

Assessing Hazard Anticipation in Dynamic Construction Environments Using Multimodal 360-Degree Panorama Videos

Kyeongsook Lee, S.M.ASCE¹; Sogand Hasanzadeh, A.M.ASCE²; and Behzad Esmaeili, A.M.ASCE³

Abstract: Given the dynamic and complex nature of a construction site, the ability to recognize hazards in a surrounding environment is highly associated with worker safety. While many studies have examined the hazard identification skills of workers, researchers have not yet explored how the dynamic nature of hazards impacts workers' hazard anticipation, hazard identification, and cognitive perception of hazards within dynamic construction scenarios. This study investigates (1) whether hazard characteristics (i.e., static versus dynamic) impact workers' hazard identification performance; and (2) how two cognitive steps (i.e., attention and perception) influence hazard identification performance for these dynamic hazards. Employing state-of-the-art 360° video panoramas, this study performed an empirical investigation experiment to assess 30 construction workers' hazard identification skills and corresponding attention and perception behaviors. The results of this study indicate that worker's hazard identification abilities are affected by the static and/or dynamic nature of hazards: Generally, workers better anticipate dynamic hazards thanks to target and context anticipatory cues. In addition, a major discriminator between workers with higher hazard identification skills and those with lower hazard identification skills for dynamic hazards manifested in their continuous awareness of hazardous situations and proper prediction of emerging or potential hazards. Beyond identifying these factors, this study discusses multiple reasons underpinning attentional failures and misperception. The study highlights the importance of applying an integrated personalized training program to address cognitive failures and hazard anticipation skills to improve occupational safety in the construction industry. DOI: 10.1061/(ASCE)ME.1943-5479.0001069. © 2022 American Society of Civil Engineers.

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Introduction

Construction is a complicated task requiring constant attention to dynamic and complex environments. Despite continuous efforts to enhance construction workers' safety performance, the construction industry still records a high number of fatalities and injuries—according to one survey conducted by the US Bureau of Labor Statistics, the construction industry accounted for 20% of all fatalities within the private sector in 2019 [US Bureau of Labor Statistics (BLS 2020)]. Such statistics drive the industry's focus on workplace safety and health, and the construction industry has made huge efforts to improve safety performance through various monitoring methods and training. While these improvements in methods and training have led to a remarkable increase in safety levels (Awolusi et al. 2018; Casey et al. 2021), safety performance within construction remains below desirable levels, prompting

further investigations and a search for a next generation of safety training able to maximize effectiveness per the exact limitations of workers (e.g., Bhandari et al. 2019; Bükür et al. 2020; Demirkesen and Arditi 2015; Eiris et al. 2018, 2021; Mo et al. 2018; Xu et al. 2019b, c).

Unidentified hazards are one of the main causal factors leading to incidents on construction sites (Bohm and Harris 2010; Choudhry et al. 2007a, b; Kim et al. 2017). Because construction sites are relatively more dynamic and complex in large part due to such characteristics as changes in physical structures, coinciding tasks, and overlapping teams (Sacks et al. 2009), these characteristics necessitate high situational awareness to identify hazards (Endsley 1995; Hasanzadeh et al. 2016, 2017a; Jiang et al. 2021; Wickens et al. 2021). Hazard recognition especially contributes to situational awareness when working in these dynamic and dangerous environments that require selective attention to hazards (Hasanzadeh et al. 2017a, 2018). In fact, researchers have revealed that attentiveness to hazard conditions is highly related to hazard identification performance (Hasanzadeh et al. 2018). Accordingly, construction workers must continuously allocate attention to the surrounding environment, perceive risk conditions, and anticipate subsequent events to avoid unsafe behaviors that may cause accidents.

To improve workers' hazard identification performance, extensive research efforts have been made. For example, advanced wearable technologies have been applied to monitor the physical and physiological responses of workers (e.g., eye movement, brain activity, and electrodermal activity), which researchers use to infer the location of hazards in the surrounding environment (Hasanzadeh et al. 2018; Jeon et al. 2020; Jeon and Cai 2021). Furthermore,

¹Ph.D. Student, Lyles School of Civil Engineering, Purdue Univ., 550 Stadium Mall Dr., West Lafayette, IN 47907. Email: lee2490@purdue.edu

²Assistant Professor, Lyles School of Civil Engineering and Construction Engineering & Management, Purdue Univ., 550 Stadium Mall Dr., West Lafayette, IN 47907 (corresponding author). Email: sogandm@purdue.edu

³Assistant Professor, Dept. of Civil, Environmental and Infrastructure Engineering, George Mason Univ., Fairfax, VA 22030. Email: besmaeil@gmu.edu

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various personal factors (e.g., personality, safety knowledge, experience, emotional states, and change blindness) have been highlighted in the literature as affecting worker hazard identification abilities (Aroke et al. 2020; Bhandari et al. 2016; Hasanzadeh et al. 2017a, 2019; Solomon et al. 2021; Solomon and Esmaeili 2020; Zhang et al. 2021); such past work argued experienced workers could have better attentional allocations while less-experienced workers were more distractor-sensitive (Hasanzadeh et al. 2017b).

Despite the significant contribution of previous research efforts, no empirical study has examined the impact of static versus dynamic hazards on worker's hazard identification skills. Specifically, most previous studies focus on static hazards already in the scenes and whether the workers will identify such hazards. However, many hazards—i.e., emerging or latent hazards—have dynamic characteristics that might materialize at a particular time. Consequently, hazard anticipation—or workers' ability to predict emerging and latent hazards based on informational cues available within a visual scene—is crucial to avoiding or mitigating active and potential hazards.

Hazard anticipation is a critical cognitive element that is highly connected to the proper situational awareness or situational awareness failures that cause various accidents (McDonald et al. 2015; Unverricht et al. 2018). Due to its importance, hazard anticipation has been actively examined in the driving-safety domain to understand how to improve drivers' hazard anticipation skills (Agrawal et al. 2018). However, the construction safety domain has not yet deeply investigated workers' ability to anticipate hazards nor hazard anticipation's impact on workers' ability to identify dynamic hazards. Furthermore, given that the human cognitive process is extremely complex and various cognitive stages are interrelated, comprehensive assessments are required to determine the causality of different elements. Hence, to properly understand a worker's true challenge regarding hazard identification and their corresponding reasons for low-hazard recognition performance, studies must consider (1) Does a worker miss a hazard because of the hazard's characteristics (e.g., static/dynamic nature)?; (2) Does the worker miss a hazard because the worker failed to allocate sufficient visual attention to it—and therefore could not recognize it (the process of monitoring and cue detection under Level 1 SA)?; or (3) Does the worker miss a hazard because the worker appropriately searched for it but failed to perceive and comprehend the risk (comprehension under Level 2 SA)? Unpacking these three interrelated questions becomes a central challenge in studying worker safety within the dynamic construction domain and also highlights the importance of hazard anticipation within this dynamic high-risk environment (projection under Level 3 SA).

To assess how these factors influence the hazard anticipation, hazard identification, and attention maintenance behaviors of workers, this study incorporated an eye-tracking experiment within 360° video panoramas to evaluate workers' hazard recognition and cognitive treatment of hazards within dynamic construction scenarios—a valuable contribution to previous work as past studies mainly used and studied static hazards. The research team evaluated whether workers recognize emerging or latent (“dynamic”) hazards, attended to these hazards appropriately, and/or require further training to better consider such hazards in future construction sites. This study provides initial evidence that hazard identification and safe/unsafe decisions regarding dynamic hazards are related to hazard anticipation and perception. This study offers valuable insights into understanding the reasons behind unrecognized dynamic and static hazards and promotes the development of more effective personalized training.

Background and Literature Review

Situational Awareness in Construction Sites

Situational awareness has received remarkable attention during the last few decades as one of the critical human factors involved in safety-related research (Endsley 1995; Katrahmani et al. 2017; Wickens et al. 2021). According to Endsley, situational awareness is demonstrated as the “perception of those elements in the environment within a volume of time and space (Level 1 SA), the comprehension of their meaning (Level 2 SA), and the projection of their status in the near future (Level 3 SA)” (Endsley 1988, p. 97). Additionally, Endsley's model indicated that several factors (e.g., individual, task, and environmental factors) can affect the maintenance and development of situational awareness. For instance, individuals whose ability to acquire SA differs will not have similar SA simply by receiving the same training. These parameters showcase the centrality of SA, and previous studies have reported that maintaining situational awareness is significantly important to keeping a person safe while they perform their task under dynamic and complex environments (Endsley 1995; Hasanzadeh et al. 2016, 2017a; Jiang et al. 2021; Wickens et al. 2021). For example, one study showed that construction workers must be aware of the elements and ongoing tasks within their surrounding environment to enhance their safety performance in construction sites (Hasanzadeh et al. 2016). Furthermore, unlike fixed industrial facilities, construction sites experience dynamic changes (e.g., various work teams with different tasks, continuous changes of physical structures and environment, and changes in weather) (Sacks et al. 2009). Such dynamics coincide with past findings to highlight the importance of assessing construction workers' situational awareness, which can cause or prevent human error. Accordingly, construction workers' cognitive processes and behaviors as related to situational awareness should be a crucial concern in the construction safety arena.

