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

Category: Research

Paper Type: application/design study

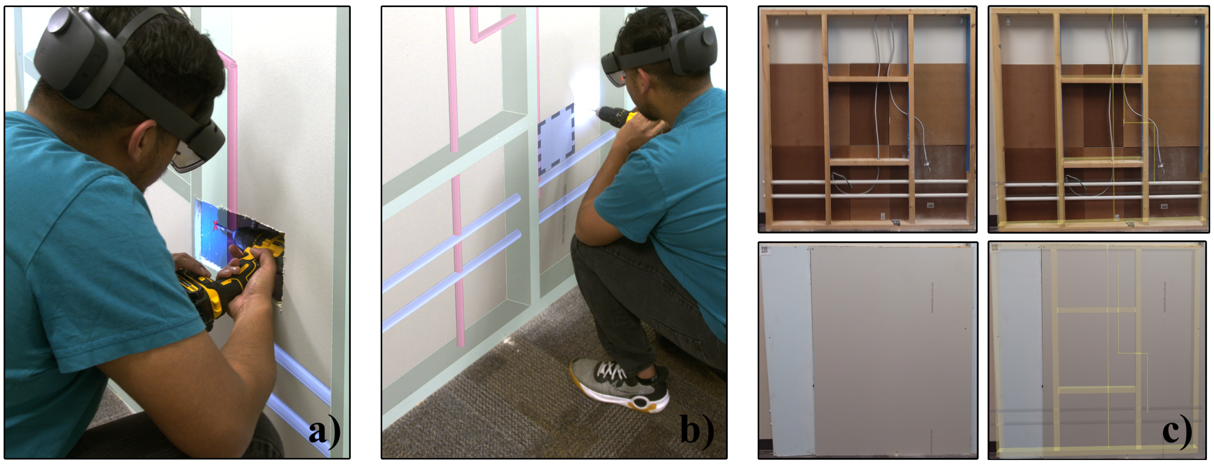


Fig. 1: Using a head-mounted AR system, obscured building information (*c*) can be displayed to improve decision-making and reduce the time required to complete complex and demanding retrofitting tasks. Spatially oriented models derived from existing building documentation can be further augmented using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

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.

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

1 Introduction

Changing energy standards and population dynamics necessitate an evolution in the *Architecture, Engineering, and Construction* (AEC) industry's relationship with sustainability. In the United States, the building sector consumes around 76% of all energy while producing up to 40% of greenhouse gas emissions [57]. To provide for buildings that are more efficient, or ones that more closely fit a changing population's needs, older buildings are often demolished, regardless of their cultural or economic connections with the local area [46, 47]. Additionally, building construction and demolition accounted for 600 million tons of debris in the United States in 2018 [18].

One solution to this important problem is increasing widespread support for *retrofitting* as an alternative to demolition and 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 [26,37]. However, the current pool of AEC professionals lack sufficient skills and experience suited for the continued growth of retrofitting as a universally viable alternative [45, 52]. These procedures also typically see high initial costs and lengthy payback periods [25, 32, 56], so reducing training costs is essential as well in spurring the industry. The integration of greater technological innovation is key for combatting these issues [10]. A predominant recent academic and industry trend is the integration of *Building Information Modeling* (BIM) and *Augmented Reality* (AR)/*Virtual Reality* (VR) to increase interactivity and understanding of building data in training and onsite work. What is less developed in this area, however, is the potential role it can play in retrofitting-specific work for both experts and non-experts.

In this paper, we present a study that investigates the impacts of using AR to visualize BIM data with the ultimate goal of improving retrofitting training (Fig. 1*a*/*b*) for less experienced workers. We define this improvement as increasing performance consistency, reducing training duration, and reducing the physical and cognitive loads that are commonly posed by retrofitting procedures. Participants are assigned the aid of either 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.

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)

BIM serves as the computerized equivalent to printed construction and maintenance documentation. By compiling all documentation into a single centralized software environment, 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 [63]. 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 difficult to use software and extra training requirements [4, 7, 14, 22, 33], 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 aims to blend interactive virtual visualizations with the real environment a user is situated in [5, 39]. As advances in computer hardware increased the viability of portable computing, the 90's and on saw greater application of AR to maintenance [19, 24, 44], medicine [54, 55], and military projects [30, 36] for training and in situ access to information.

Incorporating AR into training and onsite work provides embodied interaction with situated data [50]. Virtually augmenting the environment alters the affordances provided by it, expanding the body's natural perceptual capabilities [21]. Presenting these virtual elements using hands-free head-mounted systems allows for intuitive interactions with them, which supports the learning process [9, 62]. AR software can be designed to utilize all essential components of *4E Cognition* [42, 53]. Data on the user's environment can be contextually embedded onto their surroundings to reduce the user's cognitive load and further their cognitive relationship with their workspace [13, 61]. Interactive capabilities with virtual elements can be infinitely creative, further increasing affordances and the user's ties to their environment [58]. Binocular-vision based AR systems enable user's to more easily process depth-cues and achieve a spatial awareness of the virtual elements in the environment as they physically move about it [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 way that best suits *4E* perspectives of cognition. Virtual models and animations can act as guides for workers both on and off-site to improve performance and design understanding [11, 12, 48, 59]. [40] presents an AR system that guides workers as they lay bricks to create complex facades structures. Difficult to implement designs such as these brick facades can be evaluated in real-time to ensure accuracy to their source documentation. In a similar fashion, BIM-enabled AR systems have been used for both on-site and remote collaborative building inspection [16, 17, 43]. These systems enable workers to more quickly identify necessary maintenance tasks [31] and building defects [38], and automatically link them back to the BIM model. During the design stages of a construction project, BIM-driven AR and VR systems allow designers to explore design concepts from a more natural perspective, improving their understanding of a space's relationship with its occupants [1, 41]. This helps designers achieve quicker design iterations [28] and better communicate elements of their designs with other stakeholders [8, 65].

