Toward Personalized Safety Training: Automating the Classification of Construction Workers' Cognitive Failures

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Abstract –

Safety training has long been considered a promising method to enhance workers' hazard identification skills within construction sites. To improve the effectiveness of safety training, such varied features as a training environment, individuals' learning ability, and lesson personalization have been investigated. However, as records show workers still miss hazards even after receiving safety training, understanding the fundamental cognitive reasons for unrecognized hazards becomes a crucial step toward developing effective personalized safety training. This study used various 360° panoramas of construction scenarios to empirically examine 30 workers' visual search strategies and assess workers' hazard identification skills. Results suggest several cognitive limitations caused failures in hazard recognition, including attentional failure, inattentional blindness, and low perceived risk. Based on these findings, this study proposes a personalized safety training framework to address such cognitive limitations to improve occupational safety in the construction industry.

Keywords –

Hazard identification; Construction safety; Cognitive failures; Personalized safety training; Attentional failure; Inattentional blindness; Risk Perception

1 Introduction

Given over 1,000 recent fatal injuries in the construction industry in the U.S. [1], researchers have been trying to improve workers' hazard identification abilities to avoid injuries [2,3]. A promising approach to counteracting injuries is to provide effective safety training to enhance workers' hazard recognition performance [4]. Previous studies revealed that workers often missed hazards in their surrounding environment due to different cognitive limitations (e.g., failed attention [5], flawed risk perception [6,7]). Thus, to properly identify hazardous conditions within a dynamic construction environment, workers need to appropriately detect hazards and perceive them as risks [3], and training programs should address failures affecting this skill set. However, safety training has neither comprehensively covered these various cognitive limitations nor proven capable of customizing training per the cognitive failures of individual workers.

This study uses eye-tracking technologies to identify the types of cognitive failures affecting construction workers' safety and thereby recommend opportunities for automating personalized safety training. This study contributes to the body of knowledge and practice by proposing an advanced personalized safety training framework that can automatically translate workers' subjective test results and objective psychophysiological responses into personalized training recommendations. The outcomes of this paper will lay the necessary foundations required to build tailored training regimens to improve construction worker safety.

2 Background

2.1 Assessing Construction Workers' Cognitive Limitations via Eye-tracking Technology

Identifying hazardous situations in dynamic construction environments is a complex cognitive process. Advanced sensing technologies (e.g., electroencephalograms, eye-tracking) have been actively utilized in several studies to evaluate human cognitive processes and safety-related behaviors under hazardous conditions [3,8]. Among these sensors, eye trackers have been widely used to assess workers' cognitive failures and low–hazard identification skills because eye-movement data represent the most direct manifestation of visual attention [9,10].

In a study conducted by Hasanzadeh and her colleagues [3], three fixation-related metrics (i.e., fixation count, dwell-time percentage, and run count) were utilized to predict workers' hazard identification skills. The results indicated that hazard recognition skills remarkably affect workers' visual scanning patterns. For instance, workers with higher hazard identification skills showed higher fixation counts and run counts, and lower dwell-time percentages on various hazard types. Accordingly, eye-tracking technology provides considerable opportunities for assessing workers' different attentional distributions and for predicting cognitive failures.

2.2 Personalizing Safety Training

Researchers have investigated various aspects of safety training, such as training format [4,11,12] and workers' learning ability [13]. Among these efforts, personalized training recently received attention as the next generation of safety training [13]. Compared to traditional safety training, personalized training aims to include the assessment of individuals' differences and their resulting decisions when exposed to assorted risks on a jobsite [14]. For example, Xu et al.'s study argued that workers' learning abilities during the safety training varied, which led the study to develop a learner model that could capture and evaluate individual workers' cognitive capabilities and learning abilities [13]. Further, some studies showed the feasibility of automatically capturing and analyzing workers' visual search patterns [15]. While many studies theoretically discussed the importance of developing personalized safety training, no studies empirically develop a training framework to address these cognitive limitations.

To develop personalized safety training, it is essential to understand the reason for cognitive failures and select an appropriate training approach to counteract the problem. For instance, if someone has a poor visual search strategy, showing an expert's visual search path—which has been used among marines and radiologists to enhance visual search strategies—could function as a suitable training approach [16]. Incorporating such a design can address unrecognized hazards and promote the development of more effective personalized training.

