The Effect of Augmented Reality on Performance, Task Loading, and Situation Awareness in Construction Inspection Tasks

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ABSTRACT

The construction industry is characterized by the need to perform detail-oriented tasks in complex environments – requiring tools and systems that prioritize precision, efficiency and safety. While Augmented Reality (AR) has emerged as a potential avenue for these tools, its effectiveness and impact on performance and situation awareness, as well as the challenges it may introduce, are yet to be fully understood. This research aims to investigate the efficacy of AR's use in this domain through the representative task of inspecting prefabricated concrete panel casts, using studies complete with visual and auditory distraction simulations to explore two new AR schematic visualization systems. This work employs a dual-task user study ($N = 18$) to measure the impact of the AR on Situation Awareness, Task Loading, and Task Performance when compared to the conventional standard of paper blueprints. We find that AR solutions can lower perceived mental and temporal demands without negatively affecting situation awareness. Further, the AR solutions reduced the rate of false negatives and required less time than paper blueprints, suggesting that AR holds promise for improving construction workflows through increased performance and speed without impacting the safety provided by maintaining situation awareness.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *Visualization design and evaluation methods.*

KEYWORDS

Situation Awareness, Augmented Reality, Task Loading, Task Performance, Construction

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1 INTRODUCTION

For the majority of inspection and fabrication tasks carried out in the construction industry, traditional paper blueprints are still heavily relied upon in designing, referencing, and developing products [9, 15]. These blueprints often contain extensive and highly detailed information about product components, alignments, and assembly instructions. Complex representations such as these can be challenging to interpret, leading to time-consuming and error-prone processes, resulting in product defects, increased costs, and project delays, especially for assembly and construction personnel needing more experience or training [28]. Creating defective products results in slowed production and contributes greatly to resource wastage [8]. The construction industry, therefore, relies on maintaining a low fault tolerance [33] but still relies on manual interpretation using blueprints, which has been shown to be a frequent source of misunderstanding and a substantial source of errors [15, 28]. In an attempt to address this, a variety of quality control measures are often introduced to detect and mitigate defects and errors, but these can be limited effectiveness and extremely costly [2, 3].

In modular construction, where building components are fabricated offsite for later transportation to construction sites [57], attempts to introduce Augmented Reality (AR) technologies have been made in several ways [1, 2]. AR use in modular construction has involved superimposing designs onto an environment in 2D or 3D, providing a visual guide for how the pre-fabricated components

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should be placed and manipulated, reducing effort and errors in the interpretation of designs and quality assessment. This has been shown to improve quality control and early detection of defects, optimizing cost and ensuring products are delivered on time and as intended [3]. In addition, the benefits of AR in construction have been demonstrated more broadly, including AR's application to instructional and guidance systems having been shown to reduce mental work and task completion time [1, 9, 61]. In collaborative situations, AR can create a shared experience for simultaneous viewing and interaction by multiple people [41], can allow for proportional scaling of dimensions, proving advantageous in manual manipulation tasks [2, 3], even shortening the process life-cycles [56]. Despite the possible advantages of AR in construction, many necessary processes and requirement analyses are involved to create a reliable system. Therefore, integrating these technologies can be costly and may be out of scope for smaller-scale organizations [21]. Suggesting that relatively low-cost, simple approaches that demonstrate benefits are needed.

In construction, an important consideration for introducing technology is that it can potentially be a distraction, compromising the ability to monitor the environment for safety concerns. Situation Awareness (SA) is the ability to perceive, understand, and effectively respond to one's situation and is considered the basis for the decision-making processes[33]. SA is an essential component in ensuring safety through allowing individuals to respond effectively to emergencies and prevent hazardous incidents [53] as the better the understanding of your environment and the dynamics within it, the better informed your decision-making can be [18]. Despite their ubiquity in construction workplaces, visual and auditory environmental stimuli from direct sources, such as implicit device feedback or communication from other individuals, as well as indirectly from moving machinery or workspace congestion, are often missed by workers, reducing hazard recognition and increasing injury [4, 7, 43]. Stanton et al. highlighted that enhancing situation awareness through training, interface design, and feedback systems could significantly improve safety in different fields, from aviation to nuclear power plant operations [54]. Designing technology that does not compromise situation awareness could help ensure accidents, errors, and risks are kept to a minimum.

While the potential benefits of AR systems have been well documented, there is still little information about whether they might perform well under conditions like those that occur in real construction scenarios. In particular, there is little information about whether AR systems may present trade-offs between enhanced task performance and the potential for distractions that may escalate task load, possibly leading to diminished situational awareness and posing safety concerns. To bridge this knowledge gap, this research aims to evaluate the impact of AR systems on Task Performance, Task Loading, and Situation Awareness compared to the status quo blueprints.

We conducted an experiment focusing on a typical construction inspection task as well as a simulated safety monitoring task designed to represent the auditory and visual distractions caused by external stimuli present in real-world construction environments. We recorded task completion time and error identification rate to measure performance, as well as the Situation Awareness Rating Technique (SART) [6] and the NASA Task Load Index (TLX) [26] to measure their respective factors. With the results of these measures, we hope to approach an understanding of the questions:

- Can an AR system improve the speed and accuracy of construction inspection tasks over paper blueprints?
- What is the best way to display construction inspection information in AR?
- Does AR affect the ability to monitor the environment for safety concerns during construction?

The insights gained through this research could significantly improve safety and efficiency in construction plants using AR systems.

2 RELATED WORK

2.1 Augmented Reality in Construction

Although construction tends to lag behind in adopting new technologies compared to other industries, recently, virtual and augmented reality products have been increasingly explored [47, 48]. Studies have shown that when new technological solutions have been employed, improvements in expediting production processes, limiting risk, handling worker shortages, reducing waste, and improving efficiency, quality, safety, communication, and collaboration have been made possible [25, 33, 36]. The areas in which AR solutions have been focused have been in the planning, assembly, and inspection phases of production.