Hazard Anticipation Skills

Hazard anticipation refers to a higher cognitive ability that requires individuals to have adequate knowledge regarding construction risks, to search the safety-critical elements in the scene, and to predict whether and how a specific hazard might materialize at a particular time in the near future (Endsley 1995; McDonald et al. 2015; Yamani et al. 2021). Hazard anticipation can be considered as the Level 3 situation awareness by Endsley that states the ability to project the future actions of the element in the environment (e.g., extrapolating perceived information forward in time to determine how it will impact future states of the construction environment). In the driving-safety domain, hazard anticipation has been considered one of the primary cognitive elements affecting younger- and novice-drivers' car crashes (Agrawal et al. 2018; Yahoodik and Yamani 2020). Thus, various trainings (e.g., Act and Anticipate Hazard Perception Training, Risk Awareness and Perception Training, and Error-based Feedback Training) have been developed to improve drivers' hazard anticipation and perception skills (McDonald et al. 2015; Unverricht et al. 2018).

According to one recently published study, hazard anticipation skills can be categorized into four groups: modal, strategic, tactical, and operational hazard anticipation skills (Yamani et al. 2021) (Table 1). In addition to the categorization, the study reported that each anticipation skill requires different training programs, as these skills need varied techniques. For example, if someone has low modal anticipation skills, the person needs to improve his/her visual search strategy to properly scan the environment. Although the

Table 1. Summary of the four types of hazard anticipation skills

Type	Definition of anticipation skill	Dependent measure
Modal	Skills that are necessary to respond in a systematic way to environmental threats, e.g., the individual should continuously monitor the surrounding environment to detect immediate threats.	1. Variability of fixation • Fixation duration • Fixation counts
Strategic	Skills that are used when a cue first becomes visible to infer the existence of a potential hazard, e.g., the individual detects clues that signal them regarding an upcoming latent hazard.	2. Glance toward the clues
Tactical	Skills that detect and monitor a latent hazard in the immediate environment and strategically anticipate upcoming clues of a potential threat, e.g., the individual scans and monitors the occluded visual area in anticipation of a latent danger that may materialize.	3. Glance towards a target zone containing a latent hazard with an occluded visual area
Operational	Skills that prepare for overt control of an ongoing task in anticipation of a latent hazard.	4. Behavior related to the preparation

Source: Data from Yamani et al. (2021).

previously published studies in this area targeted the anticipation skills of drivers, the results are highly aligned with the construction safety area.

Among the four anticipation skills, modal, strategic, and tactical anticipation skills are most associated with construction workers' hazard identification capabilities. Under dynamic and complex construction sites, workers should have good modal and strategic anticipation skills to continuously check the surrounding environment, identify anticipatory cues, and predict potential and latent hazards. Furthermore, because multiple tasks are simultaneously performed and large materials are stored on jobsites, tactical anticipation skills are also remarkably important when workers pass the work zones. However, despite the importance of different anticipation skills and their role under various conditions, safety training in the construction domain often focuses on workers' general hazard identification capabilities without considering these anticipation skills. Therefore, the construction workers' hazard anticipation skills must be studied to select a more appropriate training approach.

According to one study performed by Mühl and Baumann (2018), the characteristic of anticipatory cues can significantly affect anticipation performance, which is highly related to situation awareness (Endsley 1995). The study divided cues into target and context cues based on previous literature regarding the framework of action selection and the cognitive model of situation comprehension (Baumann and Krems 2007; Mühl and Baumann 2018; Norman and Shallice 1986). Target cues are environmental elements that directly trigger the subsequent action, while context cues do not provide any indication. The results of the previous studies indicate that target cues can increase anticipatory performance (Mühl and Baumann 2018). It is, therefore, crucial to investigate how these anticipatory cues may affect workers' hazard identification performance when exposed to dynamic hazards.

The Role of Attention and Perception in Situational Awareness

Among the cognitive elements that play a significant role in the situational awareness process (Endsley 1995), attention and perception are the primary stages informing an awareness of the surrounding environment's condition. In the first stage—attending a scene—workers must distribute their attention properly across the construction scene to appropriately process the scene thereafter (Hasanzadeh et al. 2018; Wickens et al. 2021). Then, during the second—perception—stage, a worker will either perceive a selected item in the environment as a hazard or will not perceive it as a risk—a decision process based on several factors such as an individual's risk tolerance and experience. According to one study conducted by Jeelani et al. (2017), factors related to the failure of these two cognitive elements—e.g., selective attention or inattention, and misperceiving hazards as imposing low levels of safety risk—significantly affect workers' hazard identification performance, with about 40% of unrecognized hazards identified as being associated with these factors. Therefore, it is imperative to investigate the consequence and the reason behind the failure of each cognitive step separately to understand workers' mistakes and thereby develop a more precise training program.

Despite the importance of assessing these cognitive elements, few studies have performed in-depth analysis regarding the impact of these two cognitive stages in hazard identification. Additionally, even if monitoring the worker's visual search pattern can provide the information related to attentional distribution, it is not sufficient to evaluate the true challenges (e.g., workers may not perceive the hazard as a risky condition, even if they look at the hazard).

360° Panoramas

The architecture, engineering, and construction (AEC) industry have incorporated 360° panoramas for various purposes, including education, site monitoring, and safety training (e.g., Choi et al. 2018; Eiris et al. 2018; Felli et al. 2018). Among these areas, the safety training domain has actively adopted 360° panoramas to develop more effective and immersive training programs (Eiris et al. 2018; Orús et al. 2021; Pham et al. 2018, 2019).

360° panoramas provide an advanced technique for capturing visual environments' full horizontal and vertical fields (e.g., Orús et al. 2021; Pereira and Gheisari 2019). Such capability provides several advantages over other simulation methods, including cost-savings, realism, and time savings (Pereira and Gheisari 2019; Pham et al. 2019; Shojaei et al. 2020). Previously, virtual reality (VR) was widely used as a promising method for safety training due in large part to its ability to create a high sense of presence. However, studies investigating the difference between VR and 360° panoramas indicated that 360° panoramas save researchers coding time while also being more realistic, energy-efficient, and user friendly than VR platforms (Eiris et al. 2018, 2020; Pham et al. 2018). Additionally, while some studies indicated that subjects tended to show higher hazard identification ability under the VR environment, the reason behind it is that the clean and very organized virtual environment does not properly represent construction sites (Eiris et al. 2020; Moore et al. 2019). Previous studies pointed out that a disconnect between the testing environment and the real construction environment can lead to inaccurate assessments of workers' capabilities, an inaccuracy that may fundamentally debilitate effective training (e.g., Jeelani et al. 2020). To overcome this limitation, this study applied stereo 360° video—captured from real sites—to create immersive stereo-panoramic assessment environments that allow workers to feel an emotional and cognitive

presence in the scene. Moreover, studies in human behavior reported that 360° panoramas induce more realistic behavioral or emotional reactions as people get a realistic feeling in a 360° immersive environment (Reeves et al. 2021; Ventura et al. 2021).

Due to the dynamic and complex nature of the construction environment, it is crucial to identify a proper information delivery method for assessing and training purposes to best depict the true nature of this environment (Sacks et al. 2009). As this study includes the assessment of worker's cognitive processes, capturing a worker's true behavior is significantly important to extract correct results. Based on the current literature results, the research team decided to adopt 360° video panoramas in this study.

Points of Departure

This assessment study examined workers' hazard identification performance for dynamic hazardous scenarios on jobsites to determine which factors contribute to workers' hazard identification failures. Accordingly, this study investigated two driving objectives:

1. This study examined whether the dynamic nature of some construction hazards impacts workers' hazard identification abilities—and subsequently whether the dynamic versus static nature of the hazard affected workers' ability to anticipate hazards and properly allocate attention accordingly;
2. Because cognitive failures drive low-hazard identification performance, because either workers fail to see hazards and thereby do not recognize hazards (Type 1 failures) or workers see hazards but fail to recognize them (Type 2 failures), this study examined whether the dynamic versus static nature of the hazard affected whether workers experience Type 1 or Type 2 cognitive failures.

