conducted a study with 64 non-expert participants, who were asked to perform a common retrofitting procedure of an electrical outlet installation using either an AR+BIM system or a standard printed blueprint documentation set. Our findings indicate that AR+BIM reduced task time significantly and improved performance consistency across participants, while also decreasing the physical and cognitive demands of the training. This study provides a foundation for augmenting future retrofitting construction research that can extend the use of AR+BIM technology, thus facilitating more efficient retrofitting of existing buildings. A video presentation of this article and all supplemental materials are available at https://github.com/DesignLabUCF/SENSEable_RetrofittingTraining.

Index Terms—Augmented reality, AR, building information modeling, BIM, retrofitting, training

1 INTRODUCTION

Changing energy usage standards and population dynamics have necessitated evolution in the *Architecture, Engineering, and Construction* (AEC) industry's relationship with sustainability. In the United States, the building sector utilizes ~76% of all energy while producing up to ~40% of greenhouse gas emissions [60]. To create structures with greater energy efficiency and fit occupants' functional needs, older buildings are often demolished, regardless of their cultural or economic value to the community [41, 42]. The result of this is that building construction and demolition accounts for over 600 million tons of waste and debris in the United States yearly [18], causing a substantial negative impact on the environment.

One solution to this significant problem is increasing support for

building *retrofitting* as an alternative to extensive demolition and complete reconstruction. Retrofitting is a process focused on upgrading a component or feature of a structure that was not part of its initial design and manufacture [26, 38]. However, the current pool of expert AEC professionals and novice homeowners lack the sufficient skills and training needed to sustain the continued growth of retrofitting as a universally viable alternative [50, 55]. Often, retrofitting procedures have high initial costs, along with lengthy payback periods [25, 32, 59], so reducing training costs and increasing adoption is essential to spurring industry acceptance. The integration of greater technological innovation is key for reducing these issues [10]. Recently, a dominant academic and industry trend is the integration of *Building Information Modeling* (BIM) into *Augmented Reality* (AR)/*Virtual Reality* (VR) to increase interactivity and understanding of a building's data during design, inspection, and construction [2]. What is less developed in this area, however, is the potential role AR+BIM can play in retrofitting-specific work for both experts and non-experts.

In this paper, we present a study examining the impact of using AR to visualize BIM data with the ultimate goal of improving retrofitting training (Fig. 1a/b) for inexperienced non-expert workers. We define improvement as increasing performance consistency while reducing

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training duration and the physical and cognitive loads that are commonly posed by retrofitting procedures. Participants are assigned either the assistance of a BIM-enabled AR system or a set of conventional printed documentation and tools. They are then asked to perform the installation of an electric outlet, a common retrofitting task, onto a pre-constructed wall fixture. We demonstrate the impact and significant improvements of using AR+BIM to augment non-experts' performance, decrease task load, and lower task time.

The remainder of this paper will be structured as follows: first, a summary of relevant literature on BIM, AR, and BIM-enabled AR systems in AEC and retrofitting work will be presented as the basis for our work. Next, the design of our study and the systems created for it are detailed. Following this, our results and a discussion of them is included. The paper concludes with a brief summary.

2 RELATED WORK

In this section, we will review relevant concepts and related work that form the foundation of this study.

2.1 Building Information Modeling (BIM)

Different stakeholders and organizations have varying interpretations of what BIM is. [39] defines three common interpretations of BIM as 1) a product, 2) a method, and 3) a methodology. Within this article, BIM's interpretation lies closest with viewing BIM as a model, where it serves as a computerized equivalent to printed construction and maintenance documentation. From this perspective, BIM is viewed as modular software system where project information is compiled and interconnected for simulation analysis, data management, and construction tracking. BIM increases design and construction innovation and increases the collaborative potential of large-scale projects [4, 22, 29]. BIM's 3D rendering and drawing capabilities portray complex project designs at accurate scale, weight, and material at various points in the building lifecycle [66]. BIM also serves as a hub for long-term maintenance and building modifications. Changes made to structures can be effectively reflected in BIM and its virtual representations for long-term storage and display. BIM's strengths and usability are often hindered by difficulty to use software and extra training requirements [4, 7, 14, 22, 35], so finding alternative methods of utilizing its embedded data and structural models, such as AR, may increase its role in the industry even further.

2.2 Augmented Reality (AR)

Modern AR technology strives to blend interactive virtual visualizations with the user's real environment [5, 43]. As advances in computer hardware enabled viable portable computing platforms during the 1990s, and later, there were greater applications of AR to maintenance tasks [19, 24, 48], medicine [57, 58], and military projects [30, 37] for training and in situ access to information.

Incorporating AR into training and onsite work provides embodied interaction with situated data [53]. Virtually augmenting the environment alters its affordances while expanding the body's natural perceptual capabilities [21]. Presenting virtual elements using a hands-free head-mounted system allows intuitive interactions, which support the learning process [9, 65]. AR software can be designed to fully utilize the essential components of *4E Cognition* [46, 56]. The user's environment can be augmented with contextually embedded data projected onto their surroundings to reduce the user's cognitive load and further their cognitive relationship with their workspace [13, 64]. Interactive capabilities with virtual elements can be infinitely creative, which further increases their affordances and the user's ties to their environment [61]. Stereoscopic AR systems permit users to process depth cues and achieve spatial awareness of the virtual elements in the environment while physically moving around them [9].

2.3 BIM-enabled AR in AEC

Early forays into using AR as a tool for displaying maintenance information and processes by [19] established a model that would later be applied to AEC. By integrating data and models from a project's BIM system, designers, construction and operation professionals, and building managers can access building data in a fashion that maximizes

4E cognition. These virtual models and animations can act as guides for workers both on and off-site to improve their performance and design understanding [11, 12, 51, 62]. [44] presents an AR system that guides workers laying bricks to create complex facade structures, and in doing this, difficult-to-implement designs can be evaluated in real-time to ensure accuracy corresponding to their source documentation. Similarly, BIM-enabled AR systems have been used for both on-site and remote collaborative building inspections [16, 17, 47]. Such systems enable workers to more quickly identify necessary maintenance tasks [31] and building defects [40], while automatically linking performed work back to the original BIM model. During the design stages of a construction project, BIM-driven AR and VR systems permit designers to explore multiple designs using a natural perspective, improving understanding of a space's relationship with its occupants [1, 45]. Designers are able to achieve quicker design iterations [28] and improve communication about those elements of those designs with other stakeholders [8, 68].