AR has been shown to increase the conceptualization of completed projects by fostering better collaboration with customers [25]. With uses in prototyping, visualization, path planning, and optimization, recent work has found that AR could help stakeholders better understand complex design elements and spatial relationships, thus facilitating decision-making and reducing misunderstandings [59]. AR has also been shown to enhance collaboration among construction professionals, improving communication between architects, engineers, and contractors using real-time visualization of building information models in their physical contexts [23].

Outside collaboration, AR can also assist in detecting and preventing errors during the construction planning phase, greatly reducing wasted costs and time [12]. Meanwhile, in the assembly stage, AR can be used for real-time comparisons between planned and completed construction progress [23], help trainees develop better hazard recognition and safety decision-making skills [51], and improve communication between parties and reduce errors by providing accurate, up-to-date information [60]. As the industry is considered high risk, AR can be used throughout all phases of construction for real-time safety management by visualizing potential risks and allowing for better monitoring of the physical environment while digital information is displayed [33, 36]. Overall, the benefit of AR-based solutions is that they can ensure fewer errors, improve collaboration between workers, and improve the quality of work while allowing for better safety.

In the inspection phase (which is the focus of this work), AR has been used to identify and detect the presence and correct positioning of components, thus ensuring that the constructed elements correspond to the design plans [36]. AR has also enabled inspectors to visualize construction data, such as building information models, by enabling various information, such as diagrams and inspection checklists, to be overlaid on the physical construction site

[59]. This enhanced visualization can help inspectors better understand construction elements, identify discrepancies between design and actual construction, and verify compliance with regulations, thereby reducing the need for rework and associated costs [30]. By detecting and addressing issues early in the inspection process, AR can help improve overall construction quality and safety.

2.2 Augmented Reality in Inspection Tasks

AR solutions have been used to improve safety and accuracy while reducing the time and money spent on inspection tasks in industries other than construction. For example, a recent study examined the application of AR in fire safety equipment inspection and maintenance tasks, resulting in reduced inspection time [11]. In manufacturing, AR systems have been used for inspecting the dimensions of manufacturing parts and identification of defects and have similarly shown results of improved accuracy, reduction in cost and time, and improvements in instructional processes for personnel[50].

When considering construction inspection tasks, AR systems have been used to help identify defects, integrate digital documentation, and introduce interactive management of collaborative synchronous inspection tasks [21]. AR has also been adopted for the inspection of rebar placement, showing promising results in allowing the identification of missing or improperly positioned and spaced bars [13]. Based on this previous work, we believe AR can improve construction workflows and inspection tasks, especially in providing inspectors with visual cues and instructions that should ensure accuracy and reduce time and cost. However, to determine AR's safety and potential, the situation awareness, task loading and experiences of the inspector must also be assessed.

2.3 Measuring Task Loading, Situation Awareness, and Task Performance

Task Loading (TL) is a measure of a user's perceived mental and physical effort and stress focusing on the demands that a specific task or set of tasks places on an individual's cognitive system [46]. The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a subjective self-report measure of task load that asks individuals to rate their perceived mental, physical, and temporal demands, as well as performance, effort, and frustration associated with a specific task or activity [26], and is the most widely applied tool for assessing TL[19, 58].

Situation Awareness (SA) is formally defined by Endsley as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" in relation to human cognition [17, 24]. It is a critical factor in decision-making and problem-solving, particularly in dynamic or high-stakes environments such as aviation, military, and healthcare, where the ability to make quick and accurate decisions can save lives and resources [6]. The Situation Awareness Rating Technique (SART) is a subjective retrospective debriefing method used to evaluate an individual's SA during a simulated or real event [6].

Task performance (TP) is the effectiveness of an individual in carrying out a given task [27]. It is often measured as the amount of time taken to complete the task, as well as any task-specific measurements of quality or completion, such as accuracy, precision, and recall.

2.4 Task Loading and Situation Awareness in Augmented Reality

Several studies have reported that AR can decrease a user's TL by providing timely and relevant guidance, thereby improving performance and learning outcomes [32, 35, 38, 52] and by presenting information in a more intuitive and context-specific manner [39]. For example, recent work found that students using an AR application to learn about geometrical optics experienced a lower TL compared to those using traditional methods, by allowing students to visualize concepts more effectively and intuitively [29].

Conversely, in some circumstances, AR has been shown to increase TL by overwhelming users with information or requiring users to divide their attention between virtual and real-world stimuli [37]. Much of the negative impacts on TL seem to be linked to the design of the interface, as researchers have found that poorly designed AR interfaces can lead to *cognitive overload*, hindering users' understanding and performance [34] while Dünser and Billinghurst highlighted the importance of careful AR design to avoid this [16]. Dey et al. examined the effects of AR-induced TL in a simulated medical training scenario and found that poorly designed AR interfaces could increase TL and negatively impact performance [14]. The authors also suggested that optimizing AR design elements, such as information presentation and interaction techniques, is crucial for reducing TL and improving performance.

AR's ability to provide real-time information and visual cues in a user's field of view has been shown to improve a user's SA [5]. Several studies have demonstrated that AR can effectively enhance SA in fields such as aviation [31], healthcare [55], and emergency response [22]. Despite its potential benefits, AR experiences can also lead to impaired SA if users find the interface distracting or the application presents misleading, overwhelming, or irrelevant information. For example, incorrect or outdated AR overlays, such as virtual labels on real-world objects, can cause users to make ill-informed decisions and fail to recognize important environmental changes [49]. Recent work found that registration errors, where virtual objects are misaligned with real-world objects, can cause confusion and reduce SA [20]. Similarly, latency in updating AR information can lead to outdated or incorrect data being presented to users, negatively impacting SA.