Methodology

Capturing 360° Panoramas

This study used Insta360 OneX (Irvine, California) to capture videos of the construction scenarios for the experiment. Insta360 OneX's ultrawide fisheye lenses (200°) facilitate an immaculate stitch for the 360° livestream. In close collaboration with our industry partner, the research team captured various 360-construction scenarios from several construction sites (commercial buildings) in the Washington D.C. and northern Virginia areas. The scenarios

included such various indoor and outdoor activities as concrete work, erecting structures, installing HVAC, welding, painting, and lifting materials. All videos were collected in a stationary position from 5.6 ft above the ground. Moreover, a parallel 360° audio track was captured by two embedded microphones to better simulate the actual jobsites, enhance the sense of presence, and maintain ecological validity. In addition, a smart wind-reduction algorithm helped filter out the wind noise and balance the sound to better mimic how the human ear perceives. The research team then used Insta360 Studio 2021 software with Adobe Premiere Pro2020 to automatically stitch the videos.

Selection of Construction Scenarios

The study selected twelve high-quality 360° videos from a pool of more than 200 scenario videos captured from commercial construction sites. These scenario videos included various hazards, such as fall, struck-by, caught-in/between, electrocution, and housekeeping hazards that might be static or dynamic by nature. Each scenario involved three-to-five hazards identified and reviewed by professional safety managers with more than five years of experience. Fig. 1 depicts a video example used in this study. As shown, some hazards in the video scenarios occurred during the specific period when these hazards were activated by the depicted workers' dynamic tasks.

Participants

30 healthy construction workers (29 males, 1 female) were recruited from construction jobsites to participate in the hazard identification task. These workers had a mean age of 34.5 (± 10.6 years) and had an average of 8.5 years of experience in the construction industry as a laborer. These workers had received multiple on-site safety trainings from the company, and three workers reported that they also received the Occupational Safety and Health Administration (OSHA) 10-h safety training. About 50% of participants noted that they were injured or saw other workers get injured. All participants had normal or corrected-to-normal vision.

Experimental Design and Procedure

The processed videos were fed into the virtual reality headset HTC VIVE Pro Eye (HTC Corporation, Taoyüan, Taiwan)—which has been used in eye-tracking-related studies (Imaoka et al. 2020;



Fig. 1. Example of 360° video scenario, including three dynamic hazards: (a) captured at 5 s; and (b) captured at 20 s. The markings illustrate: 1 = fall hazard; 2 = struck-by hazard; and 3 = fall hazard (Note: images were cropped to magnify focused area).

Sipatchin et al. 2020, 2021)—to fully immerse the test subjects within the 360° construction scenarios. The headset consists of a Hi-Res-certified headphone and dual OLED 3.5" diagonal screen, which provides a resolution of 1,440×1,600 pixels per eye and 110° field of view. This headset also offers millisecond synchronization and a seamless and complete eye-tracking integration at 90 Hz, so worker visual attentional allocation and search strategies could be monitored while they were scanning scenarios.

Each subject joined a single 60-min session. First, the research team explained the experiment's protocols, and then the subjects filled out a survey, including demographics and risk-taking questionnaires. The subject then wore the Pro Eye head-mounted display and additional wearable sensors (capturing brain activation, heartrate, and emotions; discussion of these data are outside the focus of this paper). Subjects then completed a hazard identification experiment. As illustrated in Fig. 2, during these experiments, workers viewed the scenarios for 30 s. Then, after each scenario, the screen switched to a white screen, during which time the subjects were asked to report the number and type of hazards they had identified. After 30 s, they were automatically sent to the next scene. The whole protocol for the design, data collection, and data extraction was created in Tobii Pro Lab, which provides optimal data quality and accuracy.

Hazard Identification Index

Following the approach of Hasanzadeh et al. (2017a), the research team calculated the hazard identification index (HII) for each participant to evaluate their hazard identification ability. The hazard identification index is demonstrated as $HII_{ij} = H_i / H_{tot}$, where H_{tot} means the total number of hazards identified by professional safety managers in each scenario, and H_i represents the number of hazards reported by subject j in scenario i . The total hazard identification index for subject j ($HII_{T,j}$)—the average of HII_{ij} for all scenarios—was then calculated to compare the subject's average hazard identification performance under different experimental

designs. In addition, the average hazard identification index regarding dynamic and static hazards was also calculated to examine the impact the hazards' nature had on each participant's hazard recognition abilities; these nature-specific HIIs followed the form:

Number of hazards the subject identified/Total number of hazards = HII.

Data Analysis

To aggregate eye-tracking data related to hazards in each scenario, the research team partnered with professional safety managers to define and tag multiple areas of interest (AOI) as visual representations of hazardous areas in the videos (Fig. 3). Then, using Tobii Pro Lab, the research team extracted and analyzed five eye-movement metrics for each test subject and AOI. These eye-movement metrics included: total fixation duration (the total time each subject fixated on each AOI), fixation count (the number of fixations within each AOI), time-to-first fixation (the time to first fixation for each AOI), total visit duration (the total time each subject visited each AOI), and visit count (the number of visits within each AOI); these metrics have been commonly used in eye-tracking-related studies to understand human cognitive processes or visual search strategies (e.g., Hasanzadeh et al. 2017b; Xu et al. 2019a).

Then, workers' attentional allocation and search strategies were closely monitored across the different hazard types (e.g., fall, struck-by) and natures (i.e., static versus dynamic hazards). Previous literature revealed a close relationship between attention and eye movement (Yarbus 1967; Sun et al. 2008). Specifically, Duchowski's study indicated that people often directly look at the element they are currently attending to (Duchowski 2007). Accordingly, several eye-tracking metrics (e.g., Dwell %, fixation count, and fixation duration) have been utilized in studies to assess workers' attentional allocation (Hasanzadeh et al. 2017a, b, 2019); for example, Hasanzadeh et al. (2017b) indicated that workers with lower hazard identification skills had lower run counts and lower fixation counts

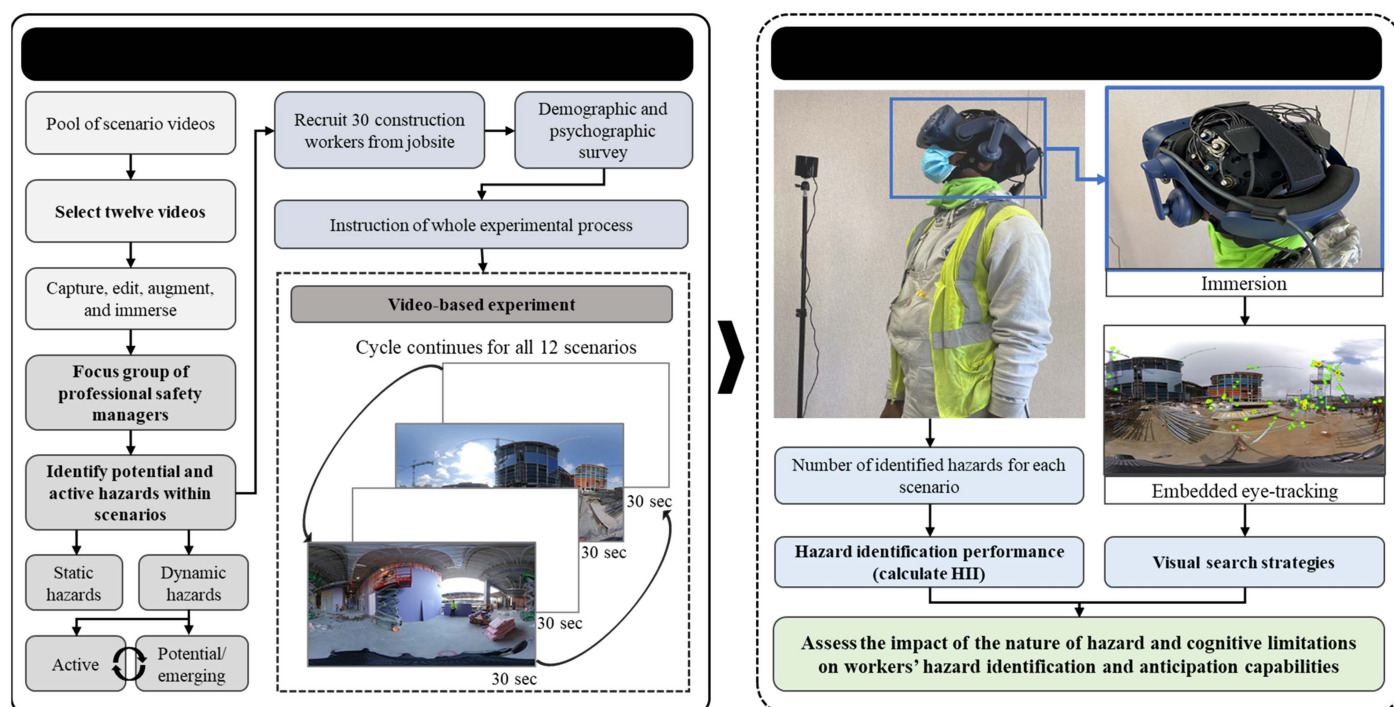


Fig. 2. Research framework.