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 new projects [2, 35], however over 90% of buildings in the United States were constructed before 1990 [64]. The sparse work within this gap has 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. [51] presented a study on how using a BIM-enabled AR system affects decision-making compared to desktop BIM-driven design tools for retrofit window facades. [15] and [34] investigated VR-BIM tools for retrofitting design evaluation team meetings. As complex as retrofitting design can be, it is only a portion of the issue. Training and on-site implementation of retrofits can be enhanced by BIM-enabled AR as well. Building information can be viewed through existing walls that would normally obscure it [60]. Large quantities of building information can be simplified using easily-understandable graphs and visualizations to reduce cognitive load and aid in decision-making [49]. For design students working on sustainably-focused retrofits, AR was found to be effective in reducing frustration and increasing 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

3.1 Participants

Sixty-six (66) student participants (45 male, 20 female, 1 other, age 18 - 45, M = 19.62, SD = 1.99) were recruited from a large southeastern US university for the study. 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 results analysis due to an inability to complete the study using their provided materials.

3.2 Study Design

Participants were assigned to one of the two study conditions: AR assisted (n = 32) and conventional printed documentation (n = 32). For both conditions, participants were brought to the enclosed study location and asked to install an electrical outlet onto a fabricated wall structure. Step-by-step instructions were provided either digitally or as a printed document and could be referred to at any point during the process. These instructions included images and were identical between groups. No time limit to complete the task was given, and participants were only halted if a mistake that would critically prevent future progress in the study was made. 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 received training on how to use their provided system. Pre- and post-study questionnaires were completed using a *Microsoft Surface Pro 4* running *Qualtrics* survey software to collect information on participant demographics and familiarity with AR and construction practices, and to measure the usability and perceived workload of the system and task. The study was approved by the university *Institutional Review Board* (IRB). No wiring that participants were able to interact with were connected to power and all study tasks related to cutting drywall were performed by the study administrator in accordance with wall markings made by participants during previous steps.

A reusable wall fabrication was constructed for use in this study (Fig. 2). 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 wooden stud to mount it onto, which is determined by the location of the pre-installed wire. Because of this, participants were instructed to first determine and locate an ideal stud, mark its position, and then identify the ideal height for the outlet. Following this, an area of the wall that was to be cut out was marked. The included instructions informed participants the area would be large enough to accommodate both the outlet and the drill. When this area was marked, the study administrator used a jab saw to remove the area of drywall. The remaining steps required participants to physically locate the wire, mark screw holes to connect the stud and outlet, and ensure there is enough room for the drill to create these screw holes. The actual drilling of these stud-holes and wiring of the outlet were

Fig. 2: The wall structure without AR visualizations (left column) and with AR visualizations (right column).

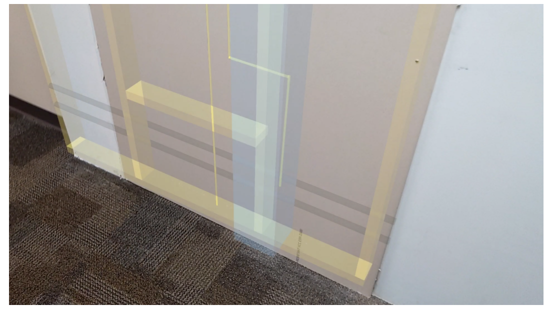
Table 1: Brief description of required tasks.

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.

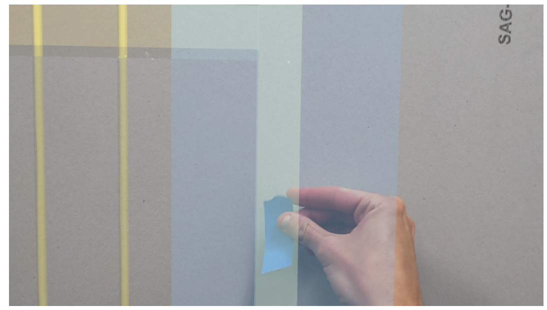
not performed to reduce the overall study time and preserve the wall fabrication for other participants. A brief summary of these tasks is provided in Tab. 1.

3.2.1 AR System

An AR software system was developed for participants assigned to the AR condition 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 added to the structure to funnel attention [27] at key identification-based tasks (for examples, see Fig. 3, Fig. 4, and Fig. 5). Prior to beginning the study, the virtual models were aligned to their real-life counterparts using a pre-positioned QR code attached to the wall structure. 100 position and rotation scans of the QR code were averaged for the position, and additional minor alignment adjustments were manually performed by the study administrator if deemed necessary. Low opacity virtual models were used to provide information on obscured structural components of the wall to participants while minimizing visual clutter when utilizing the necessary physical tools. The models provided hands-free access to building information that would inform their selection of optimal locations, reduce need for measurements, and aid in identifying details.

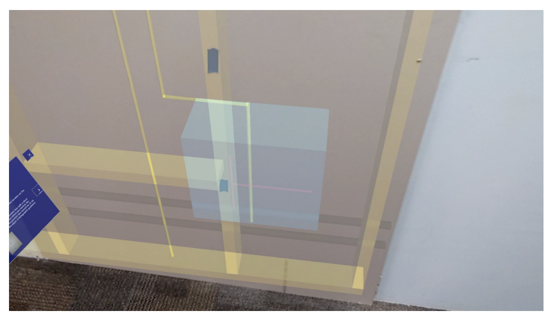


(a) Wider view of the structure with the light-blue highlighting visual.