2.4 BIM-enabled AR in Retrofitting

Currently, the majority of BIM-enabled AR/VR research is primarily centered on the design and construction of entirely new projects [2, 36], however over 90% of buildings in the United States were constructed before 1990 [67]. This has created a gap in objective studies focused mainly on retrofitting design and design evaluation. [20] developed a system for visualizing the impacts of retrofitting indoor greenery on a space's thermal conditions. [54] presented a study on how using a BIM-enabled AR system affects decision-making when evaluating retrofit window facades. [15] and [34] investigated VR+BIM tools for retrofitting design evaluation team meetings. Retrofitting design can be complex, but this is only a portion of the issue when implementing such systems. Training and on-site implementation of retrofits can be enhanced by BIM-enabled AR as well. Building information and structures can be viewed through existing walls that would normally obscure them [63]. Large quantities of building information can be simplified using easily-understandable graphs and visualizations to reduce cognitive load and assist decision-making [52]. For design students working on sustainably-focused retrofits, AR was found to be effective in reducing frustration and improving design novelty [3]. Whether these benefits extend to non-experts being trained or workers being re-trained to implement retrofits is of great interest to the AEC industry.

3 METHODOLOGY

In this section, we will discuss the design of the study and present our hypotheses. The software systems and materials that are utilized in this study are discussed as well, and are available for review and reproduction in [Sec. 6](#).

3.1 Participants

Sixty-six (66) student non-expert participants (45 male, 20 female, 1 other gender, age 18 - 45, $M = 19.62$, $SD = 1.99$) were recruited from a large southeastern US university for the study. These students were not from any particular discipline, and all had normal or corrected-to-normal vision, no reported sensory or motor/physical impairments, and no history of virtual reality-related sickness. Two (2) participants (one from each study group) were excluded from the results analysis due to an inability to complete the study using their provided materials.

3.2 Study Design

This study utilized a between-subjects design, with participants assigned to one of the two study conditions: AR-assisted ($n = 32$) and conventional printed documentation assisted ($n = 32$). For both conditions, participants were brought to the enclosed study location and asked to install an electrical outlet onto a prefabricated wall structure. The particular retrofitting task was chosen because it is common, comparatively testable, and has learning outcomes that are generalizable to other retrofitting procedures. Depending on assigned condition, step-by-step instructions were provided either digitally or as a printed document and could be referred to throughout the testing process. Each set of instructions included images and was content identical. Due to

concerns about cognitive demand on non-expert participants, there was no time limit to complete the task, and participants were only halted if they made a mistake that would critically prevent future progress in the study.

Prior to beginning, participants viewed a two-minute video explaining the purpose of the study, received a verbal explanation of the various building components (drywall, wall studs, PVC piping, wiring, and electric outlet) they were expected to be aware of, and then received training on how to use their provided system. The video explains what retrofitting is, its benefits, and a general explanation of the task. There was no mention of the two study groups or their differences. This training period introduced participants to relevant construction concepts and their assigned instruction system to negate any potential differences in familiarity with AR and construction practices.

Pre and post-study questionnaires were completed using a *Microsoft Surface Pro 4* running *Qualtrics* survey software to collect participant demographic information, their familiarity with AR and construction practices, and gather measures of system usability and perceived task workload. The study was approved by the university *Institutional Review Board* (IRB). No wiring that participants interacted with was connected to power, and all study drywall cutting and drilling tasks were performed by the study administrator using wall markings made by participants during previous steps.

A reusable wall apparatus was constructed for use in this study (Fig. 2). This structure is reusable, simulates a real scenario, and protects the participant and real infrastructure. The structure contains a pre-installed wire and embedded pipes that act as obstacles to avoid. The installation of the outlet requires selecting an ideal vertical wood stud to mount it onto, which is determined by the location of the pre-installed wire. Because of this, participants were instructed to select and locate the stud, mark its position with painter's tape, and then identify the ideal height for the outlet. Following this, an area of the wall that was to be cut out was marked using a pencil. The included instructions informed participants the area needed to be large enough to accommodate both the new outlet and a drill to create the mounting holes in the stud. After the area was marked by the participant, the study administrator used a drill and jab saw to remove the section of drywall. The remaining steps required participants to locate the wire physically and mark the mounting holes on the stud for the outlet while ensuring there is enough room to maneuver the drill to create them. The actual drilling of these mounting holes and the wiring of the outlet were not performed to reduce the overall study time and preserve the wall fabrication for other participants. A brief summary of these tasks is provided in Tab. 1.

Table 1: Brief description of required tasks.

Task	Description
1/2	Locate tools/materials to be used.
3	"Turn off" power on breaker-box.
4a	Locate ideal vertical stud.
4b	Mark ideal height for the installation.
5/6	Draw area that will be cut out of drywall.
7/8	Cut area out of drywall (Done by study administrator).
9	Locate the revealed wire in the wall interior.
10	Mark vertical stud screw holes for the outlet.
11	Ensure the power drill has enough space to drill.

3.2.1 AR System

An AR+BIM software system was developed for the AR condition and was assigned to participants to use. The system was developed for the *Microsoft HoloLens 2* (FoV: 52 degrees, (diagonal) resolution: 1440 X 936 per eye, refresh rate: 60 Hz) using *Unity 2020.3.34f1* and its *OpenXR HoloLens Feature Group*. The additional user interface and graphical systems were created using the *Microsoft Mixed Reality Toolkit 2.8.2* in *Unity*. Simulated BIM data that mirrored the fabricated wall structure (Fig. 2) was designed in *Revit 2021* and imported into the *Unity* environment as an *FBX* file. Additional virtual elements were



Fig. 2: The wall structure without AR visualizations (left column) and with AR visualizations (right column). Participants in our study who utilize AR will see virtual representations of obscured building elements derived from BIM data. These visualizations will guide them in retrofitting an electrical outlet onto the wall structure.

added to the structure to direct attention [27] during key identification-based tasks (for examples, see Fig. 3, Fig. 4, and Fig. 5). Prior to the beginning of each study session, the virtual models were aligned to their real-life counterparts using a pre-positioned QR code affixed to the wall structure. The QR code was scanned 100 times for position and rotation, and the results were averaged for the calculated position, with additional minor alignment adjustments manually performed by the study administrator if they deemed it necessary. Low-opacity virtual models were used to provide information on obscured structural components of the wall to participants while minimizing the participant's visual clutter when utilizing the necessary physical tools. The models provided hands-free access to building information that assisted the participant selection of the optimal installation location, reduce the need for measuring, and assist in spotting identifying details.

