Spatial Exposure to Dynamic Safety Hazards in Construction Sites through 360-Degree Augmented Panoramas: Ecological Validity in Safety Research

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ABSTRACT

Given the dynamic and complex nature of the construction industry, maintaining situation awareness at job sites is critical. To react properly, workers must identify dynamic safety hazards within the scene. The majority of studies assessing construction workers' situation awareness have utilized static images, virtual reality, and other types of simulation methods, but questions remain as to whether these formats are able to capture and monitor workers' naturalistic behaviors and hazard identification abilities. To identify whether the format of hazardous stimuli (i.e., static, image-based vs. dynamic, and video-based formats) impact workers' subjective and objective hazard identification and situation awareness metrics, this study developed 23 safety hazard scenarios utilizing state-of-the-art augmented 360° panoramas and then tracked differences in workers' visual search patterns and hazard identification abilities using eye-tracking technology. The workers' cognitive responses, evidenced by their eye movements, showed that workers had significantly varied cognitive processes and abilities depending on the format of stimuli: Workers with lower hazard identification skills were more likely to miss hazards in a dynamic environment. This result suggests that the experimental setting should be carefully designed to determine construction workers' natural cognitive process.

INTRODUCTION

Workplace safety and health are crucial issues in the construction industry due to its high record of fatalities and injuries. A recent survey performed by the U.S Bureau of Labor Statistics reported that 20% of all fatalities within the private sector in 2019 occurred in the construction industry (U.S. Bureau of Labor Statistics (BLS) 2020). Since a lack of situation awareness (SA) (e.g., failure to detect, perceive hazardous factors, and react properly) in construction can lead to various incidents, situation awareness has received significant attention within the construction safety domain as a vitally important human factor involved in accidents (Hasanzadeh et al. 2017a). As construction sites are dynamic and complex (e.g., face changes in physical structures, host various crews for different tasks, and include several simultaneous tasks) (Sacks et al. 2009), a worker's continuous attention is essential to maintaining situational awareness.

To properly investigate human behaviors and cognitive processes within the dynamic construction domain, researchers must conduct experiments in environments that significantly resemble real-world construction sites. However, the dynamics of these sites make scientific control—not to mention safety—a challenge, so researchers often try other methods for evaluating situation awareness among construction workers. Although a few studies have been conducted on actual construction sites (e.g., Xu et al. 2019), the majority of studies have used images or other types of simulation methods. However, these methods may negatively influence research outcomes due to information distortion (Liao et al. 2021) and lack of ecological validity (Holleman et al. 2020).

To identify the impact the format of hazardous stimuli (i.e., static, image-based and dynamic, video-based) has on construction worker's subjective and objective hazard identification and situation awareness metrics, this empirical study compared static images with dynamic videos, both of which were produced via a 360-degree camera that enhances the realism of the experimental environment. This study contributes to the literature by demonstrating that experimental design significantly affects outcomes in safety and human factor studies.

BACKGROUND

Hazard Identification by Adopting Eye-tracking Technology

Several studies have evaluated human cognitive processes and behavior in hazardous environments by adopting such advanced technologies as electroencephalograms (EEG), near-infrared spectroscopy (NIRS), and eye-tracking to enhance the safety performance of the construction site (Hasanzadeh et al. 2017a; Jeon et al. 2020; Liao et al. 2021). Among the multiple indicators that illustrate the psychological responses of workers (e.g., emotion, stress, vigilance, and attention), visual attention has recently received considerable attention because it is significantly connected to situation awareness (Hasanzadeh et al. 2017b). Attention refers to the selection process that identifies which attractive or interesting items an individual senses demand further processing (Wickens et al. 2015). In order to strengthen a worker's safety performance in the dynamic and complex construction job site, it is crucial to identify safety-relevant information and evaluate the individual's cognitive ability (Kaber et al. 2016).