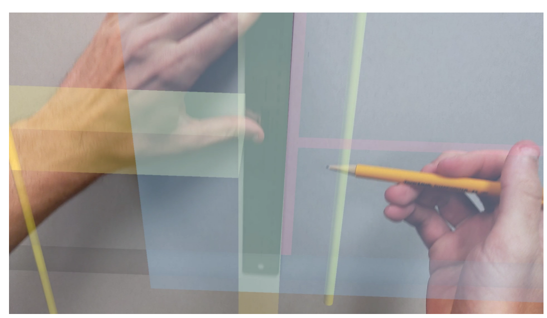


(b) Closer view of the wall with the obscured stud visualized by the AR system.

Fig. 3: Example of an 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.



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



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

Fig. 4: Example of an attention-funneling virtual imagery visible to AR participants for Step 4b. The light-blue visual indicates 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.

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 that is con-

Fig. 5: Example of an 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.

strained 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 short training period where they practiced 'pinning', manipulating, and then 'unpinning' the menu.

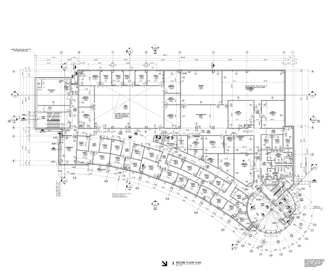
3.2.2 Printed Documents System

Participants assigned to the printed condition utilized a printed instruction set, printed modified building technical drawings, and stud finder to aid in the installation. The printed instructions set provided identical text to the AR instructions set, 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 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 fabricated wall system and piping and wiring systems into the documents while staying consistent with its style. 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. Following this, a verbal explanation of the technical drawings' organization and a purpose of each page were explained to the participants. The documents were available for review at any point during the study.

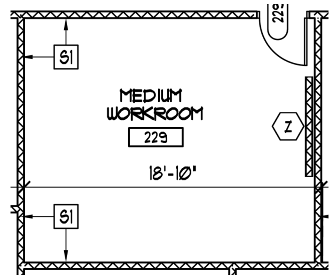
3.2.3 Procedure

Participants first read their consent form and provided their informed consent. They were then assigned their participant ID number and a

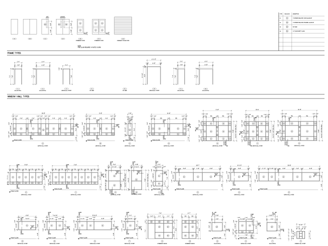
(a) The full twenty-three (23) page documentation set available to participants assigned to the Printed group. The documents are printed on 21.5x15.5 inch paper.



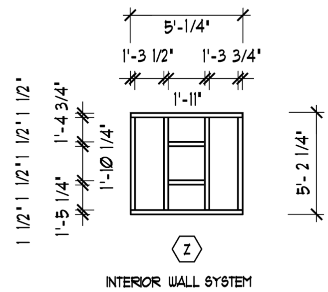
(b) The floor plan of the floor in which the study takes place. The study room (223) is located in the center of the image.



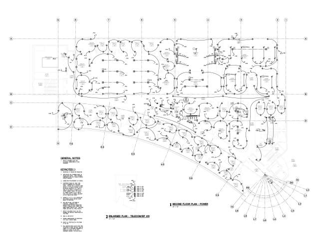
(c) A zoomed in view of the study room. The *Z-icon* shown on the right communicates to the reader that they should view the *Z* diagram on a later page of the document for more information about the structural design of the nearby wall.



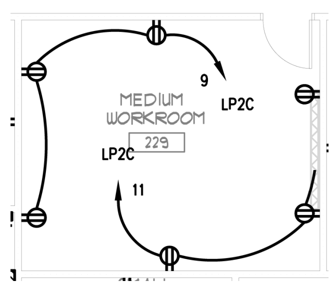
(d) The structural diagrams of various walls and windows in the floor plan diagrams. Participants can match the *Z-icon* found in Fig. 7b to the correct diagram to learn more information about the prefabricated wall structure designed for the study.



(e) A zoomed in view showing the *Z-icon* diagram of the position and scale of the wall's studs.



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



(g) A zoomed in view showing the wires in the study room. Participants were told to locate the end of the wire, as it's 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. Original pages are shown on the left and zoomed in sections of important details are shown on the right. NOTE: these images are cropped to preserve anonymity

study condition, and completed the pre-study questionnaire using the Microsoft Surface Pro 4. These forms screened for physical abnormalities, 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 wall fabricated wall structure. Participants were then asked to use a custom *Python* script to estimate the area of the wall they anticipate 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 provided. 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.

3.3 Measures

Following the completion of steps 4, 6, 8, and 11 (see Tab. 1), a brief intermission 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 picture of the final result was taken. A custom Python script was 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 timestamps of the completion of each task 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 on their experience using their provided 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.

Additional data on movement and interactions with virtual elements were 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 allows for future recreation of the participants' motion and review of their learning process (Fig. 8).

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.

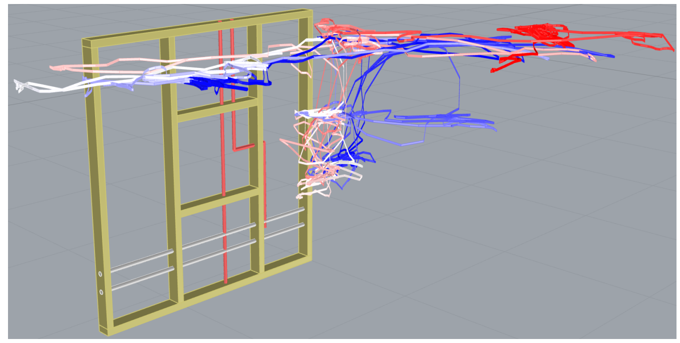


Fig. 8: Head position, head rotation, and eye gaze are logged every 0.25 seconds for all participants and can be later analyzed in a 3D modeling program. Shown here are head positions in Rhinoceros 6. The color of the line indicates at what point in the study the position occurred. As the color shifts from red to blue, time passes. Note the period in the middle-to-end of the study where this participant was kneeling in the front of the wall at the end of the wire.