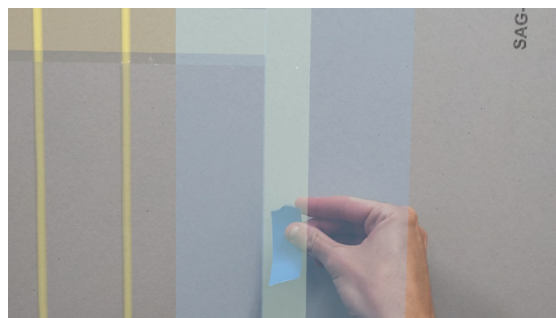
The AR system provided a virtual instruction set (Fig. 6) that participants can interact with according to personal preference. By default, these instructions are presented as a toggle-able menu constrained to their head 0.4 meters in front of them. The menu will adjust its position if the angle between its center and the head's forward vector is greater than 60 degrees. A 'Pin' toggle button constrained to the top-left of the menu can be pressed by the participant to lock the menu in place. When 'pinned,' the position, rotation, and scale of the menu can be manipulated by the participant by grabbing with one or two hands. Prior to beginning the installation task, participants were provided a training period where they practiced 'pinning,' manipulating, and then 'unpinning' the menu. The training period was three minutes long, but participants were free to stop early if they chose to do so and felt comfortable using the system.

3.2.2 Printed Documents System

Participants assigned to the printed condition utilized a printed instruction set, printed modified building technical drawings, and a stud finder to aid in the installation. The printed instructions set utilized identical text to the AR instructions but contained extra instructions on how to operate the stud finder. The technical drawings were a modified subset of the actual documentation of the study location's building and



(a) Wider view of the structure with the light-blue highlighting visual.



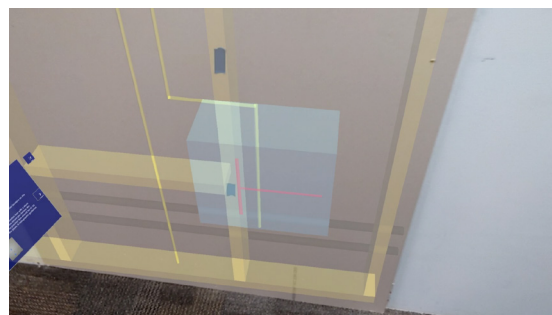
(b) Closer view of the wall with the obscured stud visualized by the AR system.

Fig. 3: Example of attention-funneling virtual imagery visible to AR participants for Step 4a. The light-blue visual indicates the optimal stud to mark using three pieces of blue tape.

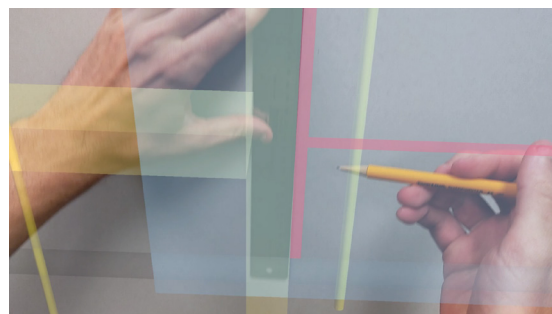
contained information on the building's structural layout, wall panel systems, water and sewage systems, and wiring (Fig. 7). *Adobe Photoshop* was used to integrate the prefabricated wall system and piping and wiring systems into the documents while keeping the style consistent. This document was twenty-three (23) pages and printed on 21.5x15.5 inch paper. Prior to beginning the installation task, participants were instructed to spend three minutes reviewing the documents to gain a better understanding of their organization and identify the participant's current location within them. This period mirrors the interface training AR participants performed. Following this, participants were given a verbal explanation of the organization of the documentation set, what data each section contained, and where the location of the current room was within each section. The documents were available for the participants to review at any point during the study.

3.2.3 Procedure

Participants first read the provided consent form and gave their informed consent. They were then assigned a participant ID number and a study condition and completed the pre-study questionnaire using the Microsoft Surface Pro 4. These forms screened for potentially limiting physical abnormalities (see Sec. 3.1), collected demographic information, and surveyed the participants on knowledge and previous experience with AR, VR, BIM, and standard construction practices. Next, they viewed a two-minute study explanation video and received a verbal explanation of relevant necessary information on the prefabricated wall structure. Participants were then asked to use a custom *Python* application to estimate the size of the section of the wall they anticipated removing and then completed the training for their specific condition. Following this, participants were instructed to complete their provided instructions set sequentially and begin whenever they were ready. No time limit was assigned. Upon completion, participants completed a ten-question survey about their experience with the study, a *System Usability Scale* (SUS) survey, and a *NASA Task Load Index* (TLX) survey.



(a) Wide view of the structure with the light-blue highlighting visual and red pencil guide.



(b) Near view with the target area and the pencil guide visualized by the AR system.

Fig. 4: Example of attention-funneling virtual imagery visible to AR participants for Step 4b. The light-blue visual indicates the general area to mark the vertical height of the outlet and the red pencil guide visual indicates the mark the participant will make on the wall using the pencil.

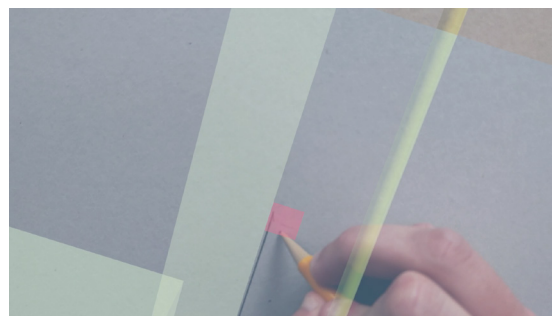
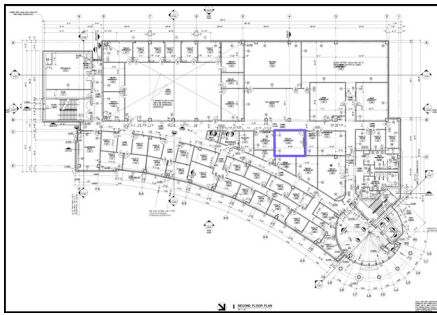


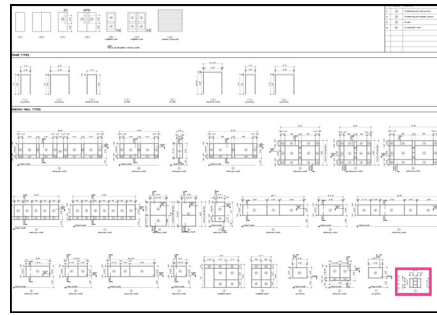
Fig. 5: Example of attention-funneling virtual imagery visible to AR participants for Step 5. The red dot in the center of the image is one of the four corner points participants will mark. These points will be connected with lines to create a rectangle, and this section of the wall will be removed using a jab saw.



