# Examining the Relationship between Construction Workers' Visual Attention and Situation Awareness under Fall and Tripping Hazard Conditions: Using Mobile Eye Tracking

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**Abstract:** The risk of major occupational accidents involving tripping hazards is commonly underestimated with a large number of studies having been conducted to better understand variables that affect situation awareness: the ability to detect, perceive, and comprehend constantly evolving surroundings. An important property that affects situation awareness is the limited capacity of the attentional system. To maintain situation awareness while exposed to tripping hazards, a worker needs to obtain feedforward information about hazards, detect immediate tripping hazards, and visually scan surroundings for any potential environmental hazards. Despite the importance of situation awareness, its relationship with attention remains unknown in the construction industry. To fill this theoretical knowledge gap, this study examines differences in attentional allocation between workers with low and high situation awareness levels while exposed to tripping hazards in a real construction site. Participants were exposed to tripping hazards on a real jobsite while walking along a path in the presence of other workers. Situation awareness was measured using the situation awareness rating technique, and subjects' eye movements were tracked as direct measures of attention via a wearable mobile eye tracker. Investigating the attentional distribution of subjects by examining fixation-count heat maps and scan paths revealed that as workers with higher situation awareness walked, they periodically looked down and scanned ahead to remain fully aware of the environment and its associated hazards. Furthermore, this study quantitatively compared the differences between the eye-tracking metrics of worker with different situation awareness levels (low versus high) using permutation simulation. The results of the statistical analysis indicate that subjects did not allocate their attention equally to all hazardous areas of interest, and these differences in attentional distribution were modulated by the workers' level of situation awareness. This study advances theory by presenting one of the first attempts to use mobile eye-tracking technology to examine the role of cognitive processes (i.e., attention) in human error (i.e., failure to identify a hazard) and occupational accidents. **DOI: 10.1061/(ASCE)CO.1943-7862.0001516.** *© 2018 American Society of Civil Engineers.*

**Author keywords:** Situation awareness; Cognitive ability; Hazard identification; Attention; Construction safety; Eye tracking.

## Introduction

Falls to the same level are one of the leading causes of occupational accidents in the United Kingdom, New Zealand, and the United States (e.g., Davis 2007; Cayless 2001; Bentley and Haslam 2001; Bentley et al. 2003; Layne and Pollack 2004; HSE 2005; Lipscomb et al. 2006; Yeoh et al. 2013; BLS 2017). Moreover, non-fall slips and trips typically result in a large number of musculoskeletal injuries, which are among the costliest to treat (Lipscomb et al. 2006; Lim et al. 2015). Although incidents of different types of accidents overall are on the decline, the frequency of injuries due to slipping and tripping hazards is increasing, and their actual risks have been underestimated (Bentley and Haslam 2001; Kemmlert and Lundholm 2001; Layne and Pollack 2004). As such, falls to the same level have become a major safety concern in both the manufacturing and construction industries (Lim et al. 2015).

Contributing to the problematic increase in frequency and costs associated with this type of injury is the reality that workers' misperceptions about the risks associated with tripping hazards cause human error—such as missing or misidentifying a hazard—and consequently unsafe behaviors (HSE 2005). In 2003, Bentley et al. (2003) reported that 75% of fall-to-same-level accidents in the New Zealand construction industry were due to workers failing to identify tripping hazards prior to the accidents. When workers fail to identify or perceive these hazards (e.g., a change in surface conditions), they do not adopt the appropriate gait for the new condition and, consequently, the likelihood of an accident increases (Bentley 2009). This ability to detect, perceive, and comprehend constantly evolving surroundings is called situation awareness (Endsley 1995), and although the topic relates to a variety of vital questions within construction safety, very few studies have been conducted in the past decades to determine the relationship between construction worker cognitive abilities and situation awareness.

One major property that is associated with situation awareness is attention. To form situation awareness, one needs to pay attention to perceive and process the environment. However, the limited capacity of human attentional resources in combination with the excessive attentional demands in a dynamic construction environment can result in a loss of situation awareness (Endsley 1995),

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which in turn can lead to accidents. The relationship between attention and situation awareness has been investigated in occupations that require high cognitive loads, such as operators of complex systems (Hauss and Eyferth 2003) and fighter aircraft pilots (Keller et al. 2004). These studies resulted in the development of guidelines for improving human performance. However, despite the importance of attention in accident avoidance, there is a lack of knowledge regarding the relationship between attention and situation awareness in construction activities.