3 Research Method

To identify the types of cognitive failures impacting construction workers' safety and thereby recommend opportunities for automating personalized safety training, this study conducted a hazard identification experiment presenting videos of a realistic construction environment to monitor subjects' visual behaviors. To create realistic scenarios able to capture the complexity and dynamics within a construction experiment, the design used several 360° video panoramas captured using an Insta360 OneX camera. The scenarios covered various construction activities (e.g., painting, erecting the structure, installing HVAC, and welding) and were recorded at commercial construction sites in Washington D.C. and northern Virginia to include different static and dynamic hazards of varying risk. Professional safety managers carefully reviewed all video scenarios in advance and identified hazards within each scenario.

For this study, the research team recruited thirty

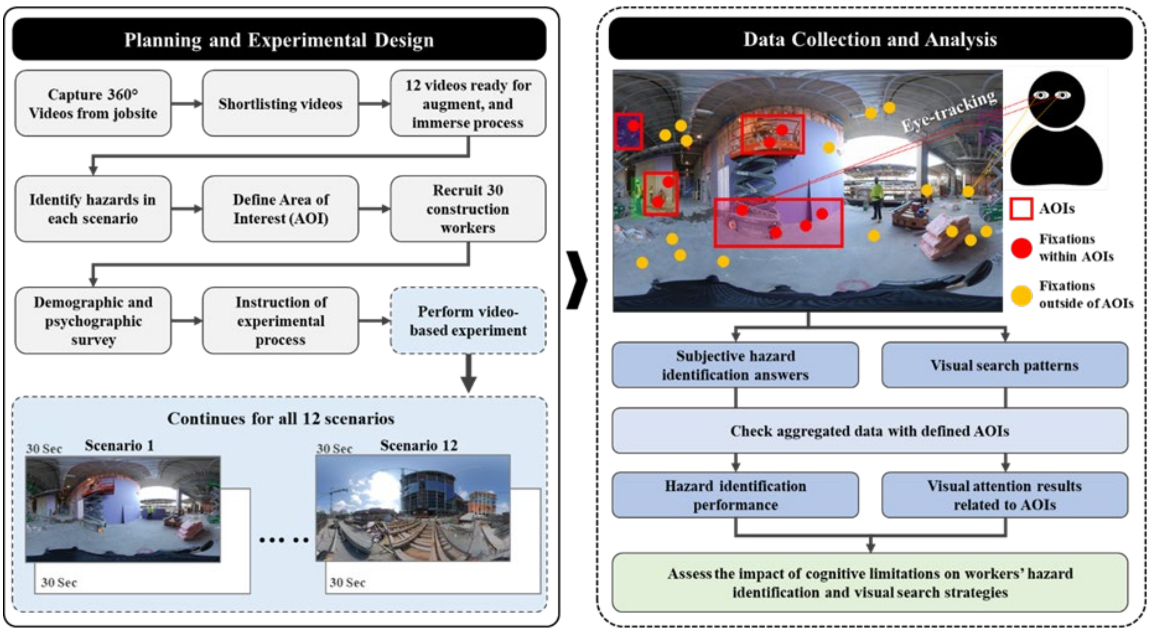


Figure 1. Research framework

experienced construction workers (29 males, 1 female; aged 34.5±10.6 years) from jobsites to collect realistic behavioral data. The participants had, on average, 8.5 years of experience, and all had received multiple safety trainings before. Each participant performed a single 60-minute session, which was delivered via the HTC VIVE Pro Eye head-mounted display. While the participants were searching for hazards in each scenario, their visual scanning patterns were captured using eye-tracking sensors embedded in HMD. In total, workers were asked to view twelve scenarios for thirty seconds, and then report the types of hazards they recognized in each scenario (Figure 1).

To analyze the subjects' resulting eye-tracking data, the research team marked multiple areas of interest (AOIs) which were predefined by safety professionals. AOIs are the boundary range of the hazardous regions in the scenarios; in this paper, analysis focuses on two major hazard categories (fall, and struck-by), though the results reflect additional findings not detailed at this time. The research team mapped subjects' fixation points on static and dynamic AOIs using image processing algorithms. Those AOIs that did not receive fixations were deemed "attentional distribution failures" whereas those AOIs that had fixations were deemed either "recognized" or "risk-perception failures" based on whether subjects self-reported identifying the hazard. Additionally, spatial attention proportion is calculated when fixation points are within the AOIs boundaries to the total number of fixation points in the entire scene. Then, by coupling the eye-tracking data with workers' self-reported hazard identification results, the research team classified the cognitive reasons behind the unrecognized hazards. The contrasts between the empirical (eye-tracking) results and subjective (self-reporting) results were then analyzed to identify training opportunities.