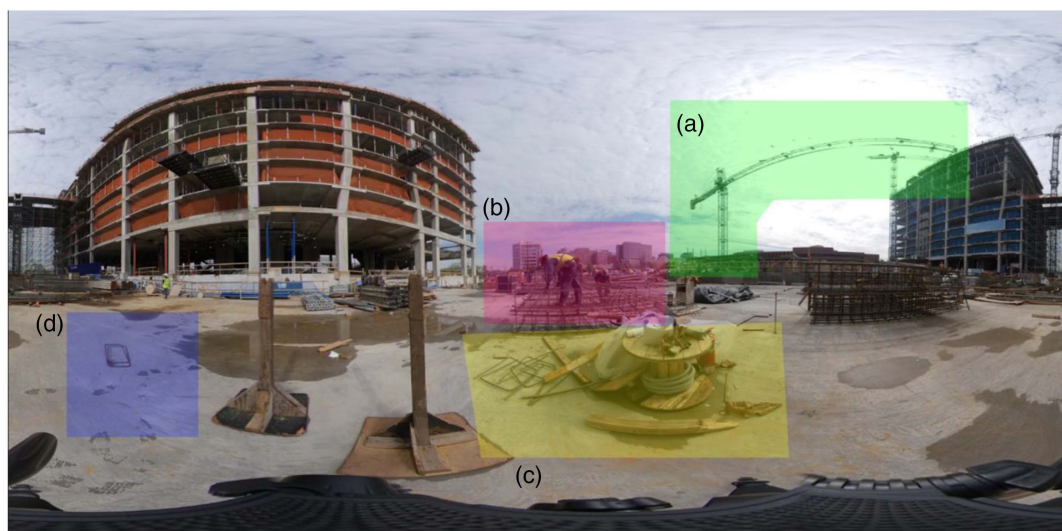


Fig. 3. An example of defined AOIs: (a) struck-by hazard; (b) fall hazard; (c) housekeeping hazard; and (d) fall hazard.

on hazardous areas within the construction scenario. Thus, Level 1 SA can be measured by monitoring visual attention of workers using eye-tracking technology. Regarding Level 2 SA, each worker's hazard identification index (HII) was cross-validated with objective attentional metrics to diagnose the subject's cognitive processing when exposed to various hazardous conditions. For example, if the test subjects missed hazards, the research team reviewed data about total visit duration (representing the total duration during which the participant fixated on each AOI) and visit count (representing the total number of visits to each AOI) to classify whether workers allocated attention to these hazards or not. If the values of these metrics equalled 0 for a specific hazard, the value indicated the worker did not see the hazard at all; however, if the values of these attention metrics were nonzero for a particular hazard, then the value may signal the workers' lack of knowledge, high-risk tolerance, low perceived risk, etc. Such instances needed further analysis.

Lastly, several statistical analyses were performed to analyze whether the nature of the hazards and individual's cognitive challenges impacted visual search strategies and workers' hazard identification capabilities. The research team also performed a normality test to confirm the appropriate significance tests for each metric (e.g., parametric and nonparametric test). Based on the normality test result, corresponding significance tests (i.e., Wilcoxon signed ranks test, parametric paired sample *t*-test, Kruskal-Wallis Test) were performed. It must be mentioned that the data for one participant was omitted from the analysis because the hazard identification score of the participant was missing. Accordingly, the data analyses were performed on the data from 29 workers.

Results

Differences in Workers' Hazard Identification Performance across Various Hazard Types and Nature

On average, participants recognized 28% of hazards in the video-based experiment. In order to understand which hazards were being missed or remained unrecognized, the research team further investigated 35 hazardous conditions in the video-based 360-scenarios. Table 2 shows more detailed information about the hazards that were missed by 80% or more participants versus those that were identified and reported correctly by more than half of the participants—with this delineation confirming performance values would not overlap.

As the table shows, more than 40% of the 35 hazards within the 360-video scenarios were missed by participants. In particular, more than 80% of subjects failed to identify 15 hazards, including fire hazards, fall hazards, struck-by hazards, caught-in/between hazards, missing PPE hazards, and housekeeping-related hazards. While the results in Table 2 show that subjects often failed to identify many fall and struck-by hazards in 360-video-based scenarios, similar hazard types were easily recognized by more than half of participants within other video construction scenarios, indicating that the types of hazards were not the central factor in subjects' hazard identification performance. Therefore, further in-depth investigation regarding the dynamic versus static nature of each hazard was necessary to diagnose the reason behind the failed hazard identification.

For further investigations, all hazards in the 360-video scenarios were categorized as dynamic (e.g., overhead crane operation, tossing material off the scaffold) or static hazards (e.g., items left on the ground, mid-rail of guardrail missing). Then, the research team calculated the HII scores for the dynamic versus static groups of hazards. Fig. 4 shows the distribution of average HII scores for dynamic and static hazards.

The results illustrate that in the 360-video scenarios, subjects showed better hazard identification abilities for dynamic hazards, with an average HII increase rate of 12%. For static hazards, most participants recognized only 20% of hazards or fewer, while they identified 20% to 40% of dynamic hazards. In addition, it is notable that the number of subjects who missed all hazards in each hazard-type group (e.g., had an HII score of zero for every instance of a given hazard type) was relatively decreased across dynamic hazards. Accordingly, the nature of hazards affects hazard recognition performance of subjects, and the reason for greater hazard identification performance among dynamic hazards might be rooted in the strategic hazard anticipation skills of subjects, as represented in their search strategies. The differences in workers' attentional distribution and search strategy across static versus dynamic hazards must therefore be considered.

Differences in Workers' Search Strategies across Static versus Dynamic Hazards

Differences between dynamic versus static hazards also manifested in subjects' visual search patterns. Table 3 presents descriptive and inferential statistics regarding changes in subjects' attentional distribution toward static and dynamic hazards.

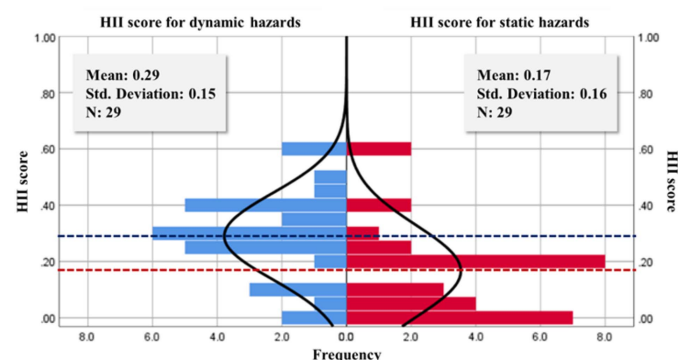
Table 2. Summary of test workers' hazard identification performance under the video-based experiment for 35 hazardous conditions depicting various hazard types and natures

Hazard identification level	Nature of hazards	AOIs	Number of subjects who missed AOIs	Percentage (%)	Hazard type
Low ^a	Static	Oxygen stored close to the operation	28	97	Fire hazard
	Static	Ladder access not compliant	28	97	Fall hazard
	Dynamic	Tape marking	28	97	Struck-by
	Static	Slippery surface	27	93	Fall hazard
	Dynamic	Leaning on guardrail	27	93	Fall hazard
	Static	Handrail displaced	27	93	Fall hazard
	Dynamic	Lifting overhead	26	90	Struck-by
	Static	Access out not accessible	26	90	Caught in/between
	Dynamic	Passing lift area	26	90	Struck-by
	Dynamic	Missing long sleeves/gloves in concrete work	25	86	Missing PPE
	Static	Access blocked	25	86	Housekeeping
	Dynamic	Area not barricaded off	24	83	Fire hazard
	Static	Area not blocked off	24	83	Housekeeping
	Dynamic	Tag line missing on crane operations	24	83	Struck-by
	Static	Impalement	24	83	Fall hazard
High ^b	Dynamic	Employee did not use the tagline	14	48	Struck by
	Dynamic	Scaffold is questionable because of scaffold boards (boards extend greater than 12 in.)	13	45	Fall hazard
	Dynamic	Tossing material off the scaffold	11	38	Struck by
	Dynamic	Reaching out of the side of the plane	8	28	Fall hazard

Note: Percentage (%): number of subjects did not recognize AOIs/total participants.