4 Results

4.1 Task Performance

An analysis of overall task performance was performed by comparing task duration and final cutout areas across our two study groups. Fig. 9 demonstrates the mean task durations for tasks related to identifying and interacting with specific components of the wall structure. Summary statistics for all task durations are shown in Tab. 2. For each task, we used an unpaired two-sided *Wilcoxon Rank Sum Test* with continuity correction at a significance level of 0.05. This test was chosen to compare the two groups, as the two were not normally distributed. These tests indicated that the task duration for AR participants were significantly different for tasks 4a, 4b, 5/6, 9, and 10 (Tab. 3).

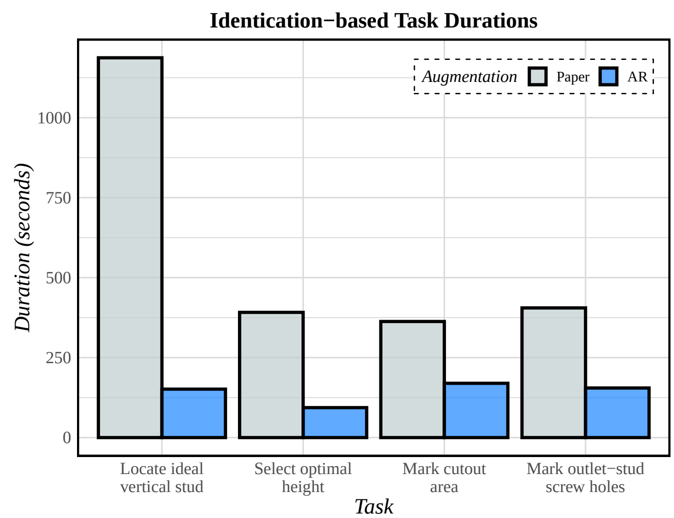


Fig. 9: Visualization of mean durations of identification-based tasks.

The calculated cutout areas of all participants are reported in Fig. 10, and the determined stud location by all participants is shown in Fig. 11. Similar to task durations, 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 ($W = 284$, $p = 0.0023$) in the median cutout area of the Paper group ($n = 32$, $Mdn = 75.73$, $SD = 32.40$) and the AR group ($n = 32$, $Mdn = 88.04$, $SD = 10.90$). The gap between the two groups' average standard deviation warranted further exploration, and *Levene's test* rejected the notion that the two groups

Table 2: Summary statistics for tasks durations.

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 durations. An asterisk indicates the value is significant.

Task	*W*	*p*
3	376	0.1004
4a	988	*<0.001
4b	953	*<0.001
5/6	793	*<0.001
9	699	*0.0054
10	850	*<0.001
11	475	0.7781

had an equal variance, F(1, 62) = 6.0017, $p = 0.0171$.

4.2 System Usability

An analysis of the usability and physical and cognitive demands of both systems was accomplished using unpaired two-sided *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. 12 and Tab. 4. The tests indicated that significantly different questionnaire scores for AR and Paper participants were found in overall system usability, required mental demand, required physical demand, performance satisfaction, and overall effort demand (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

Of particular interest was the usability of the AR system and its relation to 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. However, this test found there was no significant correlation between the two variables, $r(30) = 0.3464$, $p = 0.0521$.

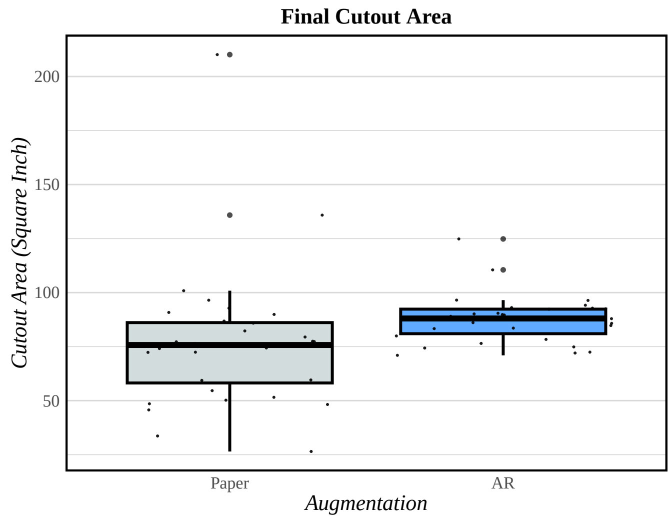


Fig. 10: Distribution of final cutout areas of the two study groups.

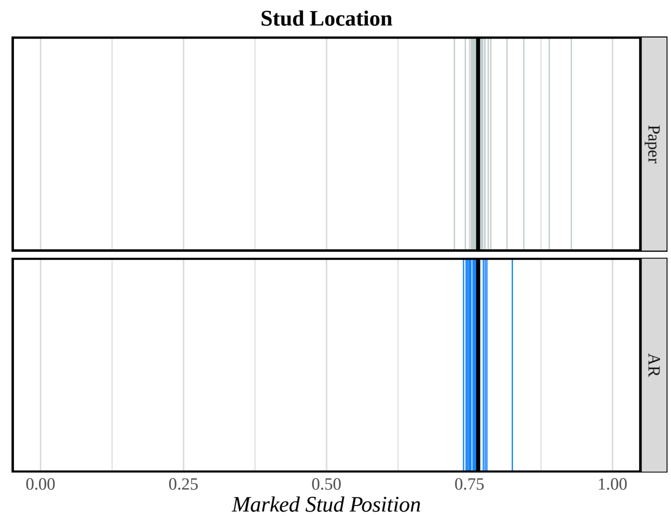


Fig. 11: Marked vertical stud locations for all participants. The ideal stud is indicated by the solid black line.