Accordingly, previous studies have assessed people's cognitive processes and hazard identification abilities—which are highly related to eye movements and gaze patterns—by using eye-tracking technologies (Hasanzadeh et al. 2018; Noghabaei and Han 2020). During these studies into various aspects related to visual attention and situation awareness, participants are typically exposed to designed hazards that were presented via different formats (e.g., image, and/or virtual reality—VR). While these past results demonstrate important connections between attention and cognitive processing, the major concern associated with hazard delivery formats is how the research team can simulate the experimental environment as realistically as possible. Conducting the experiment in a naturalistic environment is significantly important for assessing workers' true cognitive processes and patterns.

Simulating the Real-world Environment

Psychologists and social scientists have continuously argued that experimental conditions should resemble real-world environments to practically generalize the results (e.g., Zhu et al. 2020). Although the natural environment is the best option for measuring workers' true cognitive processes, as the construction site is relatively dangerous and often uncontrollable, scientific research is not always possible. Accordingly, researchers have sought other means of determining how to simulate hazardous conditions to bridge the gap between the lab and the real site. Various methods—including images of job sites (Aroke et al. 2020; Hasanzadeh et al. 2017a), VR (Noghabaei and Han 2020), computer simulation systems (Li et al. 2019), actual job sites (Hasanzadeh et al. 2018)—have been conducted.

Problematically, people's visual search patterns and abilities may be biased due to information delivery, so designing an experiment with more *ecological validity* is essential (Liao et al. 2021). Higher ecological validity refers to the experimental condition that more closely resembles the real world, and it is a fundamental consideration in delivering precise understandings of cognitive processes. While the common approach to illustrating hazards is static images of construction sites, such images fail to reflect the dynamic and complex characteristics of construction sites (Hasanzadeh et al. 2017a). Recent studies have tried to overcome this limitation by using VR, computer simulation systems, and synthetic sites at the laboratory to enhance the realism of experimental settings. However, these methods cannot provide an adequate sense of presence and may not simulate environmental factors (e.g., auditory information, weather) and physical variables (e.g., workers' tasks, other workers, changing physical structures, movement of equipment). Since environmental and physical factors can have a significant influence on visual search patterns and cognitive capacities, another experimental approach with higher ecological validity may deliver more accurate experimental results.

Beneficially, 360° videos applied in the safety training arena present various advantages to this experimental context, such as a higher sense of presence and cost-effectiveness (Eiris et al. 2020). Therefore, this study uses 360° video for hazard identification to garner more realistic—and potentially less biased—understandings of workers' cognitive patterns.

RESEARCH METHOD

Participants

Thirty healthy construction workers were recruited from construction jobsites. These workers were aged 34.5±10.6 years (mean±standard deviation), were experienced workers (on average 8.5 years of experience in the construction industry as a laborer), and had received on-stie safety training by company's safety manager. All participants had a normal or corrected-to-normal vision.

Experimental Design and Procedure

The hazard identification experiment involved eleven 360 scenario images and twelve 360 scenario videos ordered randomly and augmented with multiple hazards varying in safety risk. The scenario images and videos were taken from commercial construction sites in Washington D.C. and northern Virginia, and they covered various indoor and outdoor activities, including concrete work, erecting structures, installing HVAC, welding, painting, lifting materials, etc. All images and videos were aggregated in a stationary position, while the location of each station was varied to capture various scenarios. Each scenario involves three to five potential and active hazards that were identified and reviewed by professional safety managers.

A four-step process was utilized to prepare the scenarios: capture, edit, augment, and immerse. During the first step, the research team captured more than 400 360° spherical panoramas from real-world jobsite locations using Insta360 OneX, whose ultrawide fisheye lenses (200°) facilitate an immaculate stitch for the 360° livestream. To increase the sense of presence and ecological validity, a parallel audio track was captured to simulate the actual job sites for the video experiment. The research team then used Insta360 Studio 2021 software with Adobe Premiere Pro2020 to automatically stitch the images and videos. These images and sounds were fed into the virtual reality headset HTC VIVE Pro Eye, which immersed workers in the static and dynamic scenarios; Pro Eye offers millisecond synchronization and a seamless and complete eye-tracking integration at 90Hz, so the research team could monitor subjects' visual attentional allocation and search strategies.