The literature on TL and SA in relation to AR suggests that AR could have both positive and negative effects. The impact of AR largely depends on the design, implementation, and reliability of the technology. Well-designed AR systems can reduce task loading and enhance situation awareness, while poorly designed systems may have the opposite effect. To better understand the advantages and disadvantages of AR in construction inspections, we designed an AR system to provide basic information to support inspections with two display alternatives (as described below). We compared these with the status quo approach used in inspections (paper blue prints).

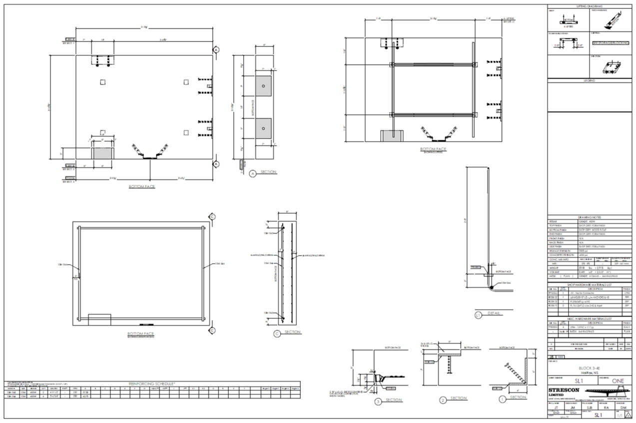

Figure 1: Printed Paper Blueprint

3 EVALUATION OF AN AR SYSTEM IN CONSTRUCTION INSPECTION

We aimed to design an experiment that assessed Task Performance (TP), Task Loading (TL), Situation Awareness (SA), and user experience in a typical construction workflow. To accomplish this, we worked with a civil engineer employed at the University of New Brunswick to design a task that could exemplify typical construction inspection workloads and processes. Together, we constructed a bed for casting and fabricating concrete panels known as a solid slab cast unit (See Figure 2). The cast unit contains various sizes of steel reinforcements (rebar), steel plates, bolts, etc., which fit precisely within a specific structural form into which wet concrete is poured to create a concrete panel. The resulting concrete panels are commonly used in the construction of both residential and commercial buildings, parking structures, and other types of infrastructure.

This cast unit served as the basis for our experiment, as participants were tasked with inspecting the unit for accuracy and completeness. This inspection procedure is often completed in the industry using a set of schematics and diagrams containing a 2d graphical representation of the unit with a description of components and their positions printed on paper (See Figure 1). To compare this paper document approach to AR alternatives, we built an AR application to provide 3D spatially anchored interpretations of those schematics.

3.1 AR System

Our AR inspection system was developed using Unity version 2022.1 and the Mixed Reality Toolkit for deployment on the Microsoft HoloLens 2. For this study we opted for the Trimble XR10, a Hololens 2 which is securely integrated into an OSHA compliant hardhat. The system was designed through a series of iterative tests and refinements to emphasize user experience and reduce, as much as possible, any confusion or problems which can occur with participants unfamiliar with mixed reality devices. A simple user interface and interaction scheme were created that allowed basic manipulation and selective hiding of different elements. The system used fiducial markers placed on the cast unit to ensure that guidance would be automatically placed and tracked by the system consistently.

3.1.1 Display Conditions. To test the efficacy of our AR system, we implemented three conditions in our experiment. In addition to the paper approach currently used in the industry described above (See Figure 1). We developed two versions of our AR system which take distinct approaches to displaying the blueprints. In both versions of the system special care was taken to ensure that all the necessary information present on the paper blueprints was included while trying to limit the cognitive overload that can come with an abundance of information being displayed to the user.

- **AR - Overlay Condition**: In this variation, we superimpose a holographic model directly on top of the cast unit and its components (See Figure 2). Overlaying the graphics on top of the physical target allows the user to make a direct, one-to-one comparison of the intended configuration and existing components. It reduces the need for the user to break focus by shifting attention away from the unit and onto the instruction set, as well as eliminating the need for the user to construct a mapping between the blueprint and the unit.
- **AR - Side-by-Side Condition**: Here, the AR system displays the same holographic 3d reference model as the overlay condition. However, it has been shifted 1.5 meters to the side of the unit being inspected (See Figure 2) rather than displayed directly atop it. While this side-by-side condition provides the same information and model for users to compare against the physical components, it was included with the consideration that while the overlay condition offers the most direct mapping, it may occlude the elements of the unit, possibly impairing users' ability to see components with sufficient detail and confidence.
- **Paper - Control Condition**: In addition to the AR systems, a paper containing a CAD drawing blueprint condition was included for a baseline comparison (See Figure 1). This condition represents the standard documents commonly used in typical construction inspection tasks, including 2D graphical representations of the cast unit from each necessary axis and additional text information to convey the details and specifications lost in the translation to a 2D paper-sized depiction.

3.2 Experimental Design

We developed a within-subjects study consisting of an inspection of the cast unit using the three aforementioned experimental conditions, with the order of conditions balanced using a Latin square.