^aLow = hazards that were frequently missed or remained unrecognized by the majority of subjects (more than 80% of participants).

^bHigh = hazards which were often identified by at least half of the subjects.

**Fig. 4.** Distribution of workers' average hazard identification index for dynamic and static hazards in 12 video-based scenarios.

The results demonstrate that there are significant differences in attentional allocation toward dynamic hazards, as compared to static hazards; subjects significantly fixated more ($t_{VC} = -5.675$, $p = 0.000$) and spent more time ($Z_{TVD} = 4.314$, $p = 0.000$) exploring dynamic hazards (Table 3), demonstrating subjects allocated their attentional resources toward observing for cues. In particular, values related to longer visit durations on dynamic hazards illustrate that subjects tended to search for related cues and anticipate the future condition of the hazards. Such results signal subjects' anticipatory recognition of hazards is affected by the nature of the hazard and the subjects' proper attentional allocation.

However, almost half of the hazards missed by the majority of subjects were dynamic hazards (Table 2). Such data show that subjects may have different hazard identification performance when exposed to dynamic hazards, a fact that may be due to whether they distribute their attention in a proper way to identify anticipatory cues within the scene.

Table 3. Differences in visual attention measures among dynamic and static hazard types

Stat measures	Eye-tracking metrics	
	TVD	VC
SMean	2.195	2.379
DMean	3.667	3.263
Test statistic	4.314 ^b	-5.675 ^a
p-value	0.000*	0.000*

Note: TVD = total visit duration; VC = visit count; SMean = mean value based on a static hazard dataset; and DMean = mean value based on a dynamic hazard dataset. * $p < 0.05$.

^aParametric paired sample t -test.

^bZ test statistics for Wilcoxon signed ranks test.

Assessing Worker Cognitive Failures as a Precursor of Low Hazard Identification

To provide insights into the cognitive mechanisms of failing to identify and anticipate hazards, the authors analyzed the visual attention data collected when subjects were scanning construction scenarios, including the 15 hazardous conditions that were missed by the majority of subjects (hazards in the low-hazard identification level group in Table 2). As shown in Fig. 5, construction workers must maintain situational awareness of their surroundings while working in high-risk construction environments, must continuously scan carefully, must identify the hazard, must make a proper and safe decision based on their perceived risk, and must execute a safe behavior. Among these steps, the stages of visual attention (sensation) and perception are highly connected to hazard identification ability. The failure of these stages can cause different consequences (e.g., Endsley 1988, 1995; Hasanzadeh et al. 2017b; Katrahmani et al. 2017; Park et al. 2022). Accordingly, it is imperative to understand the reason for these stages' failure to diagnose workers' true

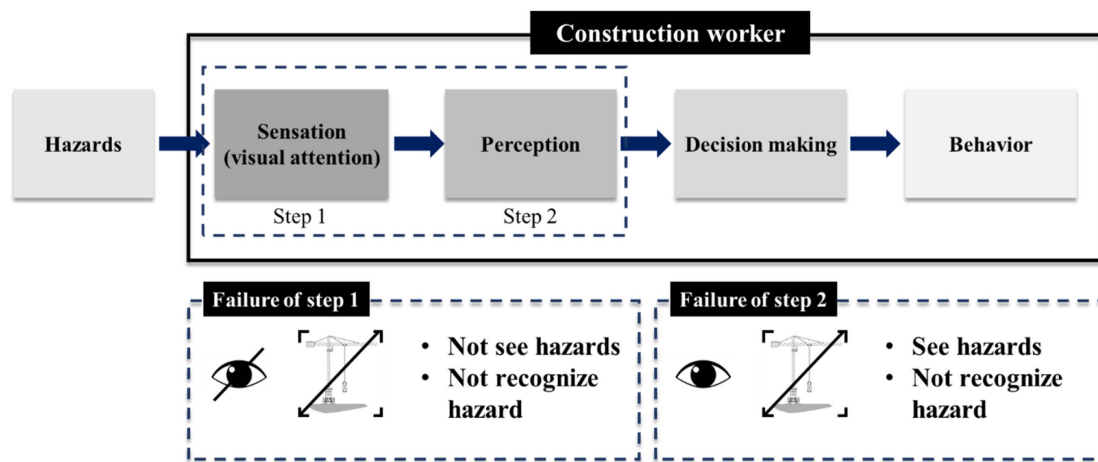


Fig. 5. Construction worker's hazard recognition process.

Table 4. Extracted cases representing attentional failure (Type I) as a precursor of low hazard identification

AOIs	Number of subjects did not recognize AOIs	Number of subjects did not see AOIs	Percentage (%)	Hazard type	Nature of hazards
Ladder access not compliant	28	27	96	Fall hazard	Static
Missing tape marking	28	14	50	Struck-by	Dynamic
Handrail displaced	27	24	89	Fall hazard	Static
Lifting overhead	26	14	54	Struck-by	Dynamic
Access blocked on ramp to ladder	25	15	60	Housekeeping	Static
Fall onto the exposed bars and implement hazard	24	14	58	Fall hazard	Static

Note: Percentage (%): number of subjects who did not see AOIs/number of subjects did not recognize AOIs.

hazards recognition limitations, which will be essential information for developing personalized safety training.

Type 1 Failures: Attentional Failure and Failing to Recognize Hazards

Table 4 shows statistics about the hazardous conditions that subjects failed to identify because they did not see the hazard—Type 1 failures, denoted by no fixations in the eye-tracking data. These AOIs were extracted from hazards in the low-hazard identification level group (Table 2), and more than half of the subjects who missed these hazards did not even see these AOIs. In particular, workers missed three fall cases, two struck-by hazards, and a housekeeping-related hazard because they failed the first stage in the recognition process by not seeing or allocating their visual attention to hazards.

Regarding all 35 hazardous conditions (all AOIs), on average, 33% of subjects who did not recognize and report the hazards within the scenes showed attentional failure, indicating they did not allocate their attentional resources to the hazards. This result indicates that the workers in this group may need to be trained regarding effective search strategies and proper attentional allocation.

Type 2 Failures: Inattentional Blindness, Risk Perception, and Failing to Recognize Hazards

Further investigation showed that subjects may look at a hazard (i.e., allocate their visual attentional resources to a hazardous area more than other AOIs) but still not recognize or report the hazard. These Type 2 failures take the form of either failed risk perception—wherein workers do not accurately perceive hazards as risk conditions due to high-risk tolerance—or

inattentional blindness—wherein workers do not notice a visual object due to a lack of active attention within the dynamic environment. On average, 67% of subjects who did not identify and report the hazards within the scene demonstrate these Type 2 failures.

Table 5 depicts data regarding hazardous scenarios that workers failed to identify even if they looked at the hazards (Fig. 5). Among the 35 hazardous conditions, seven hazards—including housekeeping (e.g., area not blocked off), missing PPE (e.g., missing eye protection), fall (e.g., hanging more than half of the body outside of the building), and struck-by (e.g., not using tagline)—were found as representative cases of failed risk perception or of inattentional blindness. For these scenarios, all subjects who failed to identify these hazards allocated their visual attention to the hazardous conditions, indicative of Type 2 failures.

One of the scenarios is presented in this section for further discussion. In this scenario, two workers were standing closely or passing by a lift (Fig. 6) while a worker performed a task on the lift. The lift area was not blocked off—the main safety concern that directly and indirectly impacted the other hazards within the scene. In addition, neither workers in the scene paid attention to the lift (and the hazards associated with the task) but instead were busy with their cell phones while they were in the unmarked unsafe zone [Fig. 6(a); AOIs 2 and 3]. These four AOIs—the unblocked area, the distracted Worker 1 on the phone 1, the distracted Worker 2 on the phone, and the worker leaning on the guardrail—each represents a hazard in this 360-video scenario.

Table 6 illustrates the descriptive and inferential statistics for the attentional distribution of the tested subjects presented with this scenario. The results of Kruskal-Wallis tests indicate that there were

Table 5. Extracted cases representing inattention blindness and misperceived risk as precursors of low hazard identification

AOIs	Number of subjects did not recognize AOIs	Number of subjects saw AOIs	Percentage (%)	Hazard type	Nature of hazards
Area not blocked off	24	24	100	Housekeeping	Static
Eye protection missing	23	23	100	Missing PPE	Dynamic
Exposed to window hanging over body	22	22	100	Struck by	Dynamic
Missing PPE for chemical	22	22	100	Missing PPE	Dynamic
Hanging over the building	21	21	100	Fall hazard	Dynamic
Employee not using proper ladder access	17	17	100	Housekeeping	Dynamic
Employee not using tagline	14	14	100	Struck by	Dynamic

Note: Percentage (%): number of subjects saw AOIs/number of subjects did not recognize AOIs.