4 Results and Findings

Figure 2 indicates the average cause-specific rate of hazard identification failures—e.g., those caused by failed attentional distribution or those caused by failed risk perception—for all hazards and the two main hazard categories detailed in this paper. Generally, more than half of hazards remained *unrecognized* even when the worker allocated considerable attentional resources to those hazardous areas, which indicates that the worker either experienced *inattentional blindness* or *did not perceive the risk* of hazards within the scene due to high-risk tolerance or lack of knowledge. On average, 43% of workers who failed to identify fall hazards illustrated inefficient visual search strategies and improper attentional allocation for fall hazards. Additionally, on average, 67% of struck-by hazards remained unrecognized because subjects failed to identify the hazardous conditions as risks, even if they allocated sufficient attentional resources to those hazards. The remaining 33% of failed struck-by identifications were hazards completely missed by workers who did not properly distribute their visual attention to struck-by hazards. These results clearly illustrate that workers missed identifying hazards due to various cognitive failures and raise the necessity of various training approaches that rely on targeted problems.

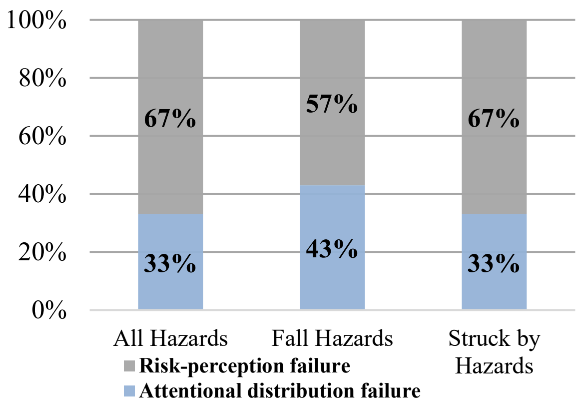


Figure 2. Average cause-specific rate of hazard identification failures

Figure 3 depicts a scenario that was selected for further investigations. In this scenario, two scissor lifts provide work platforms for workers installing wall panels and an HVAC system. In addition to the operators being at fall risk while working at height (Figure 3, *d* and *e*), workers on the ground were also at risk due to struck-by hazards from the elevated work platforms; workers on the ground would need to be aware of their surroundings and avoid working in close proximity to the lift or passing underneath it when it is raised (marked area, Figure 3, *c* and *f*) because they might get injured or killed by objects falling from the lifts or may be struck by the lift itself. At one point during the video, a worker entered the work zone (see AOI *a* in Figure 3) and passed underneath (marked areas) without checking the status of the lifts' position and without attending to the workers operating the lifts to avoid any potential struck-by hazards. In this scenario, there were also few workers performing a welding task without fire protection (Figure 3, *b*). Due to the spatial arrangement of the camera, fixations on this fire hazard (AOI *b*) overlapped with AOI *a* for a short period, a point we discuss below.

The subjective, self-reported hazard identification results show that 87% of participants (26 out of 30) failed to identify the dynamic hazard (Figure 3, AOI *a*). In these cases, the research team investigated how the subject's spatial attention was distributed over the scene—a factor in situational awareness theory [17]—to explore which