To study attention, one well-established measurement technique is to track the oculomotor behavior of subjects. Tracking eye movements of individuals provides insights into their attentional allocations, visual search strategies, and cognitive processes, which all serve as inputs to be organized and prioritized in the brain and executed as behavior (Kuzel et al. 2013; Tatler et al. 2016). Previous attempts to use eye tracking in construction safety (e.g., Bhoir et al. 2015; Hasanzadeh et al. 2017a, b, c, d) almost exclusively relied on two-dimensional (2D) displays in a laboratory setting, where images of scenes are displayed on computer screens. Although this approach offers the opportunity to control viewing conditions, it does not completely reflect the stimulus conditions in a natural, three-dimensional (3D), dynamic, complex construction environment. Without the intricacies of a real work environment, these previous studies have failed to demonstrate the breadth of inputs affecting workers' attention.

Walking safely through a construction site requires proper attentional distribution, to identify underfoot and surrounding hazards (Kaber et al. 2016). However, researchers still do not know whether workers with high or low situation awareness levels allocate attention differently while conducting construction activities. Absence of such knowledge prevents safety managers from developing effective strategies for improving workers' attentional allocations in a way that would lead to higher situation awareness and fewer errors or accidents.

To address this theoretical gap, this study tests the general hypothesis that workers with low and high situation awareness levels will allocate their attention differently when exposed to fall-to-same-level hazards. Specifically, a mobile eye tracker was used to assess the attentional distribution of participants when exposed to fall-to-same-level hazards in a live construction environment. Generally, two kinds of hazards account for most fall-to-same-level incidents: slipping and tripping hazards. Slipping hazards may happen as a result of greasy or wet surfaces. Tripping hazards may happen when a worker's foot strikes cables, ropes, tools, boxes, lumber, or legs of equipment, resulting in a loss of balance. This study focuses on tripping hazards, as this type of hazard is visibly identifiable and can be investigated by studying visual attention. In addition to demonstrating the feasibility of using mobile eye tracking to study situation awareness in construction safety, the results of this study create new knowledge about the role of attentional allocation in the behaviors that lead to tripping accidents. The findings also can be translated into practice by designing training interventions to improve the situation awareness of workers through improved attentional distribution and subsequently to test the effectiveness of such training interventions.

## Background

### *Situation Awareness*

There are diverse definitions of situation awareness in the literature; however, the most common definition of situation awareness is provided by Endsley (1988, p. 97) as the "perception of those elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in near future." Situation awareness (SA) has received considerable attention in the last few decades as one of the most pervasive elements of the human factor in accident occurrence (Endsley 1995; Wickens et al. 2013). Although the original impetus to study situation awareness came from the military and aviation domains, it is now considered a critical research theme in almost any domain involving human performance in dynamic and/or complex environments (Salmon et al. 2006).

One reason for this interest in situation awareness is the need to understand the causes of accidents in which situation awareness has been lost (Wickens et al. 2013). Previous literature has shown that maintaining situational awareness is critical for efficiently performing tasks within dynamic and safety-critical occupations such as surgeons, nuclear power plant operators, pilots, air traffic controllers, military commanders, and construction workers (Endsley 1995; Wickens et al. 2013; Hasanzadeh et al. 2016). For example, studies have shown that air traffic controllers with poor situation awareness make more technical, cognizant, and perceptual errors (Rodgers et al. 2000). Other studies have demonstrated that workers are required to be sufficiently aware of activities and elements within the work environment to improve safety on construction sites (Hasanzadeh et al. 2016). Such studies demonstrate the important role that situation awareness plays in causing—or preventing—human error and illustrate why reliable methods for measuring SA became a vital concern.