(a)



(b)

Fig. 6. Example of 360-video construction scenarios with associated AOIs: (a) area of interests and associated description: 1 = area not blocked off; 2 = distracted on phone 1; 3 = distracted on phone 2; and 4 = leaning on guardrail; and (b) movement of worker in the video.

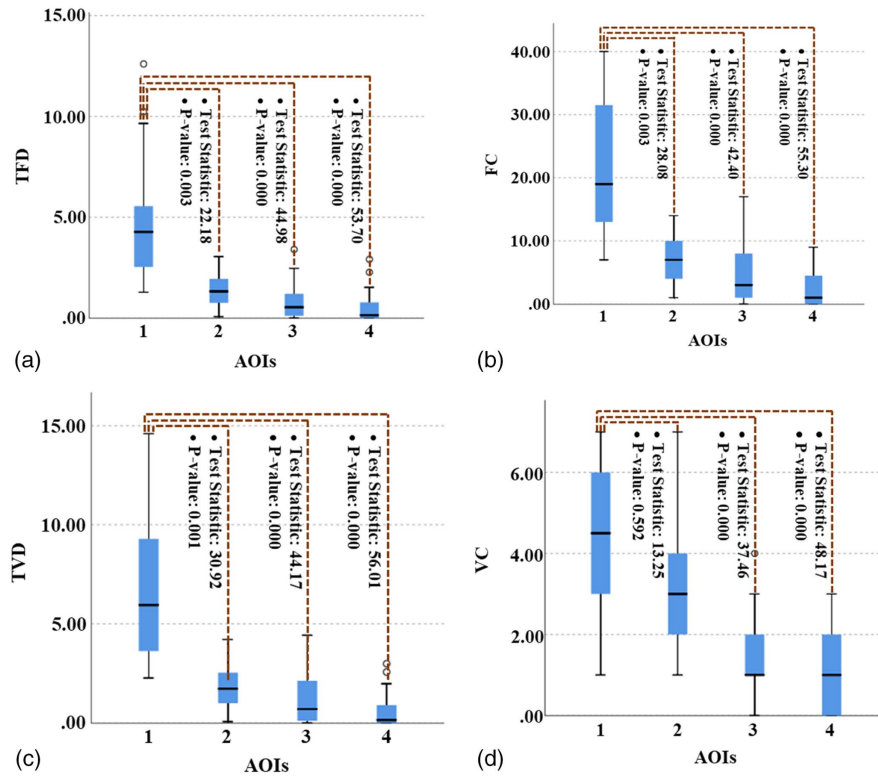
significant differences in attentional allocation metrics among the various hazards within the scenario (AOIs) ($p_{TFD} = 0.000$, $p_{FC} = 0.000$, $p_{TVD} = 0.000$, $p_{VC} = 0.000$) (see Table 6).

The pairwise comparison analyses (Fig. 7) indicate that workers spent significantly more time exploring the AOI_1 (area not blocked off) than other AOIs ($t_{TFD_1-2} = 22.18$, $p_{TFD_1-2} = 0.003$;

$t_{TFD_1-3} = 44.98$, $p_{TFD_1-3} = 0.000$; $t_{TFD_1-4} = 53.70$, $p_{TFD_1-4} = 0.000$) ($t_{TVD_1-2} = 30.92$, $p_{TVD_1-2} = 0.001$; $t_{TVD_1-3} = 44.17$, $p_{TVD_1-3} = 0.000$; $t_{TVD_1-4} = 56.01$, $p_{TVD_1-4} = 0.000$). Furthermore, subjects brought their attention back more frequently to AOI_1 as compared to the other AOIs ($t_{VC_1-2} = 13.25$, $p_{VC_1-2} = 0.592$; $t_{VC_1-3} = 37.46$, $p_{VC_1-3} = 0.000$; $t_{VC_1-4} = 48.17$,

Table 6. Statistical results of comparing attentional measures toward the studied scenario

Eye-tracking metrics	Stat measures	AOIs in Fig. 6(a)			
		1: area not blocked off	2: distracted on phone ₁	3: distracted on phone ₂	4: leaning on guardrail
Total fixation duration	Mean	4.71	1.46	0.82	0.54
	SD	2.82	0.89	0.93	0.78
	Test statistic	54.637 ^a	—	—	—
	<i>p</i> -value	0.000 [*]	—	—	—
Fixation count	Mean	21.50	7.50	5.04	2.44
	SD	10.11	3.71	5.22	3.14
	Test statistic	55.614 ^a	—	—	—
	<i>p</i> -value	0.000 ^a	—	—	—
Total visit duration	Mean	6.67	1.83	1.23	0.62
	SD	3.62	1.04	1.33	0.85
	Test statistic	57.213 ^a	—	—	—
	<i>p</i> -value	0.000 [*]	—	—	—
Visit count	Mean	4.33	3.23	1.55	0.93
	SD	1.61	1.69	1.14	0.99
	Test statistic	48.595 ^a	—	—	—
	<i>p</i> -value	0.000 [*]	—	—	—

Note: ^{*} $p < 0.05$.^aKruskal-Wallis Test.**Fig. 7.** Summary of pairwise comparisons of AOIs in the scenario depicted in Fig. 6. Visual attention measures used are (a) total fixation duration; (b) fixation count; (c) total visit duration; and (d) visit count. AOIs are: 1 = area not blocked off; 2 = distracted on phone 1; 3 = distracted on phone 2; and 4 = leaning on guardrail.

$p_{VC,1-4} = 0.000$). Although subjects showed significantly higher values in their four eye-tracking metrics regarding AOI_1, 83% (24 out of 29) of subjects failed to identify the hazard [Fig. 6(a)]. Additionally, despite the excessive fixations on AOI_1, only five subjects correctly recognized this hazard. These results demonstrate that perceiving hazards is the critical part of the hazard identification process, not merely seeing the hazards.

Discussion

Role of Anticipatory Cues in Hazard Identification Performance

To consider the role of hazard anticipation in construction safety, this study investigates workers' hazard identification performance

for dynamic versus static hazards to determine which types of failures cause workers to miss or misperceive hazards. As hazard recognition is the first step toward continuing situational awareness when working in dynamic and dangerous environments requiring selective attention to hazards (Hasanzadeh et al. 2017a, 2018), to properly understand a worker's true hazard identification capabilities and the corresponding reasons affecting hazard identification performance, several factors—such as experimental design and human cognitive processes—should be carefully considered.

The results here show that workers perform differently when identifying static and dynamic hazards—especially in terms of identifying or missing dynamic hazards—and the authors posit that the reason behind this divergent performance relates to the workers' anticipatory skills and how workers identify and perceive foreshadowing cues corresponding to dynamic hazards. Hazard anticipation is strongly connected to situational awareness (Endsley 1995). Because construction sites are very dynamic and complex (Sacks et al. 2009), each dynamic hazard can easily switch from potential to active and from active to potential (Hasanzadeh et al. 2017b, 2019). Therefore, workers must continuously check the condition of hazards and their cues to remain safe.

As discussed in the background section, target cues refer to environmental factors that directly trigger the upcoming action of the participant, while context cues just attract attention to a specific event [Figs. 8(a and b)]. In accord with driving-safety-related studies (e.g., Mühl and Baumann 2018), this study supports the importance of target cues. In particular, in the studied scenarios, target cues manifested in AOIs that signaled those worker's behaviors or ongoing tasks that may lead to high-risk situations (e.g., tossing material off scaffolds, overreaching while on a ladder). Subjects who allocated their attention to the target cues were able to anticipate the potential hazard, maintain their attention toward the potential hazardous area where the hazard may emerge, and ultimately were able to identify (and report) the emerging struck-by hazard. Such abilities indicate appropriate hazard anticipation relevant to situational awareness for dynamic hazards.

On the other hand, context cues refer to environmental elements that only require attention—not behavioral changes—to monitor potential risks [Fig. 8(c)]. Because these cues do not require immediate actions or safe behaviors, workers may overlook and fail to recognize these hazards (97% of subjects missed this hazard). Practically, the implication for training is to rely on both target and context cues at construction jobsites and to improve workers'

search strategies to identify these cues, predict the changes in the near future, and remain situationally aware.