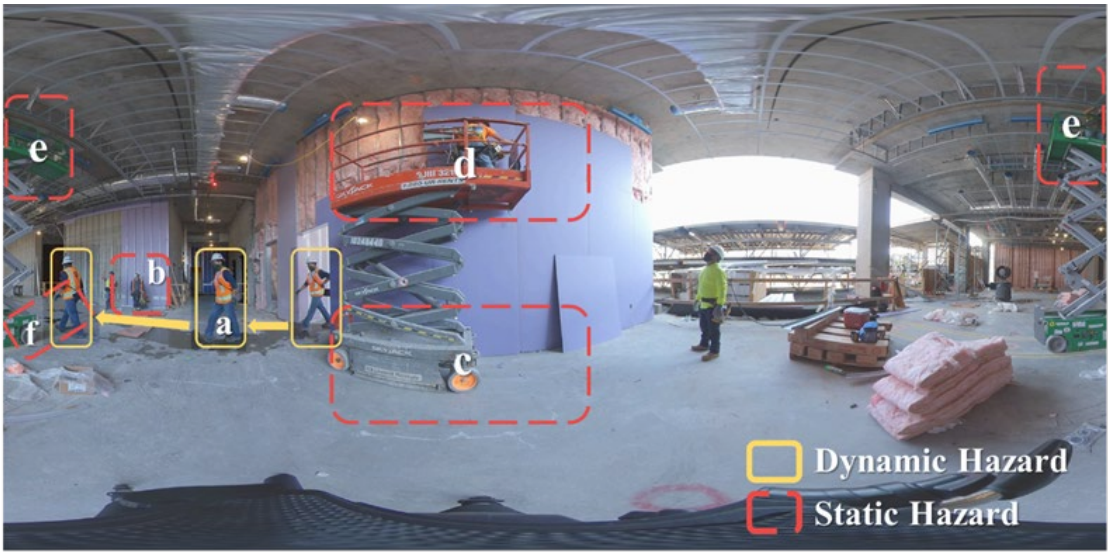


Figure 3. A representative example of a 360° video construction scenario with associated AOIs (Dynamic hazard: *a*, and Static hazard: *b, c, d, e, f*)

of three causal factors accounted for the failed identification (i.e., inappropriate attentional distribution, inattentional blindness, and lack of safety knowledge/low perceived risk). Figure 4 shows the cumulated attentional allocation (the dots represent fixation points) for all 26 participants who missed the hazard and grouped based on the cognitive challenges observed. Note: these coordinate data were extracted for the period where AOI *a* was activated.

The results indicate that 52% of subjects (Figure 4a) did not appropriately allocate their attention across the scene to recognize hazards, and therefore they failed to identify hazards. Interestingly, only 2% of their spatial attentional resources were allocated to the dynamic AOI *a*, whereas most of their fixations were on other static hazards or environmental objects. Such *inappropriately distributed attentional resources* may be counteracted through training in situational awareness, and therefore represent a way the observed eye-tracking data could provide an opportunity for improved personalized training.

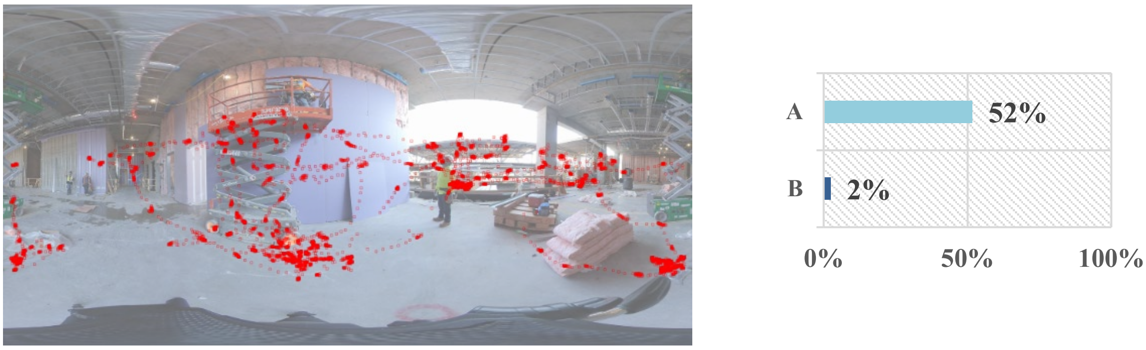
Furthermore, the results show that 20% of subjects failed to identify the potential struck-by hazard (AOI *a*) due to inattentional blindness (Figure 4b). Overall, these participants allocated 32% of their attentional resources toward the area related to AOI *a,* where the worker passed underneath the two active lifts (Figure 4b), but the subjects failed to name this hazard, an indicator of *inattentional blindness*. Such blindness may manifest when the cumulative attentional distribution map demonstrates that although a subject pays close attention to an AOI—and even brings attention back to it several times—the subject never “sees” the risky behavior and does not report the hazard in the follow-up oral report. Alternatively, workers may not “see” what they are directly looking at because they are attending to something else within the same environment (e.g., welding without fire protection). In either case, inattentional blindness appears in the data when a subject fails to perceive a clearly visible stimulus (AOI *a*) located exactly where she/he is looking (fixating), and thereby represent an opportunity for automating personalized training.

Lastly, 28% of workers failed to identify AOI *a* despite a relatively efficient visual search strategy compared to the other two groups. Specifically, these subjects distributed 60% of their spatial attentional resources within the target boundary (Figure 4c), but they still failed to identify the hazards involved in this space. Such results indicate that this group of subjects may need a different training approach to target their *knowledge level* or *risk perception skills*.

These three cognitive-failure based causes for failed hazard identification represent opportunities for personalizing safety training based on workers’ true limitations. Figure 4 contrasts the differences in eye-tracking data between the different groups’ behaviors, revealing an inroad for automating this personalization process to improve the safety levels at jobsite. In the next section, based on these findings, this study proposes the framework of personalized safety training.