A large variety of measurement techniques—including subjective, implicit, and direct measurement techniques—have been suggested to measure levels of situation awareness (Sarter and Woods 1995). Subjective measures rely on self-reporting techniques to determine individuals' situation awareness levels. Of these, the situation awareness rating technique (SART) is the most commonly used subjective measure of situation awareness. SART asks individuals to provide ratings on a Likert scale in response to questions intended to capture cognitive dimensions. Alternatively, implicit measures embed relevant information into high-fidelity scenarios that can elicit particular behaviors, which allows researchers to interpret the participants' situation awareness based on their changing behaviors (Sarter and Woods 1995; Wickens 1996). Direct measures can measure the level of situation awareness during a task (Durso et al. 2006). The situation awareness global assessment technique developed by Endsley (1990) is one of the most popular techniques for direct measurement of situation awareness levels. This scenario-based technique measures situation awareness by asking memory-based questions during the task; however, this technique has been criticized because of its overreliance on memory.

The major concern associated with all of these techniques is their inability to measure situation awareness in a dynamic and uncontrolled environment, such as a construction site. The latter two techniques (i.e., implicit and direct measures) require researchers to interrupt and control the test situation, which would be impractical in a construction environment. More importantly, even if an interruption were possible, the results would be biased due to the tester's interruptions of normal behavior, which may in turn affect how the participant approaches the task. For this reason, subjective measures—despite of all their inherent biases—have been the preferred methodology in field testing as compared with the other two techniques, as subjective approaches do not necessitate interruptions. However, finding an objective means of testing workers' situation awareness in dynamic environments (such as construction sites) continues to be desirable, as such a methodology would open the door to several innovations in detecting situationally unaware—or at-risk—workers before an accident occurs.

### *Tripping Hazards*

Situation awareness plays a prominent role in tripping events within construction because two distinct factors are at play: physical factors and human factors. Previous studies have provided an overview of a broad range of physical and human factors that contribute to tripping hazards, including underfoot conditions, footwear, activity characteristics, lighting, human gait biomechanics, aging, fatigue, and alcohol and drugs (e.g., Kemmlert and Lundholm 2001; Gauchard et al. 2001; Bentley et al. 2003; Bentley 2009; Bell et al. 2008; Yeoh et al. 2013; Sheik-Nainar et al. 2015). In terms of physical factors, various materials and by-products (e.g., pieces of wood, drywall, and concrete blocks) used in construction activities may become hazardous obstacles by restricting workers' movements on construction sites (Lipscomb et al. 2006). Additionally, poor housekeeping is a major contributing factor to most tripping accidents on construction sites (Bentley 2009), as misplaced physical elements create barriers to movement or environmental hazards that can lead to accidents.

In terms of the human factor, a lack of situation awareness plays a prominent role in tripping incidents when the subject encounters hazards (i.e., physical factors). For example, a typical situation that leads to a trip is a worker's need to move across an uncontrollable underfoot surface when multiple trades are working in proximity with each other. Even in such a simple scenario, workers must properly distribute their cognitive resources—specifically attention—to maintain environmental and situational awareness (Bentley and Haslam 2001; Bentley et al. 2003). Without such awareness, the worker may miss debris, equipment, or supplies left on the surface by other workers. Such errors in attention may lead to a trip and subsequent injury. Therefore, the excessive attentional demands placed on a worker in a dynamic construction environment make the proper allocation of attention to avoid a tripping hazard important.

### *Role of Attention in Situation Awareness*

Attention is an important cognitive element in many tasks and has been studied for decades in various disciplines. Attention is a selection process that determines which items are selected for subsequent processing (Wickens et al. 2013). Balance between selective/focused attention (focus on only one stimulus) and divided/distributed attention (splitting attention between two or more tasks/objects) reflects both the amount and quality of information that an individual is able to perceive, process, and interpret from the environment (Hasanzadeh et al. 2017a, b). In a dynamic environment, identifying relevant visual information and determining which information requires additional processing is important for individuals to maintain a safe level of performance (Kaber et al. 2016). As illustrated in Fig. 1, attention must be distributed and must balance a variety of sensory considerations to achieve situation awareness. Thus, low attention or poor situation awareness can be a substantial element of a tripping accident.