Before experimentation began, an informal preliminary study was conducted with a local construction company that had recently gained experience in testing an augmented reality system with Trimble Connect, a commercial AR collaboration system. Nine professionals at the company who had experience conducting device inspections and who had engaged with the system agreed to complete a questionnaire for us. The feedback collected via the questionnaire indicated that the professionals estimated a lower SA in AR when compared to paper, as well as a higher mental task load, stating they would prefer to use the traditional paper methods in a professional environment. When asked for comments,

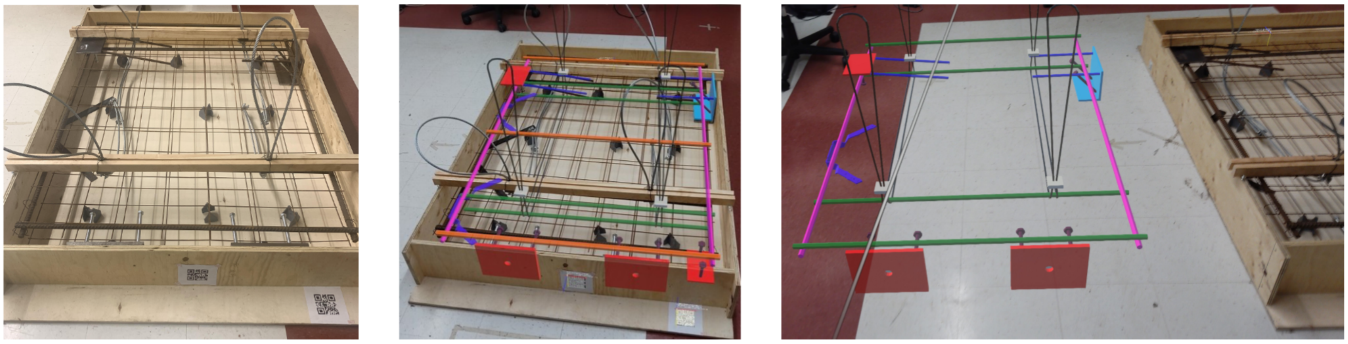

Figure 2: Solid Slab Cast Unit, Overlay Condition, and Side-by-Side Condition

participants indicated their reason for this stemmed from issues largely with the interaction mechanics and interface design of the AR system, as well as a lack of training and familiarity with AR systems. One participant (P04) stated, "I found as it took several attempts to click on anything and took away my awareness of my surroundings." while another (P09) wrote that the AR headset was "more difficult to use and it would be a challenge to have used it in a hectic and potentially dangerous environment ."This feedback reaffirms ideas brought about in previous work with AR systems and the importance of interface design and intuitiveness [14, 16, 34]. The feedback from this preliminary study influenced us greatly in identifying points of concern with experienced users when creating our interface and user experience.

3.3 Experimental Tasks & Procedure

The primary study involved two simultaneously performed tasks, each of which focused on a different aspect of the system's effectiveness, which is described in more detail below. Before beginning, participants were briefed on the task, their expected operations, the cast unit, and the technology involved. They were informed that their time would be recorded, and after ensuring the participants' understanding, a practice round was conducted to familiarize participants with the operations and procedure. Once the practice was completed, the participant would proceed through the tasks in each condition, which centred around a thorough inspection of the cast unit for discrepancies from the given blueprint, with their performance and any input they provided being recorded throughout. Between trials, questionnaires were completed, and additional participant responses were recorded; a final questionnaire was answered after all conditions had been completed.

3.3.1 Inspection Task. The primary operational task was to inspect the cast unit and identify discrepancies between the physical unit and a provided schematic. These discrepancies were classified into three error types:

1. Missing errors: Any expected components shown in the schematic but were absent from the unit.
2. Addition errors: Any unexpected components not shown in the schematic but were present in the unit.
3. Substitution errors: Any component present in both schematic and unit, but the items did not match in size, placement, material, etc.

Participants were provided with the relevant blueprints for each experimental trial and asked to initiate the task. The task ended when participants were satisfied that they had finished their inspection and identified all the present errors. The same cast unit was used for each participant, but the schematics varied for each participant's conditions, ensuring a differing pool of errors to identify each time.

3.3.2 Safety Monitoring Task. In addition to the inspection task, participants were asked to complete a number of safety monitoring measures. An application was created to run on an audio/video setup in the room, designed to enhance the simulation of a construction environment by including additional features external to the cast unit. The goal was to replicate some of the chaotic visual and auditory experiences that typically pervade these often high-risk environments. In addition to collecting and displaying performance data (such as timing), the application helped us to evaluate participants' awareness and response to noisy surroundings. The application started at the moment the task began and activated the following components concurrently:

1. *Safety Monitoring Task*: To evaluate whether participants could identify dangers in their environment while performing inspections, we added a simple safety monitoring task. On activation, a short set of flashing colours, consisting of red, green, and white, were displayed for a duration of approximately 10 seconds. These 10-second flash segments occurred randomly every 25 to 45 seconds after the previous flashes ended. A counter kept track of the number of flashes that were displayed throughout the task. During the experiment, participants were asked to count the number of flash segments. This measure allowed us to assess whether the different experimental conditions would affect participants' abilities to maintain awareness of external visual indicators of importance. This mirrors the challenges faced by workers on a construction site, who need to complete tasks while monitoring the environment for additional device indicators, environmental changes, or hazardous situations (e.g., moving machinery or vehicles).
2. *Auditory Distraction*: To bring an essential element of realism to the test environment, an audio system was incorporated to emit construction site noises loudly. A mixture of ambient and active construction site sounds was used to replicate the

typical auditory distractions prevalent in a typical construction setting. While no direct measures of audio response were recorded, this component of realism was not only to help the participant's sense of presence but also to simulate better the impact that persistent auditory stimulation can have on participants' awareness of their surroundings and their focus on the task.

3.4 Participants

Eighteen participants (11 males and 7 females) were recruited from the University of New Brunswick Civil Engineering Department. The average age of the participants was 28.9 years, with only 33.3% of the participants having any experience with AR and 44.4% having experience with inspection tasks. All participants provided informed consent, and the experimental procedure was approved by our university's ethics board (on file as UNB REB #2023 − 028). The targeted recruitment approach was necessary to establish a participant population that possessed a foundational knowledge and familiarity with the domain-specific concepts of the experiment's focus, ensuring the participant's training and skill set would be representative of those who would use such a system in the field. While the same academic department was involved in creating the cast unit as was used for recruitment, any personnel involved in the collaboration were excluded from participation.