4.1 Personalized Safety Training Framework

As illustrated in Figure 5, this study proposes an advanced personalized safety training framework



(a) Inappropriate attentional distribution

(b) Inattentional blindness

(c) Lack of safety knowledge or low perceived risk

Figure 4. Cumulative attentional distribution for each discussed cognitive limitations A: Percent of workers who failed to identify hazard *a* due to associated causal reason, and B: Spatial attention proportion distributed to the related hazard "*a*" over total fixation counts across the scene

consisting of three main stages: primary setup, assessment, and customized training. The proposed training adopts various advanced technologies (e.g., 360° panoramas, eye-tracking, wearable sensors, and artificial intelligence) to present realistic hazardous scenarios, assess workers' visual search strategies, identify their risk-perception state, and classify individual's true cognitive challenges necessitating improvement. Such a training platform could be designed in two versions: (1) desktop and (2) virtual reality delivered via VR headset to provide an immersive education experience.

During the assessment step, workers will be immersed with 360° video and images and be asked to scan the scene while their neuro-psychophysiological responses are being continuously collected to obtain information regarding the worker's attentional distribution, risk perception, and decision dynamics. Then, the workers will be presented with a quiz to assess their hazard identification performance. Like eye-tracking data directly links to workers' visual attention, physiological responses data (e.g., EDA, EEG, fNIRS) are highly connected to risk perception. Thus, by synchronizing their hazard identification performance with multiple data aggregated from the above-mentioned sensors, an automatic classification model will determine which training regimens the workers need to receive. For

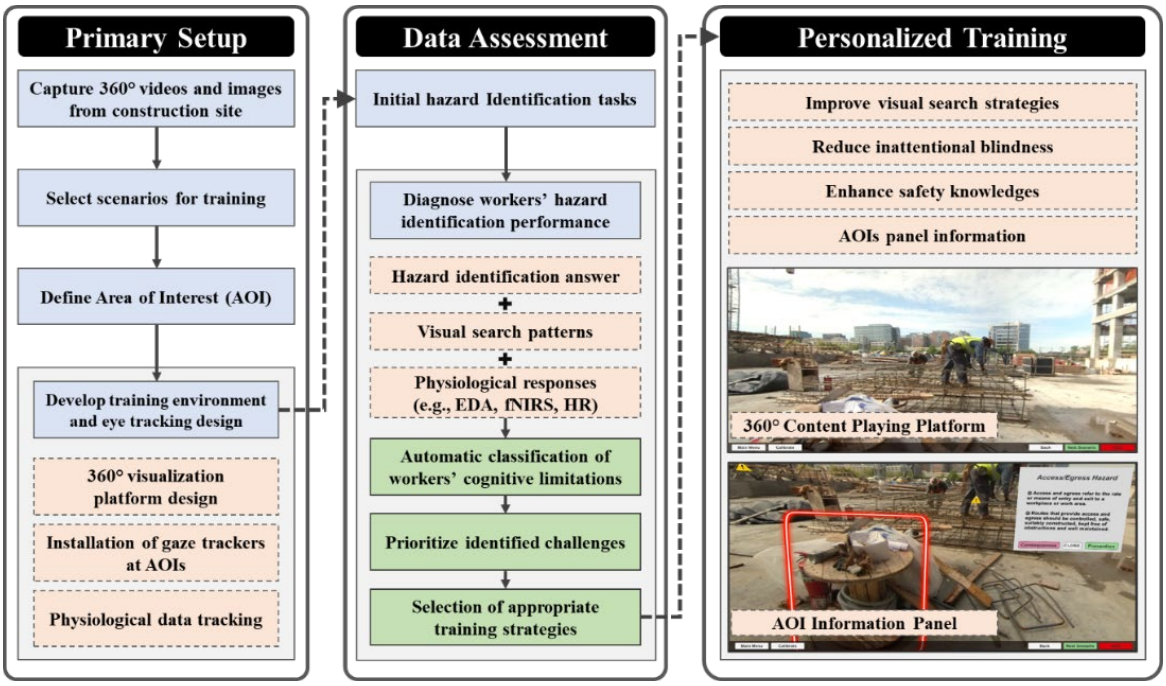


Figure 5. Proposed personalized training framework

example, the group with poor visual search abilities (those who present visual search strategies similar to Figure 4a) would be assigned training in which they would learn more about how to effectively scan the scene and allocate their limited attentional resources to hazardous areas. Another example is at-risk workers who need to receive more training regarding specific hazards they have missed. In that case, additional, user-friendly components (e.g., AOI info panels) would be embedded in the platform to highlight the overlooked hazards and provide auditory and visual information for workers regarding the description of the hazard, its consequences, and how the hazard could be prevented. Our research team is developing such a training program, and the results of this proposed framework are forthcoming.