5 Discussion

Our data analysis shows we can accept **H1**, **H2**, and **H4**, but reject **H3**.

5.1 Training Efficiency

Perhaps the most immediately striking result of this study was the drastic difference in task durations between groups, specifically on tasks related to identification and search. AR participants exhibited significantly lower durations on the majority of these tasks, and achieved much more consistent performances within the group. By directly visualizing obscured BIM data and removing the need to search through complex documentation, AR enabled greater training efficiency. Related to this is the Temporal Effort portion of the NASA TLX questionnaire. Despite significant differences in task durations, both groups reported low feelings of being pressured by time constraints. This was reasonably expected due to a lack of time limit imposed on the study tasks, however it would be likely that with a time limit, even greater differences in cognitive demand would have been reported.

Participants utilizing the AR system created much more consistent size and shaped cutouts. The included visual reference that AR par-

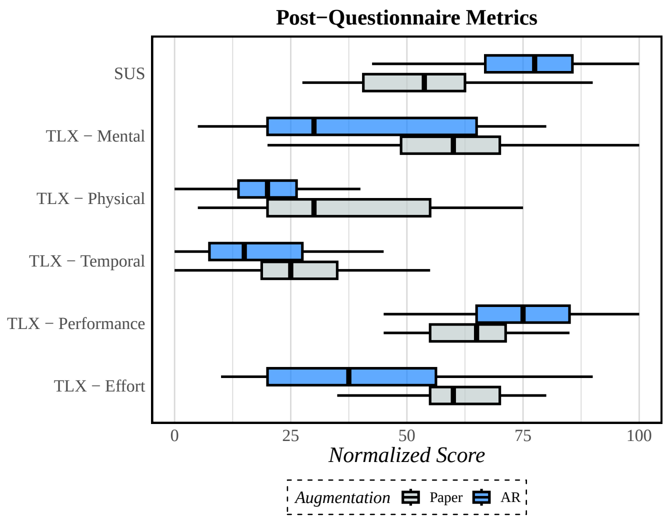


Fig. 12: System usability and effort metrics for both participant groups.

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

Metric	*W*	*p*
SUS	188.5	*<0.001
Ment. D	719	*0.0054
Phys. D	700	*0.0113
Temp. D	668.5	0.0347
Perf. D	332	*0.0155
Eff. D	804.5	*<0.001

ticipants had the option of following was approximately 82.41 inch^2. This size was chosen to provide a comfortable amount of space to accommodate the drill inside the wall's interior after cutting. Interestingly, the median cutout areas of both groups deviated from this amount by a similar quantity, about 6 inch^2. For this study, the paper group demonstrated significantly smaller cutout areas, but reaching this final state generally required more cuts and resulted in more irregular shapes, which can lead to later difficult drywall patching and repair (Fig. 13). If waste minimization was to be prioritized, the AR projected cutout area suggestion could be reduced in size, but the impact this change would have on the task's physical and cognitive demands is unknown.

5.2 Usability and Effort

The result of analyses on our post-questionnaire was informative on the potential role of BIM-enabled AR in making retrofitting training a less physically and mentally demanding process. Participants found the AR system has a much greater ease-of-use, and this was not constrained to just participants with previous AR/VR experience. The hands-free nature of the tool and the intuitive menu systems are designed to be minimally intrusive, and thus newcomers were quick to adapt. This comparatively greater accessibility likely contributed to participants in the AR group reporting lower levels of required mental physical effort to complete the installation. Participants in the AR group also reported significantly higher feelings of success upon completion, suggesting that they may have been less unsure about their learning results.

A significant difference in reported physical effort between the groups was fairly surprising. The paper group relied on using tools and their given materials for measurements and creating reference markings. The most exaggerated difference in time between the groups was the portion of the study where participants were required to locate the optimal vertical stud. This entailed repeated waving arm movements across the wall (ranging from five to thirty minutes), while constantly comparing the stud finder's readings to the provided technical drawings. Building this mental model of the wall required physical and mental