Each worker participated in a single 60-minute session. First, the workers were informed about the experiment protocol, and then they filled out a survey, including demographic, risk-taking, and risk-tolerance questionnaires. The workers then donned the Pro Eye head-mounted display and additional wearable sensors (fNIRS and heart-rate and emotional monitoring, which are not discussed in this paper due to page limits). Subjects then completed the two hazard identification experiments—one with the eleven static images and one with twelve videos. Following the testing methodology described in Figure 1, during these experiments, participants viewed the scenarios for thirty seconds. Thereafter, participants saw a white screen and were asked to report the number and type of hazards they identified in each of the 23 scenarios. The whole protocol for the design, data collection, and data extraction was created in Tobi Pro Lab, which provides optimal data quality and accuracy.

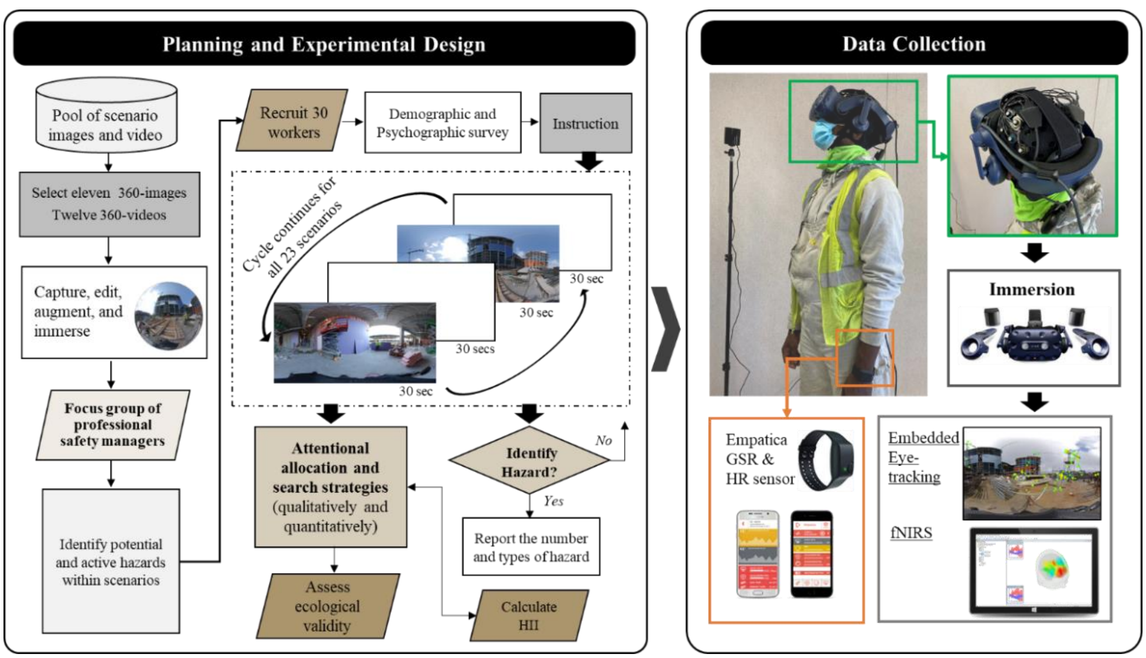


Figure 1. Research framework

Data Analysis

During the experiments, workers viewed scenarios containing multiple areas of interest (AOI), which are visual environments representing the hazardous condition in the image or video; in this study, a group of safety managers defined all areas of interest. While several types of hazards existed in the construction scenarios, due to page limit, the authors focus here on four major hazard categories (fall, struck-by, caught-in/between, and electrocution).