5 Discussion

Construction environments are complex, dynamic, and rich in detail, whereas human perceptual and cognitive resources are limited. Therefore, workers may fall prey to various failures of awareness, leading to injury. The findings of this study indicate that this failure of hazard identification is caused by different cognitive limitations, each of which essentially requires divergent training strategies. While the importance of tailoring training to an individual's cognitive limitations is pivotal, no studies to date have empirically explored these cognitive challenges to propose personalized safety training.

In this study, the research team investigated workers' cognitive failures based on subjective hazard identification performance and objective physiological data, which we combine to propose a personalized training framework. Due to the demanding and dynamic nature of jobsites, some workers may not be able to remain situationally aware of their surroundings to identify hazards. These workers may have low modal hazard anticipation skills to predict whether and/or how a specific hazard might materialize at a particular time in the near future—as particularly evidenced in the discussed case of subjects missing a worker passing underneath two raised lifts. These subjects—all experienced construction workers—primarily need to be trained to improve their visual search strategy, distribute their visual attention properly across the surrounding environment, and make the best use of their limited attentional resources to identify hazards.

The improvement of visual search strategies is crucial in various industries (e.g., military, driving, and lifeguarding), and several training approaches have been utilized [16,18]. For example, a driving-related study suggests training regimens that show an expert's visual search pattern, including more consistent and systematic scan paths [18]. In addition, the marines have recommended providing expert feedback about an individual's search path to provide another effective training method [19]. Such training systems, if combined with this study's approach to diagnosing cognitive limitations, would feasibly provide excellent inroads to improved construction safety.

Although the inattentional blindness concept is now well-established in cognitive psychology and can be prevented through education and training, it has rarely been discussed in the construction safety setting. Studies addressing inattentional blindness [6] showed that workers may allocate their attentional resources to some areas within the scene without perceiving the scene, a factor that may put these workers at a very high risk of being involved in an accident. This phenomenon has its roots in a selective looking paradigm presented by Neisser (2019) [20] and may also have roots in a tendency among individuals in high-risk environments to miss a second target after detecting the first target, a factor known as subsequent search misses [21]. Previous literature also indicated that certified training and frequent exposure to accidents showed positive impacts on reducing inattentional blindness [6]. Therefore, although inattentional blindness is a natural human cognitive limitation, an educational training method that allows workers to recognize their cognitive limitations and try to control them must be developed.

In our proposed training, workers will be shown the hazards they have missed despite looking at them, which will provide a first step toward enhancing these workers' awareness about this phenomenon. Then, they will receive training on how to allocate their attention throughout the scene, remain mindful, and avoid premature search termination.

Lastly, our results show workers may have appropriately distributed their visual attention when the dynamic hazard was activated, but they did not perceive the situation as a risky condition due to their limited safety knowledge or inordinately higher risk tolerance. Therefore, this group may require more safety knowledge-based training to understand why the condition is considered hazardous as well as the condition's risk level and consequences.

While our findings provide a unique perspective on workers' cognitive limitations and require personalized interventions, several limitations need to be noted. Due to the page and space limit, the current paper classified the different cognitive limitations by only analyzing eye-tracking data and hazard identification results. Therefore, future research needs to explore other psychophysiological responses (HR, EDA, and brain activity) to have better classification results. Second, future studies may conduct a pre-post experiment to examine the effectiveness of proposed personalized training.

6 Conclusion

Construction jobsites are complex and dynamic environments requiring constant attention, so the ability to recognize static, dynamic and emerging hazards in a surrounding environment is highly associated with worker safety. The results of this study suggest workers' hazard identification failures were predominantly affected by workers' various cognitive limitations (e.g., attentional failure, inattentional blindness)—a factor discernable in the subjects' empirically identified eye-movement behaviors. Aligned with this finding, the study proposes a framework for advanced personalized training. Such recommended training will adopt multiple sensing and visualization technologies to automate the individualized assessment of workers' true cognitive limitations and thereby select optimal training methods. The results of this paper are expected to motivate more efforts into creating a highly effective personalized training platform and ultimately improve workers' hazard recognition abilities, thereby decreasing the number of injuries and fatalities in construction.

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