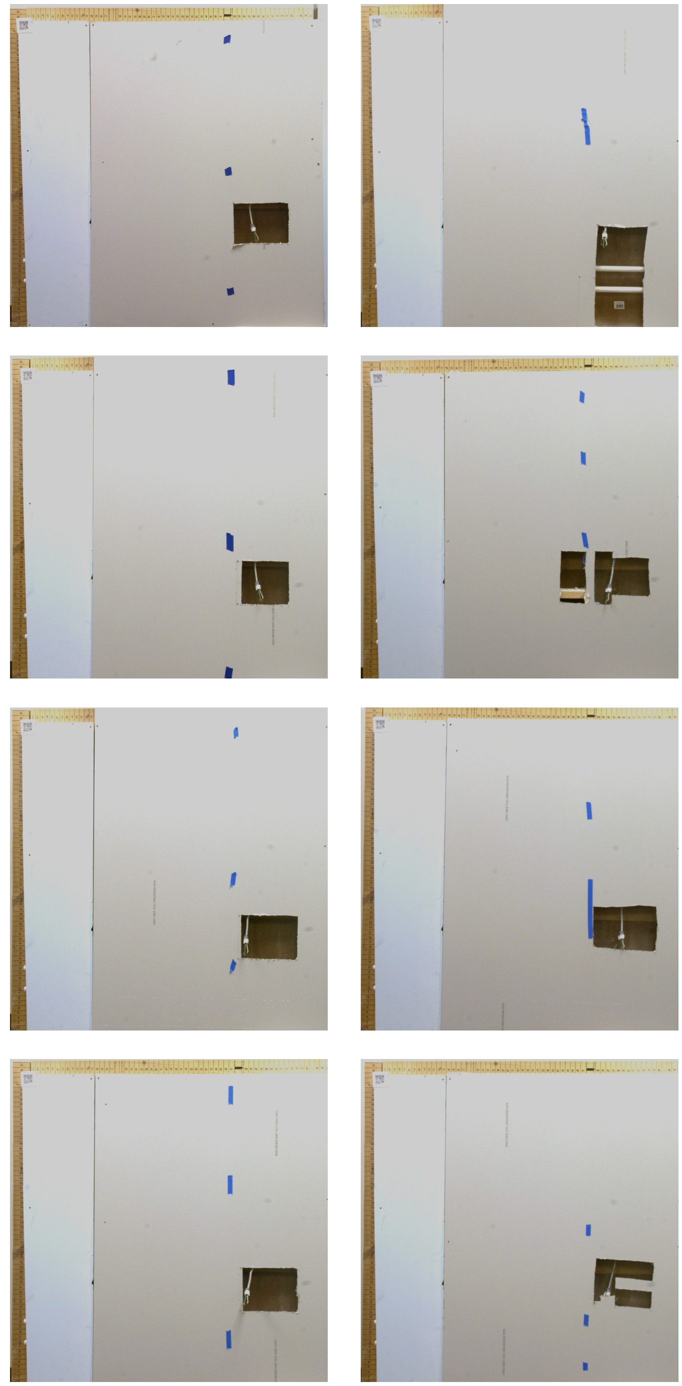


Fig. 13: Selected examples of participant cutouts for the AR group (left column) and Paper group (right column).

effort, whereas the AR system handled this interpretation and alignment automatically.

5.3 Limitations and Future Research

For this study, head and eye movement 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 benefits provided by AR may be able to be achieved by comparing how movement is affected by the provided system.

The study population consisted primarily of untrained student volunteers. While this study does provide insight on 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 as part of this paper, participants were asked to gauge their professional and personal previous experience with related AEC concepts. Future extensions of this research should investigate how levels of AEC experience impact the usability and benefits of the AR tool, and our collected data can be retroactively compared to results from future studies.

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. AR is likely best suited for identification-based tasks that involve interaction with building information and data, and these tasks were deemed safe to cut as the identification-based aspects of these tasks (marking the screw-hole positions and determining cutout area) were already completed earlier. 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. Because of this, it is essential that this increased cognitive and physical loads be reduced to not compromise worker performance. 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, installation of an electrical outlet is a very common retrofitting procedure, but is comparatively simple. Adaption of this study to more complex retrofits, such as upgrading ventilation or electronics systems, and incorporating industry professionals as participants, will aid in this area of research.

6 Conclusion

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

References

[1] Wael A. Abdelhameed. Creativity and VR Use. pages 719–728, Kyoto, Japan, 2014. 2

[2] Sepehr Alizadehsalehi, Ahmad Hadavi, and Joseph Chuenhuei Huang. From BIM to extended reality in AEC industry. *Automation in Construction*, 116:103254, August 2020. 2

[3] Steven K. Ayer, John I. Messner, and Chimay J. Anumba. Augmented Reality Gaming in Sustainable Design Education. *Journal of Architectural Engineering*, 22(1):04015012, March 2016. 2

[4] Salman Azhar. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3):241–252, July 2011. 2

[5] Ronald T. Azuma. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6(4):355–385, August 1997. 2

[6] John Brooke. SUS - A quick and dirty usability scale. *Usability evaluation in industry*, 189(194):4–7, 1996. Publisher: London, England. 5

[7] David Bryde, Martí Broquetas, and Jürgen Marc Volm. The project benefits of Building Information Modelling (BIM). *International Journal of Project Management*, 31(7):971–980, October 2013. 2

[8] Luisa Caldas and Mohammad Keshavarzi. Design Immersion and Virtual Presence. *Technology|Architecture + Design*, 3(2):249–251, July 2019. 2

[9] Gail Carmichael, Robert Biddle, and David Mould. Understanding the Power of Augmented Reality for Learning. pages 1761–1771. Association for the Advancement of Computing in Education (AACE), 2012. 2

[10] Domenico Ceglia, Mônica Cavalcanti Sá de Abreu, and José Carlos Lázaro Da Silva Filho. Critical elements for eco-retrofitting a conventional industrial park: Social barriers to be overcome. *Journal of Environmental Management*, 187:375–383, February 2017. 1

[11] Jad Chalhoub and Steven K. Ayer. Using Mixed Reality for electrical construction design communication. *Automation in Construction*, 86:1–10, February 2018. 2

[12] Adam Chernick, Christopher Morse, Steve London, Tim Li, David Ménard, John Cerone, and Gregg Pasquarelli. On-Site BIM-Enabled Augmented Reality for Construction. In Philip F. Yuan, Jiawei Yao, Chao Yan, Xiang Wang, and Neil Leach, editors, *Proceedings of the 2020 DigitalFUTURES*, pages 46–56. Springer Singapore, Singapore, 2021. 2

[13] Andy Clark. An Embodied Cognitive Science? *Trends in Cognitive Sciences*, 3(9):345–351, September 1999. 2

[14] Tracey Crosbie, Nashwan Dawood, and Saad Dawood. Improving the energy performance of the built environment: The potential of virtual collaborative life cycle tools. *Automation in Construction*, 20(2):205–216, March 2011. 2