Using Tobii Pro Lab, five eye-movement metrics (i.e., total fixation duration, fixation count, time-to-first fixation, total visit duration, and visit count) regarding each AOIs were extracted and analyzed (Figure 2 depicts a hazardous scenario using 360 image, including three hazards); these metrics have been commonly used in eye-tracking-related studies to understand the human cognitive process or visual attention (e.g., Hasanzadeh et al. 2017a).

Then, the attentional allocation and search strategies of workers were analyzed across various types of hazards and testing formats (i.e., 360 static images vs. dynamic videos). Each worker's hazard identification index (HII) score—defined as the number of hazards identified by the worker over the total number of hazards identified by safety managers for each scenario—was calculated based on the subject's average performance in identifying hazards across panoramic images and videos.

Figure 2. An example of 360 scenario, including three hazards 1) fall hazards, 2) housekeeping, and 3) struck-by hazard

RESULTS AND FINDINGS

The Difference in Self-reported Hazard Identification

Figure 3 illustrates the average HII scores of each subject across the eleven 360° images and twelve 360° videos. The results indicate that 58% of workers were able to identify more hazards in the 360° videos of construction scenarios rather than the 360° images, with an average increase rate of 30%. However, it must be noted that 38% of participants showed lower hazard identification abilities in the 360° video construction scenarios. Furthermore, the workers did not identify all types of hazards consistently.

The Difference in Visual Search

Table 1 shows the descriptive and inferential statistics regarding changes in various visual attention metrics under various hazardous conditions. The results of the Wilcoxon signed ranks tests indicate that there were significant differences in attentional allocation toward fall-related hazards under the dynamic 360° videos versus the static 360° images. Specifically, workers significantly fixated more and spent more time exploring fall-related hazardous areas in the 360°

static construction scenario images as compared to the 360° dynamic videos (Z_{FC} = -2.85, p = 0.004; Z_{TVD} = -2.37, p = 0.018) (Table 1). Moreover, the time-to-first fixation after hazard onset (TTFF), often used to examine human visual attention, was significantly varied only in the fall category. Workers also identified fall hazards in 360° static scenarios significantly faster than in dynamic videos (t_{TTFF} = -4.40, p = 0.000).