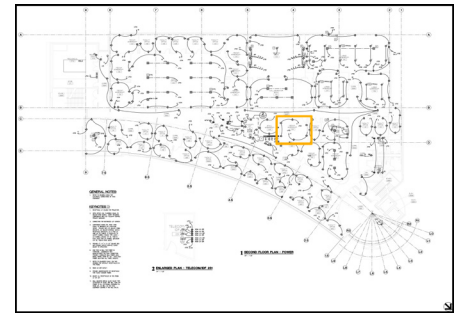
Fig. 6: Virtual instructions pinned in the environment.



(a) The floor plan of the floor in which the study takes place. The study room (223) is located in the center of the image.



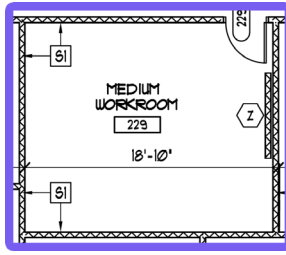
(b) The structural diagrams of various walls and windows in the floor plan diagrams. Participants can match the Z-icon found in Fig. 7e to the correct diagram to learn more information about the prefabricated wall structure designed for the study.



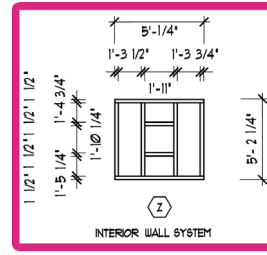
(c) The electrical layout of the floor shows the position of wires running behind the walls in the building.



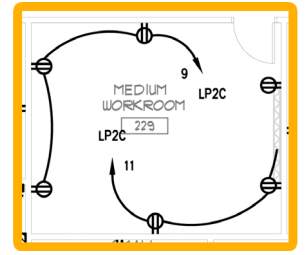
(d) The full twenty-three (23) page documentation set is available to participants assigned to the Printed group. The documents are printed on 21.5x15.5 inch paper.



(e) A zoomed-in view of the study room from Fig. 7a. The Z-icon shown on the right communicates to the reader that they should view the Z diagram on a later page (Fig. 7b) of the document for more information about the structural design of the nearby wall.



(f) A zoomed in view from Fig. 7b shows the Z-icon diagram of the position and scale of the wall's studs.



(g) A zoomed-in view showing the wires in the study room from Fig. 7c. Participants were told to locate the end of the wire, as its adjacent stud is what the outlet will be mounted on. The wire ends about halfway across the left side of the wall.

Fig. 7: Selection of the printed documents available to participants in the Paper group. NOTE: these images are cropped to preserve anonymity

3.3 Measures

Following the completion of steps 4, 6, 8, and 11 (see Tab. 1), a brief study pause was taken so a *Nikon D700* camera could capture the participant's progress up to that point. Following the completion of the study, an additional photograph of the final result was taken. A custom Python script was later used to remove camera lens distortion and perspective-correct these images. From these adjusted images, the total area of the removed drywall was calculated for each participant by manually tagging the images.

While the study was ongoing, the study administrator manually tracked the timestamps of task completion using a custom Python script. From this data, the duration of each task can be derived. Critical mistakes that would prevent participants from progressing were also manually recorded.

Two post-survey questionnaires completed by participants provide insight into their experience using their provided instruction system. The *SUS* allowed a participant to quantify their subjective view on the usability of the system using a 1 (very low) to 5 (very high) Likert scale [6]. The test scores were normalized in accordance with [6] to convert them to a one to one-hundred scale. The included *NASA TLX* collected workload ratings on five metrics: mental demands, physical demands, temporal demands, effort, and performance [23]. It consists of five questions that are scored on a 1 (very low) to 21 (very high) Likert scale. Each question corresponds to a different TLX metric, and the answers are subtracted by one and multiplied by 5 to convert them to a one to one-hundred scale.

3.4 Hypotheses

Our hypotheses primarily focus on improving training consistency while reducing the cognitive load on participants. We also investigate how AR affects training duration.

- **H1:** Participants supported by the BIM-enabled AR system will complete the training task more quickly.
- **H2:** Participants supported by the BIM-enabled AR system will have more consistent final results, shown by a smaller standard deviation of total wall area removed during the installation.
- **H3:** Participants supported by the BIM-enabled AR system will make smaller cuts, thus producing less waste when training.
- **H4:** Participants supported by the BIM-enabled AR system will report lower cognitive and physical demands when completing the training task.

4 RESULTS

In this section, we present the primary study results and statistical analysis. Because the collected data is often non-normally distributed or of an ordinal nature, comparisons between treatment groups primarily consist of employing unpaired two-sided *Wilcoxon Rank Sum Tests* with continuity correction at a significance level of 0.05. Effect size, r , is reported alongside this analysis.

4.1 Task Performance

Overall task performance analysis was calculated by comparing task duration and final wall cutout area across the two treatment groups. Fig. 8 displays the mean task duration for identifying and interacting with specific components of the wall structure. For each task, we utilized an unpaired two-sided *Wilcoxon Rank Sum Test* with a continuity correction at a significance level of 0.05, which permitted us to compare task duration between treatment groups.

Task 3 required participants to locate the simulated breaker box and turn off local power, and there was no significant difference in duration between AR ($Mdn = 62.08$, $SD = 54.96$) and Paper participants ($Mdn = 52.30$, $SD = 31.51$), $W = 376$, $p = 0.1004$, $r = -0.208$ (small

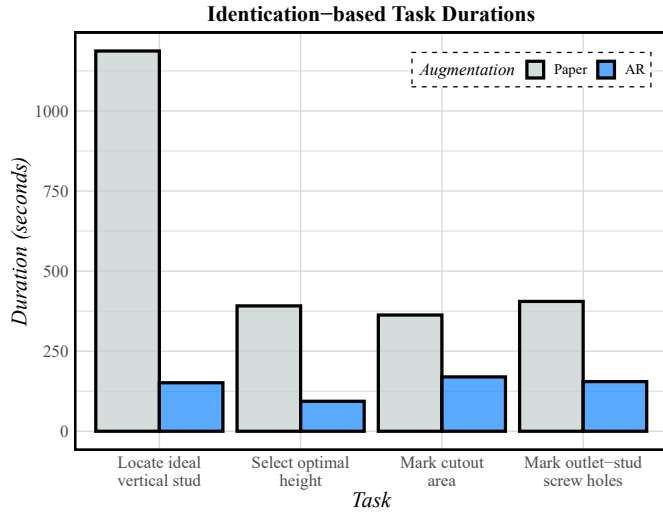


Fig. 8: Visualization of duration means for identification-based tasks. AR participants performed the four tasks (task 4a, 4b, 5/6, and 10) significantly more rapidly than Paper instruction participants.