The results here underscore prior studies' discussions regarding how the perception of situational cues provides the prerequisite for the creation of assumptions of future behavior, which refer to the anticipation of dynamic conditions (Mühl and Baumann 2018). Accordingly, when workers perceive hazardous cues, this perception activates existing safety-related knowledge from long-term memory (Baumann and Krems 2007), which promotes selective and focused sensory processing and reduces the number of unsafe behavioral repertoires (Carlsson et al. 2000). Driving safety-related studies revealed that experienced drivers show efficient visual search behaviors, with higher glance rates toward and longer times (as a percentage) fixating on anticipatory cues as compared to novice drivers (He and Donmez 2022; Stahl et al. 2019). These results suggest that driving experience is highly connected to drivers' visual scanning and anticipation ability, and drivers will naturally improve their cognitive performance. Because experienced drivers can easily imagine future conditions related to different traffic signs, they may know exactly where they need to look, whereas novice drivers may not have prior knowledge to shape their search behaviors. While these driving-related findings are important, construction sites are generally more complex and often do not include many informative signs. Accordingly, workers are required to deduce future situations solely based on their observation of the surrounding environment. It is critical to understand how the characteristics of hazards influence workers' hazard identification process.

Therefore, anticipatory cues are significantly important for accurate hazard identification and activation of safe behavior (Guo et al. 2020). The importance of this hazard anticipation skill is emphasized on construction jobsites, where the dynamic hazards might switch between active to potential/emerging and vice-versa. Especially for emerging or latent hazards, allocating proper attention to cues is crucial to continuously check the surrounding environment, identifying additional anticipatory cues, and predicting potential hazards. Our results show a difference in such anticipatory attention and perception behaviors among workers, particularly between dynamic and static hazards.

Path toward Personalized Safety Training Based on Worker Cognitive Failures

Previous studies have shown that a large number of hazards remain unrecognized because of the dynamic nature of construction sites



Fig. 8. Example of target and context cues captured from 360 video-based scenarios: (a) tossing material off the scaffold (Struck by Hazard/Target cue); (b) reaching out of the side of the plane (Fall Hazard/Target cue); and (c) tape marking (Struck-by Hazard/Context cue).

and the inspector's limited knowledge and experience (Albert et al. 2014; Mitropoulos et al. 2005; Pinto et al. 2011). Unidentified hazards have been reported as the primary factor resulting in accidents on construction jobsites (Bohm and Harris 2010; Choudhry et al. 2007a, b; Kim et al. 2017). In fact, one study indicated that about 57% of construction hazards remain unidentified on the jobsite (Liao et al. 2021), leaving the state of practice to suggest construction workers should improve their hazard identification ability (Eiris et al. 2018; Xu et al. 2019b). Accordingly, the construction industry and researchers have investigated numerous resources to develop better safety training.

Despite such efforts, studies show—and our findings confirm—that workers who received considerable safety training still may not be able to recognize all hazards within the scene (Chu et al. 2013). Traditionally, the lack of safety knowledge and skill has been accepted as the primary causal factor for the poor hazard recognition ability. However, one study identified 13 elements connected to poor hazard recognition, and lack of safety knowledge only related to one factor (Jeelani et al. 2017). In addition, it was also found that workers generally considered safety training as a mandatory requirement, without self-motivation (Xu et al. 2019c).

As current underperforming safety training focuses on transferring safety knowledge without considering specific challenges or characteristics affecting individuals' hazard recognition skills, researchers have begun investigating various features within safety training, such as training format (Bükrü et al. 2020; Eiris et al. 2018, 2021), identification of key elements related to low-hazard identification performance (Jeelani et al. 2017), personalization (Xu et al. 2019b), and worker's learning ability (Xu et al. 2019c) to determine better pathways toward improved safety training. Among these efforts, personalized training recently started to receive attention as the next generation of safety training.

Compared to general safety training, personalized training includes the assessment of an individual's cognitive processes and abilities and of their behaviors to diagnose specific challenges that workers experience at the jobsite. Based on the analyzed data, the training program can be modified or designed to improve workers' hazard recognition performance effectively. For example, Xu's study argued that workers' learning abilities during safety training varied, so the study developed a learner model that could capture and evaluate individual workers' cognitive capabilities and learning abilities (Xu et al. 2019c). Further, some studies showed the feasibility of using computer vision technology to automatically capture and analyze workers' visual search patterns, which could in turn, indicate unidentified hazards in the surrounding environment, a factor that may serve as the baseline for future personalized training programs.

Insights for Future Safety Training Pathways

This study finds various indicators related to cognitive processing failures that also provide insights for future training pathways to improve hazard identification. In particular, several participants failed to allocate their visual attention to some hazards, and as a result, they were not able to identify the hazards. This Type 1 cognitive failure was caused because of the worker's (1) low motivation toward searching the experiment, discussed subsequently; and (2) low situational awareness, evidenced by the participant's search strategy.

Motivation is one of the common limitations of human subject experiments because it is inevitable some subjects do not approach the experimental processes seriously. In the construction safety arena, it has been shown that mindfulness, personality, and attitude have a relationship with an individual's safety and work performance

(Solomon and Esmaili 2020). While most of the workers who participated in this study expressed their high sense of presence in the experiment, some participants in this study may not have bought into the usefulness of safety-related experiments or training and therefore may have manifested low motivation during the experiment. Due to this problem, they may not have distributed their attention toward various hazardous areas in the video.

Secondly, low situational awareness and inappropriate search strategies may be another reason for this Type 1 failure result (Hasanzadeh et al. 2017a). The group with lower performance often overfixated only on small regions or did not adequately distribute their attention across the scene to identify potential hazards. Fig. 9 shows an example of visual search strategies of a participant who had a relatively low situational awareness. As shown, there are four hazards (AOIs) within this scenario. The worker's visual attention data—a scan path representing the time sequence of their visual scanning—indicated that the worker primarily focused on the central part of the scenario and did not widely or properly explore the scene to identify hazards. Accordingly, the subject failed to recognize a displaced handrail and a noncompliant ladder access, both visible in the side regions of the image.

Fig. 10 shows four hazards (AOIs) within the scenario alongside the gaze plot of the subject who had a more efficient search strategy. Compared with the previous subject, this participant properly distributed his attention across the scene to identify different hazards, identify anticipatory cues, predict future risk, and continuously check active tasks with potential risks. Although the subject showed remarkably better visual search strategies, he did not see AOI_IV even one time. This result may occur because of safety knowledge. For instance, workers may not know why this

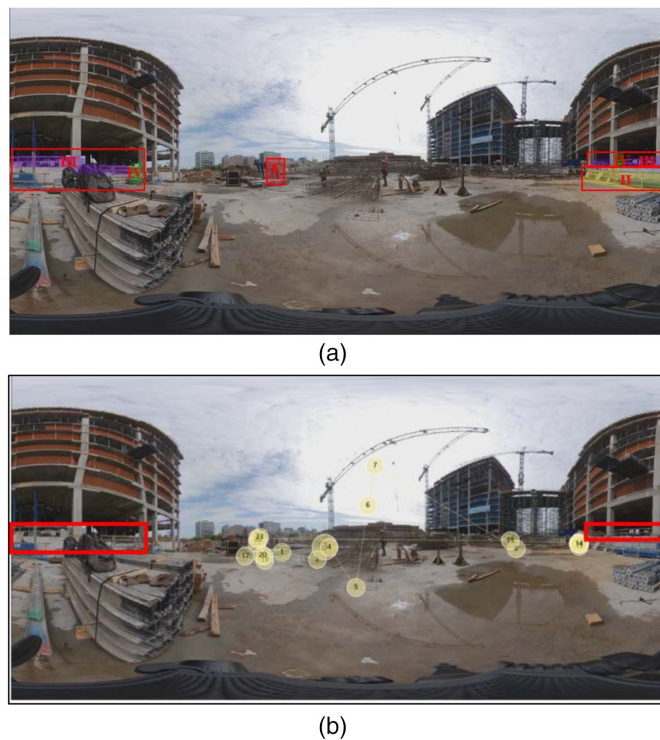


Fig. 9. Example of inefficient visual search strategy of a worker who failed to identify hazards in (a) original picture; and (b) original picture overlaid with subject's inefficient scanpath. AOIs are: I = employee is not using proper ladder access; II = access blocked on-ramp to ladder; III = handrail displaced; and IV = no-compliant ladder access.