[15] Fábio Matoseiro Dinis, Luís Sanhudo, João Poças Martins, and Nuno M.M. Ramos. Improving project communication in the architecture, engineering and construction industry: Coupling virtual reality and laser scanning. *Journal of Building Engineering*, 30:101287, July 2020. 2

[16] Jing Du, Yangming Shi, Zhengbo Zou, and Dong Zhao. CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users. *Journal of Construction Engineering and Management*, 144(2):04017109, February 2018. 2

[17] Khaled El Ammari and Amin Hammad. Remote interactive collaboration in facilities management using BIM-based mixed reality. *Automation in Construction*, 107:102940, November 2019. 2

[18] Environmental Protection Agency. Advancing Sustainable Materials Management: 2018 Fact Sheet. Technical report, United States Environmental Protection Agency, 2020. 1

[19] Steven Feiner, Blair Macintyre, and Dorée Seligmann. Knowledge-based augmented reality. *Communications of the ACM*, 36(7):53–62, July 1993. 2

[20] Tomohiro Fukuda, Kazuki Yokoi, Nobuyoshi Yabuki, and Ali Motamedi. An indoor thermal environment design system for renovation using augmented reality. *Journal of Computational Design and Engineering*, 6(2):179–188, April 2019. 2

[21] James J Gibson. *The Ecological Approach To Visual Perception: Classic Edition*. Psychology Press, 1978. 2

[22] Ning Gu and Kerry London. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19(8):988–999, December 2010. 2

[23] Sandra G Hart. NASA Task Load Index (TLX), 1986. 5

[24] Steven Henderson and Steven Feiner. Exploring the Benefits of Augmented Reality Documentation for Maintenance and Repair. *IEEE Transactions on Visualization and Computer Graphics*, 17(10):1355–1368, October 2011. 2

[25] Nevenka Hrovatin and Jelena Zorić. Determinants of energy-efficient home retrofits in Slovenia: The role of information sources. *Energy and Buildings*, 180:42–50, December 2018. 1

[26] Rehmaashini Jagarajan, Mat Naim Abdullah Mohd Asmoni, Abdul Hakim Mohammed, Mohd Nadzri Jaafar, Janice Lee Yim Mei, and Maizan Baba. Green retrofitting – A review of current status, implementations and challenges. *Renewable and Sustainable Energy Reviews*, 67:1360–1368, January 2017. 1

[27] Enes Karaaslan, Ulas Bagci, and Fikret Necati Catbas. Artificial Intelligence Assisted Infrastructure Assessment using Mixed Reality Systems. *Transportation Research Record: Journal of the Transportation Research Board*, 2673(12):413–424, December 2019. 3

[28] Imad A. Khalek, Jad M. Chalhoub, and Steven K. Ayer. Augmented Reality for Identifying Maintainability Concerns during Design. *Advances in Civil Engineering*, 2019:1–12, March 2019. 2

[29] Ayaz Khan, Samad Sepasgozar, Tingting Liu, and Rongrong Yu. Integration of BIM and Immersive Technologies for AEC: A Scientometric-SWOT Analysis and Critical Content Review. *Buildings*, 11(3):126, March 2021. 2

[30] J LaViola, B Williamson, Conner Brooks, Sergiu Veazanchin, Robert Sottilare, and Pat Garrity. Using augmented reality to tutor military tasks in

the wild. In *Proceedings of the Interservice/Industry Training Simulation & Education Conference, Orlando, Florida*, 2015. 2

[31] Sanghoon Lee and Ömer Akin. Augmented reality-based computational fieldwork support for equipment operations and maintenance. *Automation in Construction*, 20(4):338–352, July 2011. 2

[32] Guo Liu, Xiaohu Li, Yongtao Tan, and Guomin Zhang. Building green retrofit in China: Policies, barriers and recommendations. *Energy Policy*, 139:111356, April 2020. 1

[33] Yan Liu, Sander van Nederveen, and Marcel Hertogh. Understanding effects of BIM on collaborative design and construction: An empirical study in China. *International Journal of Project Management*, 35(4):686–698, May 2017. 2

[34] Yifan Liu, Jennifer Lather, and John Messner. Virtual Reality to Support the Integrated Design Process: A Retrofit Case Study. In *Computing in Civil and Building Engineering (2014)*, pages 801–808, Orlando, Florida, United States, June 2014. American Society of Civil Engineers. 2

[35] Zhansheng Liu and Wenyan Bai. Building Information Modeling Methods for Post-Earthquake Retrofitting Visualization of Buildings Using Augmented Reality. *Applied Sciences*, 11(12):5739, June 2021. 2

[36] Mark A. Livingston, Zhuming Ai, Kevin Karsch, and Gregory O. Gibson. User interface design for military AR applications. *Virtual Reality*, 15(2-3):175–184, June 2011. 2

[37] Zhenjun Ma, Paul Cooper, Daniel Daly, and Laia Ledo. Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings*, 55:889–902, December 2012. 1

[38] Kieran W. May, Chandani Kc, Jose Jorge Ochoa, Ning Gu, James Walsh, Ross T. Smith, and Bruce H. Thomas. The Identification, Development, and Evaluation of BIM-ARDM: A BIM-Based AR Defect Management System for Construction Inspections. *Buildings*, 12(2):140, January 2022. 2

[39] Paul Milgram and Fumio Kishino. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329, 1994. Publisher: The Institute of Electronics, Information and Communication Engineers. 2

[40] Daniela Mitterberger, Kathrin Dörfler, Timothy Sandy, Foteini Salveridou, Marco Hutter, Fabio Gramazio, and Matthias Kohler. Augmented bricklaying: Human–machine interaction for in situ assembly of complex brickwork using object-aware augmented reality. *Construction Robotics*, 4(3-4):151–161, December 2020. 2