effect). For **Task 4a**, participants had to locate the correct horizontal position for the ideal installation stud, which indicated there was a significant difference between AR ($Mdn = 129.23$, $SD = 81.02$) and Paper participants ($Mdn = 1142.34$, $SD = 655.27$), $W = 988$, $p < 0.001$, $r = 0.852$ (*large effect*). **Task 4b** required participants to identify the ideal height for the installation where a significant difference was calculated between AR ($Mdn = 82.22$, $SD = 45.84$) and Paper participants ($Mdn = 293.02$, $SD = 267.64$), $W = 953$, $p < 0.001$, $r = 0.791$ (*medium effect*). **Tasks 5/6** were combined for analysis, and required participants to identify and mark the section of the wall that was to be removed during the installation. A significant difference was found between the AR ($Mdn = 163.38$, $SD = 62.51$) and Paper groups ($Mdn = 375.68$, $SD = 140.31$), $W = 793$, $p < 0.001$, $r = 0.644$ (*medium effect*). Participants had to locate and verbally identify the wiring within the wall for **Task 9**, with a significant difference found between the AR ($Mdn = 14.72$, $SD = 9.74$) and Paper groups ($Mdn = 24.30$, $SD = 63.49$), $W = 699$, $p = 0.0054$, $r = 0.352$ (*small effect*). Following this, participants were required to mark screw hole locations on the side of the stud for **Task 10**, with AR participants ($Mdn = 130.12$, $SD = 97.91$) demonstrating a significant advantage over Paper participants ($Mdn = 360.58$, $SD = 262.36$), $W = 850$, $p < 0.001$, $r = 0.614$ (*medium effect*). Finally, for **Task 11** participants verified there was enough space where the wall was cut away to accommodate a power drill, with no significant computed difference in duration between AR ($Mdn = 217.66$, $SD = 135.52$) and Paper participants ($Mdn = 203.23$, $SD = 130.71$), $W = 475$, $p = 0.7781$, $r = -0.036$ (*negligible effect*). The summary statistics for each participant group is reported in [Tab. 2](#), with the statistical test outcomes organized in [Tab. 3](#).

The calculated area of the wall cutout for all participants is reported in [Fig. 9](#), and the determined stud location by all participants is shown in [Fig. 10](#). Similar to task duration, an analysis of the final cutout areas for both groups was performed using an unpaired two-sided *Wilcoxon Rank Sum Test* with continuity correction at a significance level of 0.05. This test indicated that there was a significant difference ($W = 284$, $p = 0.0023$, $r = -0.38$ (*small effect*)) in the median cutout area of the Paper ($Mdn = 75.73$, $SD = 32.40$) and AR groups ($Mdn = 88.04$, $SD = 10.90$). The difference between the two groups' standard deviations warrants further exploration, and *Levene's test* led us to reject that the two groups had a statistically equivalent variance, $F(1, 62) = 6.0017$, $p = 0.0171$.

4.2 System Usability

An analysis of usability along with the physical and cognitive demands of both systems was accomplished using an unpaired two-sided

Table 2: Summary statistics for task duration.

Task	Cond.	N	M	Mdn	SD
3	AR	32	75.47	62.08	54.96
3	Paper	32	55.71	52.30	31.51
4a	AR	32	151.48	129.23	81.02
4a	Paper	32	1187.23	1142.34	655.27
4b	AR	32	93.61	82.22	45.84
4b	Paper	32	391.44	293.02	267.64
5/6	AR	32	169.72	163.38	62.51
5/6	Paper	32	362.88	375.68	140.31
9	AR	32	16.36	14.72	9.74
9	Paper	32	51.42	24.30	63.49
10	AR	32	155.04	130.12	97.91
10	Paper	32	405.37	360.58	262.36
11	AR	32	230.86	217.66	135.52
11	Paper	32	224.04	203.23	130.71

Table 3: Unpaired two-sided *Wilcoxon Rank Sum Test* results for task duration. An asterisk indicates the value is significant.

Task	W	p	r
3	376	0.1004	-0.208 (<i>small</i>)
4a	988	* <0.001	0.852 (<i>large</i>)
4b	953	* <0.001	0.791 (<i>medium</i>)
5/6	793	* <0.001	0.644 (<i>medium</i>)
9	699	*0.0054	0.352 (<i>small</i>)
10	850	* <0.001	0.614 (<i>medium</i>)
11	475	0.7781	-0.036 (<i>negligible</i>)

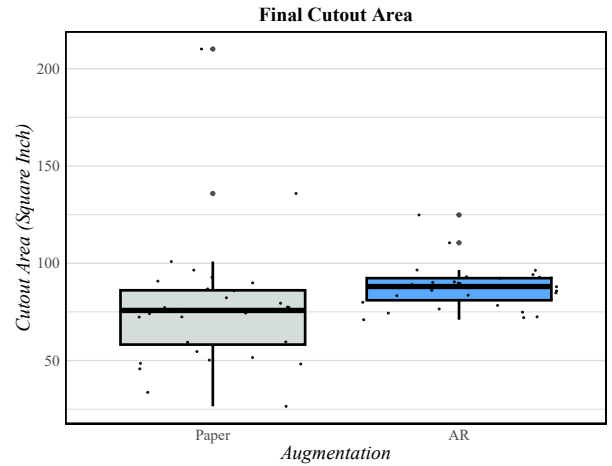


Fig. 9: Distribution of final cutout areas of the two study groups. AR participants created significantly larger cutout areas, but the variance of the cutouts was smaller. This indicates AR was effective at guiding participants toward consistent performances.

Wilcoxon Rank Sum Test with continuity correction at a significance level of 0.05. Boxplot visualizations and summary statistics for these questionnaires are reported in [Fig. 11](#) and [Tab. 4](#).