Further complicating this issue is the question of attentional capacity, which is one of the major limitations to situation awareness. In a seminal study conducted by Endsley (1995), proper allocation of attention was at the core of situation awareness in high-risk environments. This finding was further underscored by results that showed how, in complex and dynamic environments, excessive attentional demands can result in lost situation awareness (Wickens et al. 2013; Banbury et al. 2007). A worker's ability to simultaneously detect and perceive all hazards in a dynamic construction environment will be constrained by the limited capacity of his or her cognitive resources (attention), and when the demands exceed capacity for attention, this excess can considerably degrade the worker's level of situation awareness (Hasanzadeh et al. 2016).

Previous studies have highlighted how attentiveness to hazards is crucial for avoiding tripping incidents in different work environments (e.g., Wooley et al. 1997; Gauchard et al. 2001; Leclercq and Thouy 2004). Although walking is considered an automatic process that can be done with little consciousness (Kaber et al. 2016), it still requires cognitive resources such as attention. To walk safely, workers distribute their attention properly—most often from visual cues—to search for hazards (Sheik-Nainar et al. 2015). Specifically, these workers need to: (1) obtain feedforward information about potential sources of tripping hazards; (2) detect immediate tripping hazards; and (3) visually scan surroundings to maintain environmental awareness.

Workers obtain feedforward information about potential sources of tripping hazards several feet ahead of them by directing their gaze downward (Land 2006; Kuzel et al. 2013; Ayres and Kelkar 2006; Buckley et al. 2011). This distance—or "effective visual field"—is often 3 m ahead and slightly below horizontal (Whetsel and Campbell 2016). Obtaining such feedforward information helps the subject assess safety risks, project the proper response in choosing a safe path, and then adjust his or her gait to accommodate obstacles and other potential tripping hazards before encountering them. In addition to obtaining feedforward information, workers must look down to detect potential sources

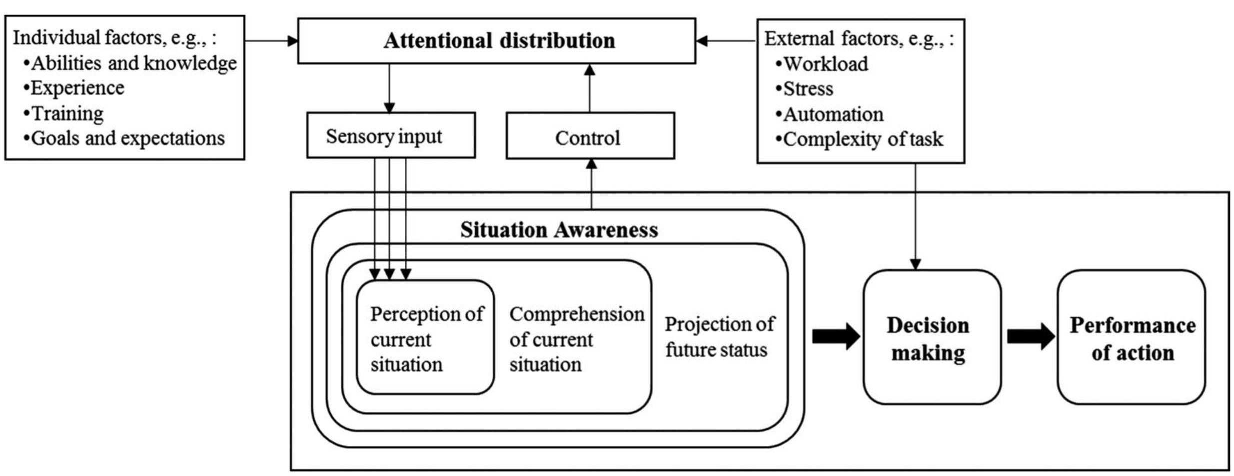



**Fig. 1.** Framework of situation awareness. (Adapted from Endsley 1995.)

of tripping hazards on the surface immediately underfoot, which becomes more difficult for people who have not obtained feedforward information. Finally, workers need to be aware of environmental sources of hazards that could influence their gait. For example, the surrounding environment at a jobsite might include various trades working simultaneously; any movement of other workers or equipment performing a task nearby may lead to struck-by or fall-to-same-level hazards. In addition, a subject may strike against stored materials and lose his or her gait control. Therefore, only looking down at the exact landing area of one's steps would not be sufficient to identify hazards. Workers must maintain a broader awareness of their surroundings to avoid errors and injuries.