[41] Ali Motamedi, Zhe Wang, Nobuyoshi Yabuki, Tomohiro Fukuda, and Takashi Michikawa. Signage visibility analysis and optimization system using BIM-enabled virtual reality (VR) environments. *Advanced Engineering Informatics*, 32:248–262, April 2017. 2

[42] Albert Newen, Shaun Gallagher, and Leon De Bruin. 4E Cognition: Historical Roots, Key Concepts, and Central Issues. In Albert Newen, Leon De Bruin, and Shaun Gallagher, editors, *The Oxford Handbook of 4E Cognition*, pages 2–16. Oxford University Press, September 2018. 2

[43] Duy Cuong Nguyen and Chang Su Shim. Developing a mixed-reality based application for bridge inspection and maintenance. page 13, Teeside University, 2020. 2

[44] Riccardo Palmarini, John Ahmet Erkoyuncu, Rajkumar Roy, and Hosein Torabmostaedi. A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing*, 49:215–228, February 2018. 2

[45] Friedemann Polzin, Colin Nolden, and Paschen von Flotow. Drivers and barriers for municipal retrofitting activities – Evidence from a large-scale survey of German local authorities. *Renewable and Sustainable Energy Reviews*, 88:99–108, May 2018. 1

[46] Preservation Green Lab. Older, Smaller, Better: Measuring how the character of buildings and blocks in uences urban vitality. Technical report, NATIONAL TRUST FOR HISTORIC PRESERVATION, May 2014. 1

[47] Preservation Green Lab. Reuse and Revitalization in Jacksonville: Discovering the value of older buildings and blocks. Technical report, NATIONAL TRUST FOR HISTORIC PRESERVATION, May 2017. 1

[48] Günther Riexinger, Andreas Kluth, Manuel Olbrich, Jan-Derrik Braun, and Thomas Bauernhansl. Mixed Reality for On-Site Self-Instruction and Self-Inspection with Building Information Models. *Procedia CIRP*, 72:1124–1129, 2018. 2

[49] Valentino Sangiorgio, Martiradonna Silvia, and Fabio Fatiguso. Augmented Reality to Support Multi-Criteria Decision Making in Building Retrofitting. In *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 760–765, Toronto, ON, Canada, October 2020. IEEE. 2

[50] Dieter Schmalstieg and Tobias Hollerer. *Augmented Reality: Principles and Practice*. Addison-Wesley Professional, 2016. 2

[51] John Sermarini, Robert A. Michlowitz, Joseph J. LaViola, Lori C. Walters, Roger Azevedo, and Joseph T. Kider Jr. BIM Driven Retrofitting Design Evaluation of Building Facades. In *Proceedings of the 2022 ACM Symposium on Spatial User Interaction*, pages 1–10, Online CA USA, December 2022. ACM. 2

[52] Muhammad Shafique and Reeho Kim. Retrofitting the Low Impact Development Practices into Developed Urban areas Including Barriers and Potential Solution. *Open Geosciences*, 9(1), June 2017. 1

[53] Lawrence Shapiro and Shannon Spaulding. Embodied Cognition. In Edward N. Zalta, editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, winter 2021 edition, 2021. 2

[54] Tobias Sielhorst, Marco Feuerstein, and Nassir Navab. Advanced Medical Displays: A Literature Review of Augmented Reality. *Journal of Display Technology*, 4(4):451–467, December 2008. 2

[55] Son-Lik Tang, Chee-Keong Kwoh, Ming-Yeong Teo, Ng Wan Sing, and Keck-Voon Ling. Augmented reality systems for medical applications. *IEEE Engineering in Medicine and Biology Magazine*, 17(3):49–58, June 1998. 2

[56] Steve Sorrell, editor. *The economics of energy efficiency: barriers to cost-effective investment*. Edward Elgar, Cheltenham ; Northampton, Mass, 2004. OCLC: ocm56437345. 1

[57] United States Department of Energy. 2015 Quadrennial Technology Review. Technical Report 2015, United States Department of Energy, 2015. 1

[58] Francisco J Varela, Evan Thompson, and Eleanor Rosch. *The Embodied Mind: Cognitive Science and Human Experience*. MIT Press, 1991. 2

[59] Xiangyu Wang, Mi Jeong Kim, Peter E.D. Love, and Shih-Chung Kang. Augmented Reality in built environment: Classification and implications for future research. *Automation in Construction*, 32:1–13, July 2013. 2

[60] Anthony Webster, Steven Feiner, Blair MacIntyre, William Massie, and Theodore Krueger. Augmented reality in architectural construction, inspection and renovation. In *Proc. ASCE Third Congress on Computing in Civil Engineering*, volume 1, page 996, 1996. 2

[61] Margaret Wilson. Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4):625–636, December 2002. 2

[62] William Winn. Learning in artificial environments: Embodiment, embeddedness and dynamic adaptation. *Technology, Instruction, Cognition and Learning*, 1(1):87–114, 2002. 2

[63] Xun Xu, Ling Ma, and Lieyun Ding. A Framework for BIM-Enabled Life-Cycle Information Management of Construction Project. *International Journal of Advanced Robotic Systems*, 11(8):126, August 2014. 2

[64] Xue Yang, Semiha Ergan, and Katie Knox. Requirements of Integrated Design Teams While Evaluating Advanced Energy Retrofit Design Options in Immersive Virtual Environments. *Buildings*, 5(4):1302–1320, December 2015. 2

[65] Reza Zaker and Eloi Coloma. Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. *Visualization in Engineering*, 6(1):4, December 2018. 2