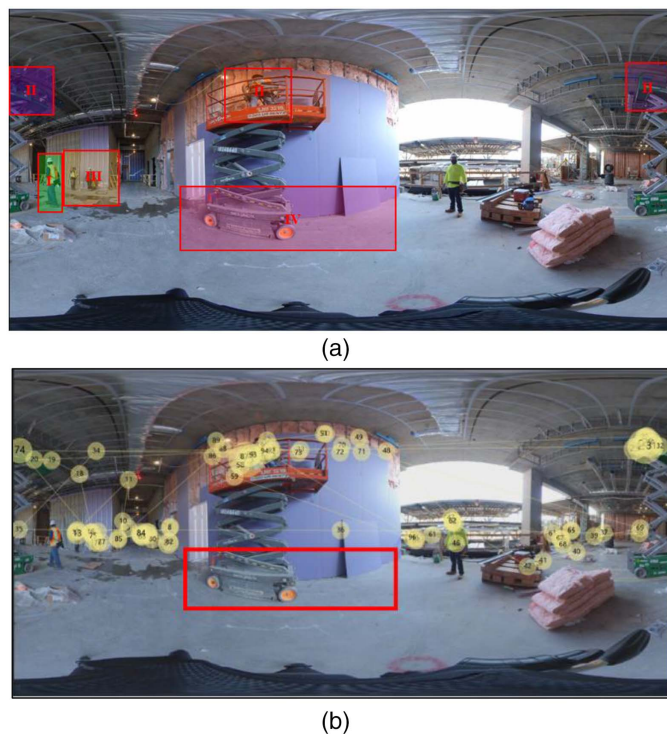


Fig. 10. Scanpath of a worker who had more efficient search strategy in (a) original picture; and (b) original picture with worker more efficient scanpath. AOIs are: I = worker passing lift area without paying attention; II = check arrest system; III = no fire protection; and IV = no tape marking.

AOI is hazardous because there are no ongoing tasks or other workers in the vicinity.

Because there are varied reasons that cause the failure of attentional distribution, this finding suggests the necessity of personalized construction safety training developed based on the individual's actual limitations and needs instead of general construction safety training, which is often designed based on broad, higher-level knowledge. It must be noted that all participants previously received multiple on-site safety trainings, which further highlights the need for more personalized training targeting the needs and limitations of at-risk workers. For example, the participant whose scanpath is depicted in Fig. 9 needs to improve their situational awareness to properly distribute his visual attention across the scene.

Moreover, some subjects fixated on specific AOIs significantly more frequently and for longer duration than other AOIs in the same scenario while failing to recognize the hazard. This result may be explained by inattention blindness. Inattention blindness generally occurs when the workers cannot identify hazards because their attention was engaged on another task, event, or object, even if they fixated on specific hazards. Park's study previously reported that inattention blindness accounted for 50% of the failures within their study of safety risk perception (Park et al. 2022). Thus, inattention blindness can be one of the primary reasons for the results in Table 5 (the failure of risk perception). These findings highlight the need to develop a multimodal hazard identification assessment to obtain and study subjective and objective data from workers.

Based on the abovementioned findings, the research team proposes various training strategies for future personalized training development. In particular, as shown in Table 7, different training approaches for three cognitive failures (i.e., attentional failure,

Table 7. Workers' cognitive failures, causes, and proposed training strategies

Cognitive failures	Causes	Proposed training strategies
Attentional failure	Lack of knowledge	Hazard awareness training: train for missed and unrecognized hazards, the consequences, and prevention measures
	Inefficient search strategy	Visual scanning and cue training: train to implement efficient visual search strategies
Inattention blindness	Lack of knowledge	Hazard awareness training: train regarding missed and unrecognized hazards, focusing on the consequences, and prevention measures
	Improper use of limited attentional resources	Inattention blindness training: train to understand the limits of attention, allocate attention properly throughout the scene, remain mindful, and avoid premature search termination
Low perceived risk	High-risk tolerance or risk propensity	Risk perception training: raise awareness regarding risk (costs) associated with missed and unrecognized hazard

inattention blindness, and low perceived risk) are recommended. For the case of attentional failure, which can occur due to a lack of safety knowledge or an inefficient visual search pattern, hazard awareness training as well as visual scanning and cue training can be incorporated to improve workers' search strategies by providing expert feedback and an efficient visual scanning pattern. Managers can address inattention blindness by enhancing workers' ability to manage their limited attentional capacity and allocate attention properly throughout the environment. Lastly, for workers with low risk-perception, training could emphasize the risks (losses) associated with missed hazards and the potential consequences of low risk-perception to increase the internal cost-benefit analysis these at-risk workers perform. The specificity of these training suggestions clearly shows the opportunity of varying training strategies based on the individual cognitive failures impacting a specific worker.

Ecological Validity of 360-Degree Panoramas

Selecting the correct delivery method that can closely simulate the real-world hazardous environment is necessary. This suggestion aligns with the ecological validity perspective, highlighting the impact of the experimental setting on the subject's behavior and cognitive process (Holleman et al. 2020). Liao et al.'s recent study argued that the reduction of dimensionality may cause an oversimplistic representation of hazardous conditions and may distort information. Due to this distortion, the outcome of the experiment can have a bias, and recorded participants' behavior may not be the same as the real pattern (Liao et al. 2021). As the primary goal of a hazard identification study is to investigate construction workers' cognitive process and naturalistic behavior, studies in this area should consider enhancing ecological validity by authentically mimicking dynamic and complex construction environments. Most of previous studies employed image-based hazard identification tests that cannot represent how the hazard will be perceived on construction sites; specially due to dimensionality reduction, information shrinkage, lack of environmental modalities (e.g., noise), and

inability to demonstrate changes and movements. Due to the recent technological advancements, various test formats (e.g., virtual reality and 360 panoramic) can be utilized to develop ecologically valid hazard identification tests. Therefore, this study adopted 360° videos in a VR head-mounted display to provide an immersive and realistic environment that relied on actual recordings of the job site, demonstrating one of the highest ecological validities that can be potentially used in future hazard recognition assessment and training activities.

Conclusion

Under various immersive, dynamic hazardous scenarios, this study assessed construction worker hazard anticipation, hazard recognition performance, and visual search strategies to decipher whether workers treat dynamic hazards differently than static hazards. The results revealed that workers' hazard identification performance was predominantly affected by the dynamic and/or static nature of the hazards, rather than by the hazards' type. Specifically, in dynamic jobsites—represented by our study's dynamic visual scenarios—workers anticipated and/or recognized emerging or latent hazards by visually processing target and context anticipatory cues.

Furthermore, workers may experience cognitive failures at various stages (attention or perception stage), which affects their search patterns and hazard recognition performance. The eye-tracking data of participants who failed in the attention stage (Type 1 failures) show that they did not properly allocate their attentional resources to scan the scene and its hazardous areas, which is explained by low motivation and low situational awareness, and/or inefficient search strategies. On the other hand, other workers failed in the perception stage (Type 2 failures), because they properly allocated their attention toward the surrounding environment and fixated on hazards but failed to perceive hazards as threats due to inattentional blindness.

While there are many studies related to assessing various factors associated with hazard identification ability, none has targeted the reason behind workers' various cognitive limitations and the influence the nature of construction hazards has on hazard recognition performance. In addition, worker's hazard anticipation abilities have often been neglected in previous studies. Therefore, this study contributes a fundamental understanding of workers' anticipation abilities and cognitive limitations and highlights the necessity to develop personalized safety training to improve workers' safety performance in dynamic jobsites. Furthermore, this study provides insights as to the ecological validity of 360-videos for assessing workers' hazard identification performance, since videos enable depicting the dynamic nature of the jobsite to examine whether a worker allocates sufficient attention to anticipatory cues.

Despite these considerable contributions, some limitations need to be noted. First, this paper mainly focused on subjective and objective measures of hazard anticipation and detection; further risk-perception related assessment can be used in future studies to obtain a comprehensive overview of workers' situational awareness. Further, this study did not compare the 360-video techniques with 360-images, VR-related, or other types of safety assessment. Future research can expand on the ecological validity and compare hazard detection performance in different simulated and actual construction environments.

In sum, the findings here enhance understandings of workers' cognitive processes regarding the anticipation and identification of dynamic construction hazards within construction environments. Such findings provide insights into the importance of

(1) improving worker hazard anticipation skills in dynamic jobsites, and (2) developing real-time personalized safety training to target cognitive failures at the attention and/or perception stage. Researchers can use these findings to better design and assess training approaches to improve worker safety. Practitioners can use these findings to support workers in identifying the anticipatory cues necessary to recognize and address dynamic hazards. Together, such contributions will help support workers' safety outcomes in the near and long term.

Data Availability Statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

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