This trifold dynamic at play in workers' ability to avoid tripping hazards and maintain situational awareness opens the door for innovations in objectively measuring situation awareness to identify at-risk or error-prone workers. Although the role of attention in identifying tripping hazards has been inferred in the previous literature (e.g., Bentley et al. 2003; Mitropoulos et al. 2009; Bentley 2009; Segev-Jacubovski et al. 2014), it has been difficult to test this hypothesis empirically due to the absence of a reliable measure of attention. Fortunately, it is well established that visual scanning behavior is highly correlated with human attention, such that where one looks is often indicative of where they are attending (e.g., Kuzel et al. 2013; Duchowski 2007). Thus, understanding where and when one looks helps identify which visual inputs the brain is using to make decisions and execute behaviors (Kim et al. 2016). In particular, the seminal studies of Yarbus (1967) and more recent task-dependent, laboratory-based studies have linked eye-movement patterns to individual cognitive goals. For this reason, eye movements have become critical to studying the behavior and cognitive processes that are organized and prioritized in the brain (Tatler et al. 2016; Wickens et al. 2013). Tracking eye movements thereby yields the most direct and continuous measures of attention, which in turn opens the door for improved metrics of situation awareness.

### *Measuring Attention Using Eye Tracking*

Eye trackers use near-infrared technology and high-resolution cameras to track corneal reflections and gaze direction, which enables researchers to continuously monitor the point of a subject's gaze on a 2D screen or in a 3D environment. Given that where one looks correlates with attention, this tool helps researchers assess subjects' attentional allocation. There are two types of eye trackers: remote eye trackers (which require subjects to sit in front of a screen and conduct an experiment) and mobile eye trackers (which allow subjects to move freely). Eye movements are typically analyzed in terms of fixations (a relatively stationary eye position of 100–200 ms duration) and saccades (the rapid movements of the eye between fixation points). Because little to no visual processing is obtained during saccades and visual acuity is suppressed, perception mostly occurs through fixations (Salvucci and Goldberg 2000), which makes them a vital metric for measuring cognitive processes such as attention.

Because eye tracking provides a large amount of data, the visualization of eye-movement patterns can provide additional insight when paired with a comprehensive statistical analysis. Visualization techniques commonly used for representing eye-tracking data are heat maps and scan paths (Raschke et al. 2014). A heat map is a 2D visualization in which all fixation values that were analyzed are represented in color scales (Bojko 2009). Heat maps can be created for an individual or to aggregate data from a group of people. This type of visualization provides useful summary information, as it can incorporate vast amounts of numerical data in a large, comprehensive, and understandable picture. Eye-tracking heat maps are widely applied in web usability studies (Cutrell and Guan 2007; Buscher et al. 2009) and serve as useful tools to illustrate observers' viewing behavior and attentional allocation when accompanying a statistical analysis. Analyzing heat maps may also help to define an observer's principal area of interest when viewing an image (Wooding 2002). Moreover, heat maps can represent various types of data, so choosing the appropriate heat map is significantly correlated with research objectives.

Different types of heat maps are summarized in Table 1.

Alternatively, a scan path is a compelling visualization of eye movements defined as a spatial arrangement of a sequence of saccade-fixation-saccade. The optimal scan path is a straight-line eye movement between desired targets, with a short fixation on the targets. Previous studies have argued widely that scan paths reveal considerable information about visual attention and other underlying cognitive processes involved in eye movements (Laeng and Teodorescu 2002; Raschke et al. 2014). Additionally, because a scan path demonstrates the sequential order of observed areas, it can provide more meaningful information than visualizations of fixation locations (Raschke et al. 2014). In particular, scan path–related metrics provide an indication of relative search efficiency (Goldberg et al. 2002). For example, a study of the scan path variability between the eBay and Amazon front pages suggested that complexity of web page design visual complexity contributes to eye-movement behavior (Pan et al. 2004). This study demonstrates the applicability of using scan path and its quantitative measures to study how viewer visual behavior is changed due to individual characteristics of the viewer as well as the stimuli type.