3.5 Results

3.5.1 Situation Awareness and Safety Monitoring. **Situation Awareness (SA)** scores for the three experiment conditions were collected using the Situation Awareness Rating Technique (SART), and subsequent analysis employed the Friedman test to discern differences between the conditions (See Table 1). Considering the computed overall SART scores, while the side-by-side scored slightly higher than the others, no statistically significant differences were observed ($\chi^2 = 1.391, p = 0.449$).

In the **Safety Monitoring** task, the count of displayed blinks is compared to the number of participant-recorded blinks, as differences in blink count would indicate reduced awareness. Across all conditions, the differences in participants' perceived blinks and actual blink counts were not statistically significant ($\chi^2 = 0.538, p = 0.764$) (see Table 2). This suggests that irrespective of the conditions used, participants had comparable levels of awareness, with none of the conditions allowing for significantly better awareness.

3.5.2 Task Loading. The Task Loading (TL) of each condition was quantified using the NASA Task Load Index (NASA-TLX), and subsequent analysis employed the Friedman test to detect potential statistical differences among the conditions for each component of the TLX and the aggregated score that combines all components. All results can be found in Table 3, and below, we only describe significant findings.

The condition used led to significant differences in mental demand ($\chi^2 = 6.517, p = 0.038$. Using the Conover test for post hoc pairwise comparison, the paper blueprint was rated as more mentally demanding for Side-by-Side than Paper blueprints ($p = 0.016$), but no other differences were significant.

Considering temporal demand, a significant effect of the condition used was observed ($\chi^2 = 8.375, p = 0.015$) when compared to the AR conditions. Conover post hoc for pairwise comparisons show that there was no difference between Overlay and Side-by-Side conditions($p = 0.5387$), but found that paper had a significantly higher time demand than Overlay ($p = 0.008$) and Side-by-Side ($p = 0.037$).

3.5.3 Task Performance. Table 4 shows the Task Performance (TP) results. To provide a more nuanced understanding of performance, we divided errors into two types: False Positive, in which participants incorrectly identified an error or problem that was not present, and False Negative, in which participants missed identifying a present discrepancy between blueprints and the cast unit. A significant difference was found among False Negative Rates, with the Paper condition showing the highest rate ($\chi^2 = 20.478, p < 0.001$). People missed significantly more defects with Paper than Overlay ($p < 0.001$) and Side-by-Side ($p < 0.001$). There was no significant difference between the three conditions for the False Positive Rate ($\chi^2 = 4.323, p = 0.115$).

The True Positive rate shows the instances where participants correctly identified a genuine discrepancy. Significant differences were observed ($\chi^2 = 13.942, p < 0.001$). Participants identified significantly more genuine errors with Overlay than Paper ($p = 0.007$) and more with Side-by-Side than Paper ($p = 0.001$).

We also analyzed Precision and Recall, representing the fraction of genuine defects that are present and identified. Significant differences were detected in Recall ($\chi^2 = 25.404, p < 0.001$), with both Overlay and Side-by-Side having significantly higher Recall than paper ($p = 0.001$). No significant difference was detected for Precision ($\chi^2 = 4.938, p = 0.085$).

We also measured the completion time (in seconds) as a measure of TP, and a significant difference was found, with participants using the Paper method taking considerably more time compared to when using the AR systems ($\chi^2 = 22.333, p < 0.001$). Paper was significantly slower than both Overlay ($p = 0.001$) and Side-by-Side ($p < 0.001$).

3.5.4 Participant Feedback. In addition to the quantitative data recorded above, qualitative feedback was collected through informal interviews and ranked ordering of participants' perception of each condition's ability to maintain situational awareness (SA), to work quickly, and to work accurately (See Figure 3).

The rankings of the conditions' potential for speed and accuracy aligned with the task performance (TP) scores observed as the participants ranked the AR conditions nearly entirely over the paper condition in both metrics. Participants' rankings of the conditions' ability to maintain SA were more evenly distributed, with the paper condition slightly outperforming the AR conditions.

In the informal interviews, participants expanded on the issues affecting SA during the inspection, with most naming limitations with the headset. Participant 10 stated, "The paper was easier as I had all the angles of my eyes in action without the headset blocking my view." While Participant 7 praised the AR Overlay condition but identified similar issues: "Overall, the overlay is much better; however, the headset is heavy and wiggly. I might get tired of using it if I'm tasked to do it as part of my full-time job; a lighter headset would be much more comfortable."

Despite issues with the cumbersome nature of the headset, most participants praised the AR conditions and the direct mapping of

Table 1: Situation Awareness Rating Technique Scores by condition: mean (std dev), results of Friedman test.