The **SUS** measured the perceived usability of the system, and a significant difference between AR participants ($Mdn = 77.50$, $SD = 14.48$) and Paper participants ($Mdn = 53.75$, $SD = 19.26$), $W = 188.5$, $p < 0.001$, $r = 0.544$ (*medium effect*) was determined. The first of the **NASA TLX** metrics is **Mental Demand** and a significant difference in the required mental effort was reported between the AR ($Mdn = 30.00$, $SD = 24.76$) and Paper groups ($Mdn = 60.00$, $SD = 20.83$), $W = 719$, $p = 0.0054$, $r = 0.349$ (*small effect*). Similarly, **Physical**

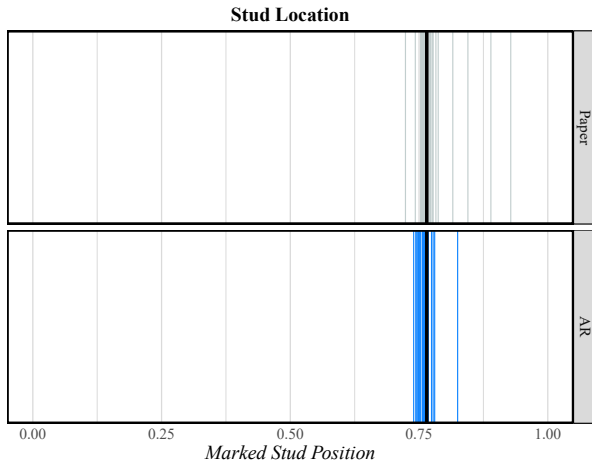


Fig. 10: Marked vertical stud locations for all participants. The ideal stud is indicated by the solid black line. Both groups were accurate, but the Paper participants made more initial mistakes in determining this location.

Demand is the task's required physical effort, and the study found a significant difference between the AR ($Mdn = 20.00$, $SD = 20.16$) and Paper groups ($Mdn = 30.00$, $SD = 20.09$), $W = 700$, $p = 0.0113$, $r = 0.318$ (*small effect*). The **Temporal Demand** indicates how "rushed" participants felt during the study, but there was no statistical difference between the AR ($Mdn = 15.00$, $SD = 15.29$) and Paper participants ($Mdn = 25.00$, $SD = 17.75$), $W = 668.5$, $p = 0.0347$, $r = 0.265$ (*small effect*). The TLX's fourth metric is **Performance Demand**, measuring the self-perceived success in completing the tasks, and our research detected a significant difference between the AR ($Mdn = 75.00$, $SD = 17.36$) and Paper groups ($Mdn = 65.00$, $SD = 19.13$), $W = 332$, $p = 0.0155$, $r = -0.304$ (*small effect*). The final TLX metric was **Effort Demand**, describing the required overall effort to complete the task, with a significant difference measured between the AR ($Mdn = 37.50$, $SD = 22.70$) and Paper groups ($Mdn = 60.00$, $SD = 13.91$), $W = 804.5$, $p < 0.001$, $r = 0.494$ (*small effect*). As in the previous section, summary statistics for each participant group are reported in [Tab. 4](#), and these statistical test outcomes are organized in [Tab. 5](#).

Table 4: Summary statistics for post-questionnaire surveys.

Metric	Cond.	N	M	Mdn	SD
SUS	AR	32	75.39	77.50	14.48
SUS	Paper	32	53.59	53.75	19.26
Ment. D	AR	32	38.59	30.00	24.76
Ment. D	Paper	32	57.81	60.00	20.83
Phys. D	AR	32	22.66	20.00	20.16
Phys. D	Paper	32	34.53	30.00	20.09
Temp. D	AR	32	17.97	15.00	15.29
Temp. D	Paper	32	26.56	25.00	17.75
Perf. D	AR	32	72.97	75.00	17.36
Perf. D	Paper	32	62.50	65.00	19.13
Eff. D	AR	32	40.94	37.50	22.70
Eff. D	Paper	32	62.81	60.00	13.91

Table 5: Unpaired two-sided *Wilcoxon Rank Sum Test* results for post-questionnaire surveys. An asterisk indicates the value is significant.

Metric	W	p	r
SUS	188.5	* <0.001	-0.544 (<i>medium</i>)
Ment. D	719	*0.0054	0.349 (<i>small</i>)
Phys. D	700	*0.0113	0.318 (<i>small</i>)
Temp. D	668.5	0.0347	0.265 (<i>small</i>)
Perf. D	332	*0.0155	-0.304 (<i>small</i>)
Eff. D	804.5	* <0.001	0.494 (<i>small</i>)

Of particular interest was the usability of the AR system relative to the participant's previous experience with VR and AR systems. *Spearman's Rank Correlation* was computed to assess the participant-reported level of experience with AR/VR (1 = very inexperienced, 10 = very experienced) and SUS score. From this test, we found there was no significant correlation between previous experience and the subject system's usability, $r(30) = 0.3464$, $p = 0.0521$.

In a similar vein, a participant's previous experience performing construction activities might affect how they interact with their provided system. An unpaired two-sided *Wilcoxon Rank Sum Test* with continuity correction at a significance level of 0.05 was calculated to compare the self-reported previous experience between the AR ($n = 32$, $Mdn = 1.00$, $SD = 1.10$) and Paper groups ($n = 32$, $Mdn = 2.00$, $SD = 1.46$), but the resulting difference was not found to be significant, $W = 374$, $p = 0.052$, $r = -0.24$ (*small effect*). Additional summary statistics of self-reported pre-questionnaire data are included in [Tab. 6](#).

5 DISCUSSION

Our data analysis shows evidence supporting the acceptance of **H1**, **H2**, and **H4**, and the rejection of **H3**.

5.1 Training Efficiency

Regarding **H1**, perhaps the most immediately visible result of this study was the drastic difference in task duration between groups, specifically for those related to identification and search. AR participants took significantly less time on the majority of these tasks, and the group achieved more consistent performance. We believe that directly visualizing obscured wall elements with BIM data and removing the need to search through complex documentation, AR enabled greater training efficiency. One issue related to this is the *Temporal Demand* as measured by the NASA TLX questionnaire. Despite significant differences in task duration, both groups reported not being pressured by time constraints. We expected this since there was no time limit for the study tasks, however, we suspect with a time limit, it would be likely that greater differences in cognitive load would have been reported.

Participants utilizing the AR system created more consistent size and shaped wall cutouts, which was evident both visually ([Fig. 12](#)) and

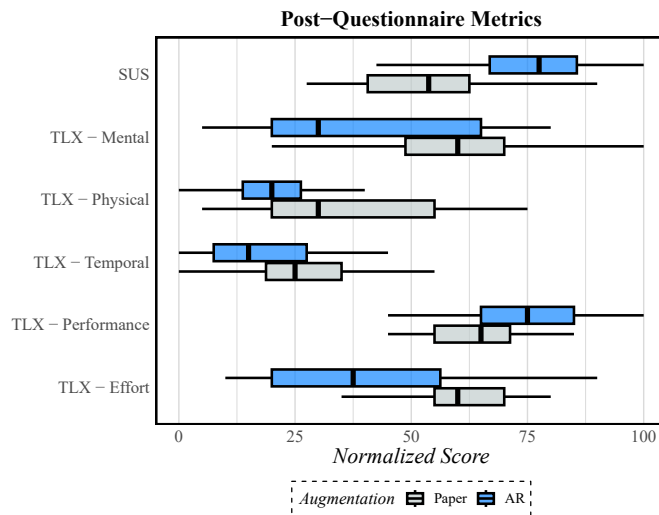


Fig. 11: System usability and effort metrics for both participant groups. AR participants reported their system to be significantly more usable, and required significantly lower mental, physical, and overall effort demands. They also felt more confident in their performance of the installation task.