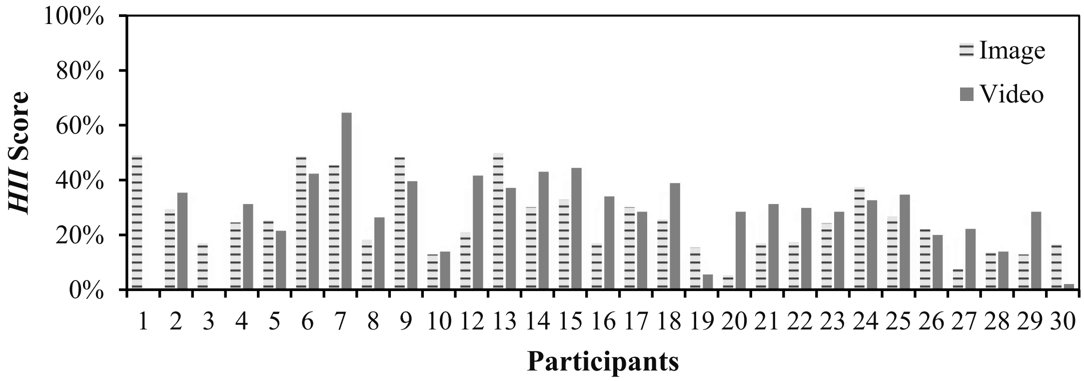


Figure 3. Average hazard identification index of each subject

Table 1. Summary of statistical analysis

AOIs	Stat Measures	Eye-tracking Metrics				
		TFD	**FC**	**TTFF**	**TVD**	**VC**
Fall	*I*Mean	2.49	13.73	8.17	3.47	3.05
	*V*Mean	0.43	10.35	10.68	3.05	3.28
	Test Statistic	-0.95[b]	-2.85[b]	-4.40[a]	-2.37[b]	-1.65[a]
	p-value	0.344	0.004*	0.000*	0.018*	0.109
Struck-by	*I*Mean	1.62	9.24	11.03	2.34	2.23
	*V*Mean	2.44	11.88	11.74	3.38	2.76
	Test Statistic	-3.04[a]	-2.55[a]	-0.85[a]	-2.77[b]	-3.20[a]
	p-value	0.005*	0.016*	0.403	0.006*	0.003*
Caught in/between	*I*Mean	0.58	4.27	11.38	0.88	1.86
	*V*Mean	1.06	5.84	7.60	1.39	3.28
	Test Statistic	-2.58[b]	-1.53[b]	-1.82[b]	-1.87[b]	-3.21[b]
	p-value	0.010*	0.126	0.068	0.062	0.001*
Electrocution	*I*Mean	1.20	8.03	9.72	1.86	2.36
	*V*Mean	2.92	13.43	10.03	3.90	3.00
	Test Statistic	-3.07[b]	-2.78[b]	-0.09[b]	-3.12[b]	-1.55[b]
	p-value	0.002*	0.005*	0.927	0.002*	0.120

TFD: total fixation duration, *FC*: fixation count, *TTFF*: time-to-first fixation, *TVD*: total visit duration, *VC*: visit count *IMean*: mean value based on an image dataset, *VMean*: mean value based on a video dataset

[a] Parametric paired sample t-test,

[b] Z test statistics for Wilcoxon signed ranks test

$^{*}\rho < 0.05$.

In contrast, the mean of several visual attention metrics from the 360° dynamic scenarios indicated higher values than the static scenarios (Table 1). This study found that workers allocated statistically significantly greater attention toward the struck-by, electrocution, and caught in-between hazards in the dynamic 360° videos as compared to static images. Regarding struck-by hazards, workers fixated more frequently (t_{FC} = -2.55, p = 0.016), spent significantly more time on exploring the sources of hazards (t_{TFD} = -3.04, p = 0.005, Z_{TVD} = -2.77, p = 0.006), and brought their attention more frequently to hazardous areas (t_{VC} = -3.20, p = 0.003). Similarly, for electrocution hazards, workers fixated more frequently (Z_{FC} = -2.78, p = 0.005) and spent considerably more time on exploring the sources of hazards (Z_{TFD} = -3.07, p = 0.002, Z_{TVD} = -3.12, p = 0.002). Lastly, workers fixated over a longer period (Z_{TFD} = -2.58, p = 0.010) and returned their attention more frequently (Z_{VC} = -3.21, p = 0.001), to caught-in/between hazardous areas.