SART Item	Overlay	Side-by-Side	Paper	Kendall's W	χ^2	p
Instability	3.167 (1.383)	3.167 (1.465)	3.833 (1.724)	0.149	5.353	0.069
Complexity	3.556 (1.381)	3.500 (1.339)	3.944 (1.862)	0.006	0.222	0.895
Variability	3.500 (1.543)	3.667 (1.414)	3.667 (1.534)	0.036	1.292	0.524
Demand on Attentional Resources	10.222 (3.574)	10.333 (3.742)	11.444 (4.382)	0.055	1.966	0.374
Arousal	4.489 (1.720)	5.111 (1.641)	4.778 (1.865)	0.060	2.150	0.341
Concentration	4.611 (1.539)	4.944 (1.626)	4.722 (1.074)	0.022	0.809	0.667
Attention	4.389 (1.195)	4.111 (1.491)	4.278 (1.274)	0.032	1.170	0.557
Spare Mental Capacity	4.500 (1.383)	4.056 (1.731)	4.111 (1.530)	0.051	1.849	0.397
Supply of Attentional Resources	17.889 (4.199)	18.222 (4.760)	17.889 (4.057)	0.006	0.209	0.901
Information Quantity	4.556 (1.199)	4.778 (1.263)	4.556 (1.199)	0.014	0.490	0.783
Information Quality	4.667 (1.029)	5.111 (1.231)	4.944 (0.938)	0.106	3.815	0.148
Familiarity	5.111 (1.323)	5.444 (1.199)	4.722 (1.487)	0.113	4.073	0.131
Understanding of the Situation	14.333 (2.910)	15.333 (3.068)	14.222 (2.962)	0.077	2.772	0.250
SART	22.000 (8.095)	23.222 (7.448)	20.667 (7.616)	0.039	1.391	0.449

Table 2: Safety Monitoring task scores by condition: mean (std dev), results of Friedman test.

	Overlay	Side-by-Side	Paper	Kendall's W	χ^2	p
Blinking difference	0.222 (0.647)	0.222 (0.428)	0.389 (0.778)	0.015	0.538	0.764

Table 3: NASA-TLX scores by condition: mean (std dev), results of Friedman test.

TL Item	Overlay	Side-by-Side	Paper	Kendalls W	χ^2	p	
Mental Demand	4.000 (1.815)	3.556 (1.464)	4.667 (1.572)	0.181	6.517	0.038	*
Physical Demand	2.556 (1.504)	2.000 (1.283)	2.611 (1.685)	0.115	4.136	0.126	
Temporal Demand	3.333 (1.572)	3.389 (1.614)	4.278 (1.708)	0.233	8.375	0.015	*
Frustration	5.000 (1.372)	4.944 (1.434)	4.389 (1.577)	0.055	1.962	0.375	
Effort	2.944 (1.392)	3.222 (1.437)	3.667 (1.715)	0.050	1.792	0.408	
Performance	2.278 (1.018)	2.556 (1.617)	2.722 (1.227)	0.057	2.042	0.360	
NASA-TLX Composite Score	20.111 (4.185)	19.667 (3.481)	22.667 (5.760)	0.063	2.267	0.322	

Table 4: Task Performance scores by condition: mean (std dev), results of Friedman test.

TL Item	Overlay	Side-by-Side	Paper	Kendalls W	χ^2	p	
False Positive Rate (FPR)	0.111 (0.323)	0.278 (0.669)	0.611 (0.916)	0.120	4.323	0.115	
False Negative Rate (FNR)	0.389 (0.697)	0.389 (1.037)	2.111 (1.605)	0.569	20.478	<.001	***
True Positive Rate (TPR)	3.056 (1.305)	3.667 (1.029)	1.722 (1.227)	0.387	13.942	<.001	***
Recall	0.900 (0.174)	0.939 (0.150)	0.492 (0.319)	0.706	25.404	<.001	***
Precision	0.981 (0.054)	0.933 (0.164)	0.755 (0.341)	0.137	4.938	0.085	
Completion Time	89.33 (59.593)	80.833 (38.903)	157.444 (84.771)	0.620	22.333	<.001	***

$*p < 0.05, **p < 0.01, *p < 0.001$

the blueprints. Participant 15 wrote: "The overlay allowed me to orient the model and the blueprint with ease, without figuring out the orientation of the paper drawings."

3.6 Summary of Results

We summarize the results of the studies around our three main groups of metrics: Task Performance, Task Loading, and Situation Awareness.

- **Task Performance:** The Overlay and Side-by-Side conditions performed significantly better than Paper Blueprints in inspection tasks for Completion Time, False Negative Rate, True Positive Rate and Recall.
- **Task Loading:** Participants found Paper Blueprints more mentally demanding than Side-by-Side, and Paper Blueprints more temporally demanding than Side-by-Side and Overlay.

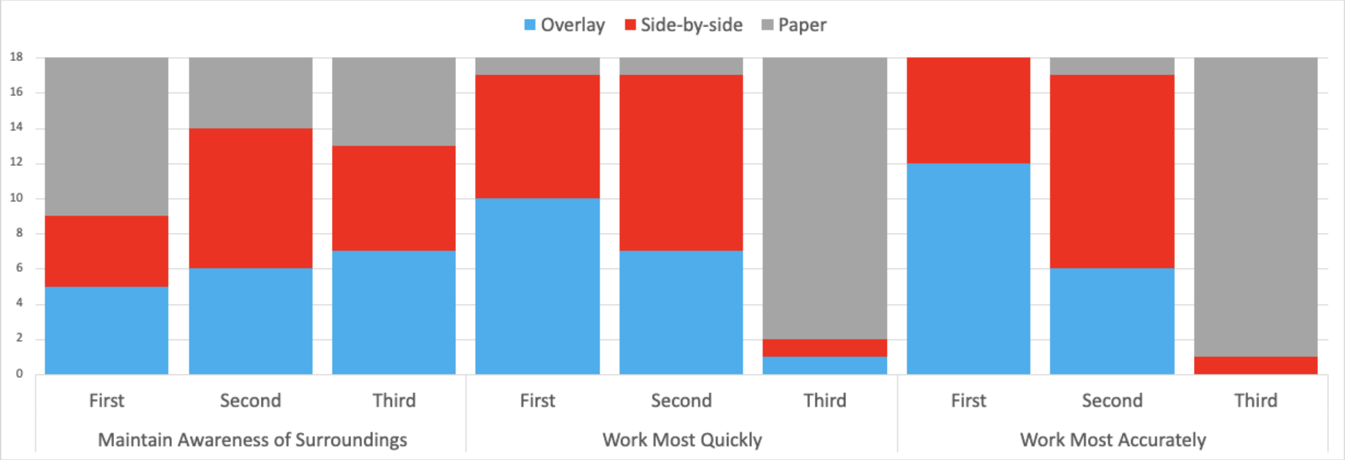

Figure 3: Conditions Ranked by Participants

- **Situation Awareness:** None of the conditions performed better in terms of Situation Awareness or ability to monitor the environment for safety concerns.