Table 6: Summary statistics for pre-questionnaire data. Note: experience is abbreviated as *exp.* and frequency is abbreviated as *freq.*

Metric	Cond.	N	M	SD	Scale
Age	AR	32	19.53	1.29	18 - 45
Age	Paper	32	19.69	2.49	18 - 45
Prev. AR Exp.	AR	32	1.96	1.33	1 - 7
Prev. AR Exp.	Paper	32	2.56	1.44	1 - 7
Prev. VR Exp.	AR	32	3.00	1.65	1 - 7
Prev. VR Exp.	Paper	32	3.44	1.46	1 - 7
Prev. 3D Modeling Exp.	AR	32	2.06	1.68	1 - 7
Prev. 3D Modeling Exp.	Paper	32	2.47	1.44	1 - 7
Prev. Construction Exp.	AR	32	1.88	1.10	1 - 7
Prev. Construction Exp.	Paper	32	2.53	1.46	1 - 7
Gaming Freq.	AR	32	4.44	2.06	1 - 7
Gaming Freq.	Paper	32	4.41	1.95	1 - 7
Computer Work Use Freq.	AR	32	6.63	1.21	1 - 7
Computer Work Use Freq.	Paper	32	6.78	0.55	1 - 7
Physical Activity Freq.	AR	32	6.53	1.70	1 - 10
Physical Activity Freq.	Paper	32	6.94	1.76	1 - 10

with difference in group variance. This result supports **H2**, although this group favored larger cutout wall sections than participants using the paper system, a result which contrasts with **H3**. The included visual reference that AR participants had the option of following was approximately 82.41 in² (the top-left corner of this reference square is shown in Fig. 5). This size was chosen since it provided a comfortable amount of space to accommodate the drill inside the wall's interior to create the mounting holes. Coincidentally, the median wall cutouts for both groups deviated from this area by a similar amount, around 6 in². For this study, the Paper group cut significantly smaller wall areas, but required more adjusting cuts to reach the final state, which resulted in more irregular shaped holes. This can lead to difficulties later when patching drywall. Because of the flexibility in the AR system, if waste minimization was prioritized, the suggested projected cutout could be reduced in size. We have not studied the impact this change would have on the task's physical and cognitive demands so they remain unknown.

5.2 Usability and Effort

The analyses of the post-task questionnaire support **H4** and gives insight into the informative potential of BIM-enabled AR's ability toward making retrofitting training a less physically and mentally demanding. Participants found the AR system was much easier to use, with effect not restricted to participants with AR/VR experience. The hands-free character of the tool and the intuitive menu system is designed to be minimally intrusive, permitting newcomers to quickly adapt. This comparatively greater accessibility likely contributed to participants in the AR group reporting lower required levels of mental effort to complete the installation. Additionally, participants from the AR group also reported a significantly higher feeling of success upon completion, we believe this suggests that they were less unsure about their learning results. Because of this, we believe that this result will give non-experts more confidence to perform future retrofitting tasks.

A significant difference was also reported in the physical effort between the groups. The Paper group relied on using tools and their given materials for measurements and creating reference markings. The largest difference in time between the groups was the task where participants were required to locate the optimal vertical stud. This entailed repeated waving arm movements across the wall while operating the stud finder (ranging from five to thirty minutes), and comparing that tool's readings to the provided technical drawings. Building this mental model of the wall required physical and mental effort, whereas the AR system handled this interpretation and alignment automatically.

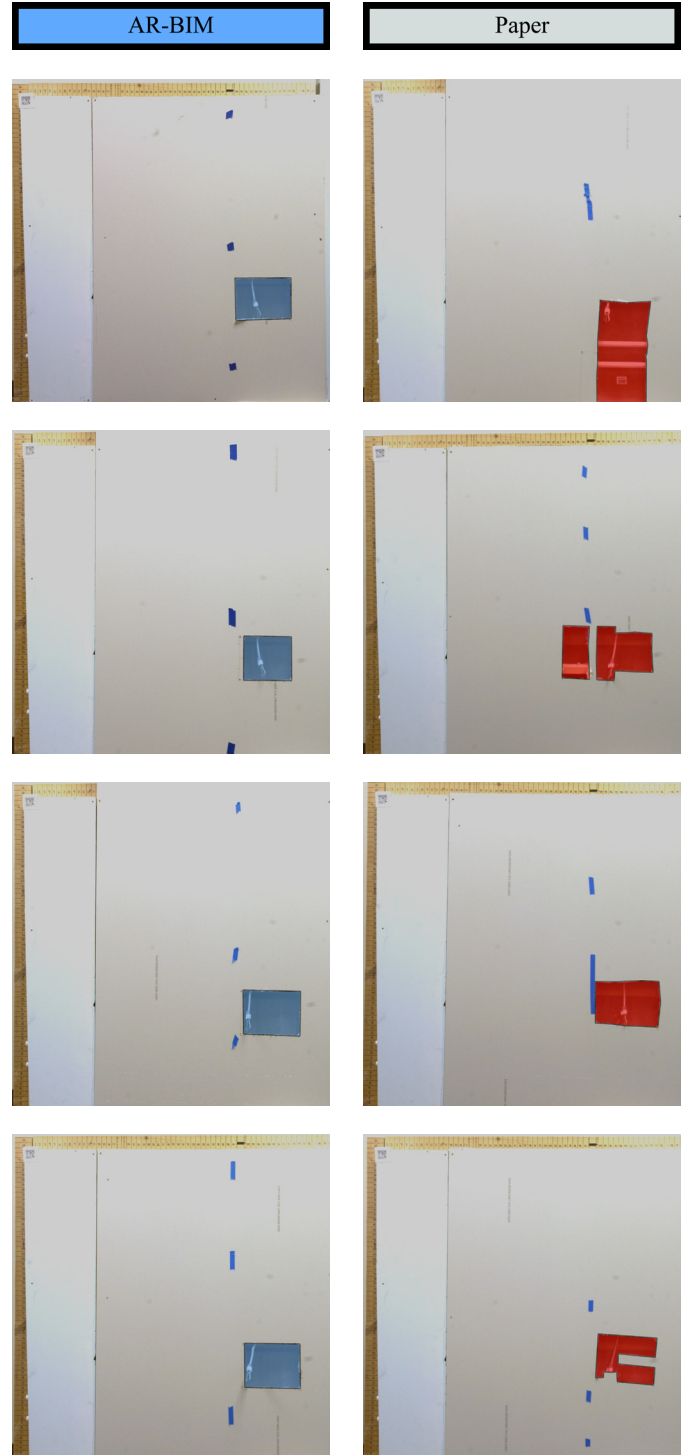


Fig. 12: Selected examples of participant cutouts for the AR group (left column) and Paper group (right column). Cutout areas are highlighted for easier identification. The cutouts by the Paper participants were noticeably more irregular, which would be more difficult to patch up following the installation.