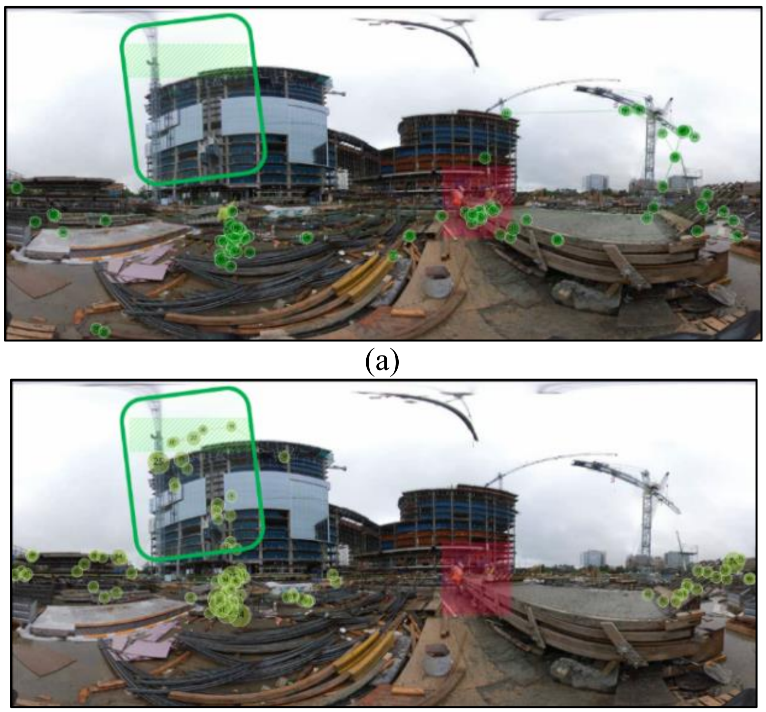
DISCUSSION

Hazard identification is a first step toward maintaining situation awareness when working in those high-risk environments that demand selective attention to the potential and active hazard (Hasanzadeh et al. 2017b, 2018). To study such considerations safely, experimental designs must address both the variables of interest and the delivery mechanisms that may mediate outcomes. Thus, the purpose of this study is to determine the strength of association between the various hazard identification delivery formats and workers' hazard identification performance.

The results showed that participants' hazard identification abilities differed depending on the delivery format. Workers allocated more attentional resources to fall hazards in static 360° scenarios, and they were able to identify these hazardous areas sooner. This result may be due to fall hazards' characteristics, which are relatively less dynamic than other hazard types (e.g., if the scenario contains tasks on a high platform, participants will see a potential fall hazard, even if the image cannot include movement or behavior). Thus, the location and position of information may be enough to identify fall hazards, while other hazards may demand further information. Whatever the explanation, the resulting differences between the static and dynamic image experiments reveal that delivery format affects hazard identification performance in research.

This result may relate to anticipatory cues (Scialfa et al. 2013), which are crucial for accurate hazard identification (Guo et al. 2020). Hazard identification is a complex skill necessitating workers to look ahead for potential sources of hazards, assess the severity, and make a reasonable judgment on how to prevent negative incidents (Guo et al. 2020). The limitation with static images is that anticipatory cues are often reduced or missing entirely (Scialfa et al. 2013). Specifically, motion cues that indicate information regarding the current behavior of construction workers, the movement and proximity of construction equipment (e.g., crane and moving lift), and other workers' tasks are missing in static images. For example, an image cannot contain dynamic information that might be crucial in detecting struck-by hazards. Therefore, participants may find struck-by hazards easier in dynamic video formats, which may explain the differences in performance. Furthermore, timing within scenarios plays a crucial factor that may distort hazard identification information. For example, a static image may obscure an electrocution hazard if a worker is approaching a dangerous electrical cable but appears in the image as far away from the hazard. Thus, dynamic formats may assist subjects in identifying hazardous situations.

In the case of the differing HII between the two experimental settings, individual differences in visual search strategies may cause the differences in HII scores (Borowsky et al. 2010; Hasanzadeh et al. 2017a). For example, Figure 4 illustrates the gaze plots (search strategies) of two participants, one with low and one with high HII scores. The two subjects' searching patterns are significantly different, even under the same experimental condition. Furthermore, as shown in Figure 4, the worker with lower hazard identification skills (HII= 22%) could not recognize the approach of the rigger and the materials being unloaded. In comparison, another worker who had higher hazard identification skills (HII= 39%) constantly checked the location of the crane's rigger and loaded material.



(a)

(b)

Figure 4. Visual search strategies of workers who had (a) lower and (b) higher hazard identification skill. The green rectangle represents a dynamic hazardous zone (crane approaching the workers while carrying load) that differs between the two subjects.

This observation in the results likely corresponds to the fact people have various search patterns and behaviors, and these factors can affect their visual search abilities (Hasanzadeh et al. 2017b). Since a static image is not similar to what construction workers actually experience in the job site, the results of an image-based experiment may fail to reflect subjects' real visual search behaviors. In general, search demands are remarkably greater when the objects and environment are constantly moving and changing (Scialfa et al. 2013). As the video can provide dynamic environments similar to real working conditions, the result of the video-based experiment might be closer to participants' actual search abilities and may reflect the correct pattern and behavior. In other words, the results of this study indicate that the static image can influence the results of the experiment and may overestimate a worker's hazard search skill.