4 DISCUSSION AND FUTURE WORK

Our simple approach of displaying 3D models in AR for inspection guidance corroborates recent findings demonstrating the efficacy of this general approach [13, 21]. Our work provides valuable new findings by substantially deepening previous experimental methodologies (by incorporating safety monitoring tasks and comparing two main display alternatives) and in our data collection and analysis (incorporating situational awareness measures and a much more nuanced understanding of task performance). We organize the remainder of our discussion around questions raised by our findings.

4.1 Why did AR improve Task Performance?

Considering Task Performance, the industry-standard Paper Blueprints condition had the highest rate of both false negative and false positive errors, the lowest recall, and required the most time. It seems that in the noisy and complex task environment, we created in our study to simulate construction sites, the simple model information displayed with the HoloLens in AR was easy to view and use. While this might seem obvious, given that the Paper Blueprints required examining information that was more abstract and not directly analogous to the concrete cast that was being inspected, the comparison with Paper Blueprints was important because some previous work cautioned about the potential of distractions in AR systems leading to higher false positive rates [14, 16]. Our findings are instead supported by previous works that suggest AR displays can improve speed [1] and accuracy in visual inspection tasks [21, 42, 44, 50], and can reduce mistakes by providing real-time, contextual information [44]. While the ability to present the model in a spatially orientated and dimensionally matched manner, as well as hands-free operation, are unique benefits of the AR systems, to what extent the observed impacts were due to the reduction in cognitive demands for mental assembly, mental rotation, or physical object management is unknown. In future work, comparing AR conditions to other methods of displaying the 3D model, such as a mobile device AR view, a manipulable model on a tablet, or even a high-resolution printout of the same 3d model, could help isolate the impact of the AR application on task performance.

4.2 Why did AR improve elements of Task Loading?

Overall, the composite NASA TLX results did not show significant differences. However, when examining the assessment's individual sub-scales, we find notable differences, specifically in the perceived temporal pressure felt by participants, which was notably higher for the Paper condition. This supports the theory that there is a benefit in AR displays easing cognitive burden during inspections [13, 21]. In the participant's rankings of each condition's ability to allow them to work quickly, 16 of 18 participants placed the paper condition in the bottom spot, with Overlay and Side-by-side AR systems being the top pick 10 and 7 times, respectively. Participant feedback when discussing the speed allowed by the AR systems was quite positive, with multiple participants crediting the reduction in temporal pressure to the accuracy and intuitive interpretation of the blueprints provided by the direct mapping of the model. The significant difference, the perception of quicker operation, as well as its faster completion time, exemplifies AR's potential to reduce time-based stressors.

Our findings that Side-by-Side (but not Overlay) performed significantly better for mental demand aligns with previous work that indicates that dual displays (one for information and another for task) reduce cognitive demands [40, 62]. This result is interesting since we found no other differences between Side-by-Side and Overlay. We initially chose Side-by-Side because we felt that Overlay could potentially obfuscate the real-world components that were being inspected, which we observed in piloting with it. This result suggests that while performance was not affected by Side-by-Side, participants may have noted the extra effort required to determine whether a real part may or may not have been present underneath the semi-transparent Overlay information.

4.3 Why were there no differences between conditions for Situation Awareness?

Considering the results relating to the SART scores for Situation Awareness and our safety monitoring task, we did not find any significant statistical differences. Initially, this was surprising given that AR has previously been seen to increase situational awareness by providing digital information that is layered over the environment, allowing people to monitor the environment better while consuming digital information [22, 31, 55]. However, our AR system's ability to maintain and guide users' attention may lead to a stronger directed focus, even while making it easier to spot inconsistencies. This echoes the findings of Billinghurst et al. [5], who noted that AR systems could improve SA by directing relevant information into the user's field of view. Therefore, the advantages of AR in terms of added information may have been counterbalanced by added distraction from the real-world environment.

While participants' feedback on the AR systems was positive overall, several participants raised concerns about the physical headset, stating that the HoloLens 2 was heavy, unstable when moving, and uncomfortable for the duration of the inspection. This active discomfort could negatively affect SA as the focus is drawn to the device's presence and away from the task at hand. As AR technology continues to advance and available devices become lighter and less intrusive to wear, these limitations can be reduced, which may lead to less distraction.

Regarding the safety monitoring task, we believe another important factor was that the ephemeral nature of the blinking screen may have been too challenging to monitor while not providing salient enough information for participants. Recall that our novel safety monitoring task required participants to count the number of times a monitor flashed while completing the inspection task. While this task was emphasized to participants, the flashes only lasted for several seconds and required participants to maintain the monitor in the field of view at all times, which they often did not do to better complete the inspection task. The monitoring may have been too difficult compared to analog real-world tasks, where dangers may be larger and longer lasting. For example, a dump truck moving towards a worker would both be a larger, more visible object and a longer-lasting event. Even so, some safety concerns occur quickly and are less pronounced than in this example. Future work could consider monitoring safety concerns with varied prominence and temporal properties to better understand how AR technology may allow people to react and attend to them.