5.3 Limitations and Future Research

Additional data on movement and interactions with virtual elements were automatically recorded for AR participants. Head position, head rotation, eye gaze direction, and the position, rotation, and scale of all virtual elements were logged every 0.25 seconds. This permits researchers to re-create the participants' motion and review their learning

process (Fig. 13). These movements, however, were only tracked for participants assigned to the AR group. While this data will be important for later investigation within that group, greater insight into the embodied and enactive benefits provided by AR may be able to be achieved by comparing how movement, performance, and task time are affected by the provided system.

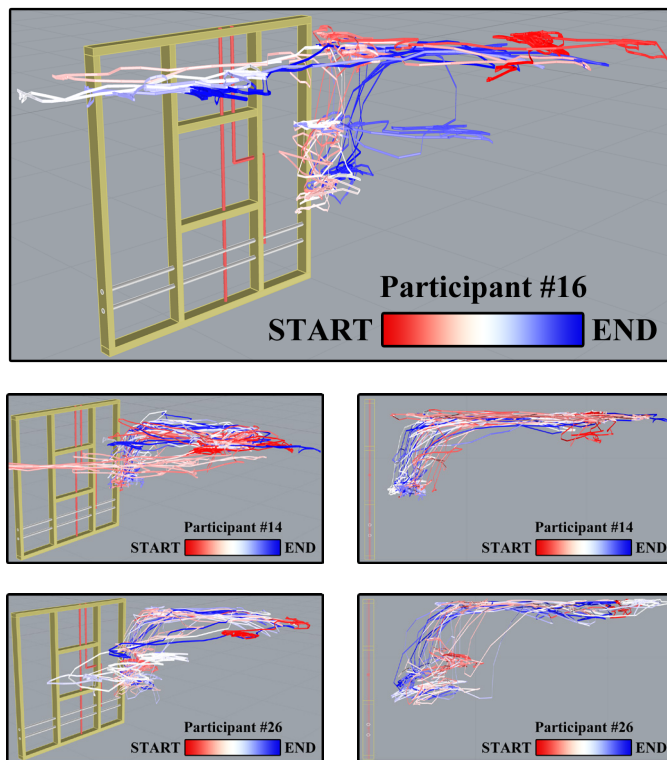


Fig. 13: Head position, head rotation, and eye gaze are logged every 0.25 seconds for all participants and can be later analyzed in a 3D modeling program. Shown here are head positions in *Rhinoceros 6* for three participants. The color of the line indicates at what point in the study the position occurred. As the color shifts from red to blue, time passes. Note the period in the middle-to-end of the study where the participants were kneeling in front of the wall at the end of the wire.

The study population consisted of untrained, non-expert volunteers. While this study does provide insight into the benefits of BIM-enabled AR for this population, its effect on those who have worked as an AEC professional in some capacity previously is of great interest as well. While it is not reported on extensively in this paper, participants were asked to gauge their professional and personal previous experience with related AEC concepts. Future extensions of this research should focus on how AEC experience and expertise level impact the usability and benefits of the AR tool, and our collected data can be retroactively compared to results from future studies. This study focused on the impacts of non-experts since many retrofitting tasks often face challenges. We believe retrofitting will need to be democratized for future built environmental efforts.

The study population was also unintentionally heavily skewed towards young men, which is unfortunately a common bias in AR/VR studies [49]. This reduces the generalizability of the results, and further efforts should be taken to combat this in future related work or replication.

Additionally, resource limitations necessitated that the final steps of an outlet installation (creating the screw holes in the studs, screwing the outlet to the stud, connecting the pre-installed wiring to the outlet, and patching the cut drywall) were not included in the study. We believe AR is best suited for identification-based tasks that involve interaction with building information and data, and because of this, these tasks were

deemed safe to remove as the identification-based aspects of these tasks (marking the screw-hole positions and determining cutout area) were already completed. Still, the impact of including these tasks should be studied in future work.

The complexities of typical construction activities are often amplified when performed as a retrofit, as space constraints are generally tighter, and established building norms and aesthetics must not be affected [33]. While this study primarily focused on training, an extension of this AR system to in situ work is a natural progression. The designed system is extendable, and replacing the simulated BIM data (i.e., the fabricated wall virtual model) with actual BIM data of a worksite can be done using pre-positioned QR codes in the worksite environment. Additionally, the installation of an electrical outlet is a very common retrofitting procedure faced by experts and non-experts, but the task is comparatively simple to other, more advanced procedures. Adaption of this study to more complex retrofits, such as upgrading, piping, ventilation, or electronics systems, are future areas to study, in addition to incorporating expertise levels of industry professionals to compare the impact of AR+BIM on differing experience levels.

6 CONCLUSION

In this paper, we presented a human-subject study investigating the impacts of including a BIM-enabled AR system in an electric outlet installation, a common retrofitting task. Participants utilizing the system performed the installation using a significantly more consistent methodology, and they took significantly less time to complete tasks that required interfacing with current paper-documented building information. These participants also reported the system to be significantly more usable than conventional methods, and that it required less physical and mental effort to complete their training. These results indicate that BIM-enabled AR supports a better understanding of the required building knowledge when completing spatially-constrained retrofitting tasks for a non-expert population and that there is a role for it in the future expansion of retrofitting that will aid in helping us reach our energy goals.

SUPPLEMENTAL MATERIALS

All supplemental materials are available for download on *GitHub* at https://github.com/DesignLabUCF/SENSEable_RetrofittingTraining, released under a Apache License, Version 2.0.

The repository includes (1) necessary *Unity* project files, (2) data collection and processing *Python* scripts, (3) pre and post-questionnaire materials, (4) study videos, and (5) the provided instructions set. A digital copy of the physical building blueprints is not available due to potential security concerns.

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