Ecological Validity of 360° Dynamic Augmentation

The values of various eye-tracking metrics related to visual search in the two experiments reveal participants with significantly different cognitive and search patterns relied on the format of the stimuli to assess hazards. This result aligns with Liao et al.'s recent study highlighting how planar stimulus distorts information, which can cause a bias when trying to understand participants' visual search patterns (Liao et al. 2021). Although 2D images or videos that have been widely used in previous hazard identification studies contain robust information, this reduction of dimensionality may result in an over-simplistic representation of hazardous conditions. Therefore, the visual search pattern that was measured in the image-based experiment may be distorted and diverge from the actual search pattern. Furthermore, our results uphold the outcome of Perlman's 2014 study revealing the using virtual construction sites enhanced risk-perception levels as compared with images (Perlman et al. 2014). Consequently, to increase the accuracy of hazard identification performance findings, future research may consider the limitations of static images or other simulation methods and interrogate how these methods could affect the research outcome.

Our study's outcomes suggest a solution may arise in improved ecological validity. Since the ultimate goal of a hazard recognition study is to understand construction workers' natural cognitive processes and to prevent unsafe behaviors, studies in this domain should consider how best to authentically simulate dynamic and complex construction environments (Liao et al. 2021). Despite the importance of the experimental setting, some previous studies have underestimated or overlooked the value of sense of presence and ecological validity in construction safety research and simply used construction images. However, this study's results indicate that static images have critical limitations and appear to reduce ecological validity. Additionally, as images cannot involve auditory information that can attract worker's visual attention or help to detect potential hazards (e.g., the approach of construction equipment), the ecological validity of image-based experiments will be significantly low. Therefore, this study adopted 360° videos in a VR head-mounted display to pursue the highest ecological validity. This choice provided an immersive and realistic environment that relied on actual recordings of the job site. The differences between subjects' behaviors in the static versus dynamic 360° setting highlight the potential of 360° dynamic augmentations for future hazard recognition assessment and training activities.

There are several limitations associated with the current paper. The scope of this study was limited to changes in hazard identification and attentional allocation of workers under static versus dynamic 360° panoramic scenarios. However, future research needs to explore changes in visual attention metrics and other related psychophysiological responses (HR, EDA, and brain activity). Second, this study only considered static versus dynamic 360° images captured in real construction sites. It remains unknown whether 360° videos from real sites have a higher ecological validity as compared with alternative formats, e.g., simulated. To validate this consideration and to identify the optimal experimental setting, future research is needed to compare various simulated environments and actual construction environments.

CONCLUSION

To evaluate whether information delivery methods in the experimental setting affect subjects' hazard identification performance, this study compared construction workers' visual search patterns and hazard identification abilities under both a static and a dynamic 360° setting. The results indicate that workers often had higher hazard identification performance and better search strategies in dynamic scenes for struck-by, caught-in/between, and electrocution hazards. Moreover, several eye-tracking metrics associated with visual search patterns and cognitive processes varied significantly depending on the experimental setting. The results also show that workers with lower hazard identification capabilities often failed to identify hazards in the dynamic scenarios that could significantly influence their projection and decisions about potential hazards. These results affirm the experimental setting significantly affects workers' natural cognitive processes and safety behaviors, which the authors posit is due to how the setting biases subjects' comprehension and reactions toward the scenes. This study reveals that future research should pursue more efforts to create a more realistic experimental environment, which may lead workers to demonstrate their true cognitive process and hazard identification skills. In particular, given the outcomes of this research, the authors recommend 360° video to stimulate a higher sense of presence and ecological validity for future safety research or training purposes.

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