4.4 What role did familiarity with the conditions play in the results?

Promisingly, the lack of familiarity with mixed reality displays did not seem to limit participants' ability to perform the inspection using the AR conditions. While only 33.3% of the participants had any previous experience with XR devices, participants were able to use Overlay and Side-by-Side to perform the inspections without issue. As previously discussed, this follows expectations as the AR displays allowed for directly comparing the 3D model with the concrete cast, while the Blueprint condition provides a more abstract and less direct means to conduct the inspections. Importantly, however, our experiment used real blueprints and participants who were familiar with blueprints and their use for inspection. While our participants were not full-time inspectors, it has been noted that blueprints and their 2D depictions still lead full-time, professional inspectors to make frequent errors [15, 28]. So, even when Blueprints are used frequently, it seems likely that an AR display, such as the Overlay or Side-by-Side systems, would outperform the paper standard.

4.5 What is the AR best display alternative for construction inspection: Overlay or Side-by-Side?

Both Overlay and Side-by-Side demonstrated similar results and performed better than Paper Blueprints in terms of Task Performance and Task Loading for the representative inspection task. However, we did note one aspect where the results slightly differed. Only Side-by-Side performed better than Paper for mental demand. While this result may hold in future studies, we believe there is still value in designers supporting multiple view styles despite the lack of clear differences. As stated, AR could lead to occlusion problems, and allowing an inspector to quickly switch between possible view styles (i.e., Side-by-Side or Overlay view) would allow them to choose an approach that best suits their preferences or needs in different situations.

The choice of display style for AR remains an important one for designers and future researchers to consider. The success and effectiveness of AR technologies are heavily influenced by how they are designed and presented to the user [10, 45]. When using either display method ensuring safety is paramount, and higher cognitive demand can lead to lapses in attention, potentially resulting in overlooked safety hazards. While there is no recorded significant difference in SA through the SART or in the flashing measure, our study demonstrates that AR is no worse than Paper, and we believe it is safe. However, further research regarding safety is needed. Future studies should explore different safety stimulus and task scenarios to help provide a deeper understanding of any potential nuances to how AR technology might interact with real-world environments that might affect the ability to monitor the environment for safety. The intent here is not to question the safety of AR displays in such environments but rather to identify opportunities to create designs that can improve and support safe use and operation.

4.6 Should construction inspection adopt AR displays?

Our findings resonate with earlier studies suggesting that AR systems can improve task performance and efficiency in various domains, particularly precision, recall, and speed [21]. However, the somewhat more modest advantages in task loading and lack of clear advantage for situation awareness suggest that while AR has clear benefits, some of these may be context-dependent. Factors such as the specific design of the AR interface, the complexity of the task, and the training of the users could all play a role, and further studies would be invaluable in better understanding these factors. Still, there may be some concerns regarding the adoption of

AR technology for construction inspection. Some researchers warn about potential over-reliance on AR systems, leading to reduced situation awareness in contexts where the AR system might fail or provide misleading information [37]. This study, however, didn't show a significant drop in situation awareness with AR usage. This could be explained by many factors, such as the controlled environment in which the experiment took place or the relative simplicity of the task and system. Therefore, real-world studies could provide more insight and validate these findings further.

Another possible limitation of the findings from our study is the use of a controlled environment. While it was necessary to maintain a safe environment in this stage of early testing, it means that our testing environment may not have captured the complexities and unpredictability inherent in real-world construction site conditions to a satisfactory degree. Although measures were taken to simulate some of the distractions and challenges found in a construction environment in our experiment (e.g., playing loud site noises and the simulated safety monitoring task), controlled settings often lack the variety of challenges and unpredictability found in the context of the real-world counterpart. While we did not find any explicit reason to believe that our findings would change, testing in the field could reveal any hidden considerations. Additionally, while all participants in our participant group were civil engineering students who possessed the required knowledge, the experience, routine, and nuanced understanding of experienced inspectors could provide an invaluable new perspective on the system's efficacy as well as the adoption of workflow changes in real-world situations.

4.7 Limitations

We identified several limitations to our work that should be addressed in future work. First, although our participant pool was limited by our selection criteria, our study involved a relatively small ($N = 18$) pool of participants. While we chose this sample size to align with previous related work, future work might target a larger sample size to provide further confidence in the potential benefits of AR technology for construction inspection tasks.

Second, many participants noted weight and discomfort due to the headset during the AR conditions, while nothing was required to be worn during the paper condition. Our research made use of the Trimble XR 10, which is a customized version of the HoloLens 2 attached to a hardhat. The hardhat adds substantial additional weight over a standard HoloLens 2 form factor. This may have biased some participants against the mixed reality system due to reasons associated with comfort. Future work should take care to include personalized protective equipment equally between conditions to best capture real world factors and provide a fair comparison.

Thirdly, our safety monitoring task was developed to broadly represent the types of sensory stimuli that can occur on construction sites and attract attention. However, expanding the scope, variety, realism and immediacy of simulated distractions in future work could provide a more accurate representation of the high-risk and dynamic conditions common in construction environments and may improve understanding of their effects on situation awareness and task loading.

5 CONCLUSION

In this work, we have provided further evidence that AR systems can provide substantial benefits in construction inspection tasks. Importantly, it provides valuable new findings about the specific advantages in performance and task loading that AR can provide. We also demonstrate how situation awareness and safety can be evaluated, which concerns many domains like construction and manufacturing, where physical hazards and dynamic environments are common.

Our findings strengthen the case for integrating AR systems into inspection tasks. The results of this research strongly suggest that they hold real potential in enhancing the speed and performance of inspection tasks. The successful implementation of AR technologies in inspecting, for example, concrete casts is not merely about procuring and deploying the right equipment – it will require a holistic approach encompassing training, monitoring, continuous improvements, and a keen focus on user experience and safety. This work exemplifies critical next steps in maturing and deepening practices around the use of spatial user interfaces in challenging environments and domains.

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