The immense potential of using such eye tracking to improve construction safety has led to an increasing number of laboratory-based studies in recent years. These studies have measured the effect of safety training and knowledge, years of experience, personality, risk perception, and past injury exposure on workers' attentiveness and ability to identify hazards (Bhoir et al. 2015; Hasanzadeh et al. 2016, 2017a). Furthermore, previous studies have shown that monitoring the eye movements and attentional allocation of workers in real time may be beneficial in detecting at-risk workers who have lower situation awareness (Hasanzadeh et al. 2017b) and identifying the hazards that they may fail to detect for the purpose of developing personalized safety training in the future (Hasanzadeh et al. 2017d). However, most previous eye-tracking studies in construction safety shared a limitation: They used remote eye trackers in the laboratory and static images that might not capture all of the characteristics of a real-world construction site.

Attentional distribution differs in the laboratory as compared with real-world settings, as the complexity and dynamic nature of real-world events significantly affect an individual's attentional allocation (Hayhoe and Ballard 2005; Smilek et al. 2008; Gidlöf et al. 2013). To overcome this challenge, a new generation of comfortable, lightweight, and unobtrusive eye-tracking glasses has been introduced. These advanced wearable eye trackers provide greater flexibility for researchers, particularly for studies in which the experimental content involves body movements, such as sports, driving, shopping, or construction activities (Shinoda et al. 2001; Land and McLeod 2000; Brône et al. 2011; Pfeiffer and Renner 2014; Hasanzadeh et al. 2016). In addition, mobile eye trackers provide quick and persistent calibration and a minimum loss of gaze while recording eye movements (Kiefer et al. 2012). These benefits have fueled an incredible growth in studies of visual attention and eye movement in natural settings (e.g., walking and driving) (Shinoda et al. 2001; Jovanevic-Misic and Hayhoe 2009), and have opened the door for a wide variety of applications in construction safety.

**Table 1.** Different types of heat maps in eye-tracking studies

| Type | Definition | Application | Limitation |
|---|---|---|---|
| Fixation-count heat map | Shows the accumulated fixation locations across observer(s) | To examine the search efficiency and/or to determine the amount of interest generated by a stimulus during a free-view task | Fixation values are the same regardless of duration<br>Areas of the same color have different gaze times<br>Individual heat maps are better representations, as heat maps from all observers have some biases related to differences in individual interests in the stimulus<br>This heat map is not the right choice when exposure time is not equal across participants |
| Absolute gaze–duration heat map | Shows accumulated time spent by observer(s) at different areas, representing their levels of cognitive processing. Color values of points change according to the proportion of duration | To examine the amount of time spent on different areas of a scene stimulus | Can be misleading because it displays different facts in the exact same way. For example, this type of heat map represents a participant's 200-ms gaze in the same color as two 100-ms gazes<br>This heat map is not the right choice when exposure time is not equal across participants |
| Relative gaze–duration heat map | Shows the cumulative time each participant fixated on different areas divided by the total time spent for free viewing | To examine the relative time spent on different areas of a scene when the exposure time is different across observers | Can be misleading because it displays different facts in the exact same way. For example, this heat map represents a participant's 200-ms gaze in the same color as two 100-ms gazes |
| Percentage heat map | Shows the percentage of participants who fixated on different areas of a scene | To illustrate the noticeability of a special element | The number of fixations and their durations are not represented in this type of heat map |

## Point of Departure

Given that situation awareness plays an important role in fall-to-same-level accidents (Segev-Jacubovski et al. 2014), and attention (specifically, visual sensory input) helps one detect and perceive tripping hazards to take proper action prior to a tripping incident (Grönqvist et al. 2001), the question of identifying workers with poor situation awareness through the study of their visual attention provides an opportunity to find workers at risk for a tripping accident. In particular, situationally aware workers must obtain feedforward information about hazards, detect immediate tripping hazards, and recognize other environment-related hazards. Interestingly, however, no study has empirically measured the influence of situation awareness on attentional allocation or how situation awareness affects tripping-hazard detection. Furthermore, although some studies have investigated the role of attention in accidents in construction safety (e.g., Hasanzadeh et al. 2017a, b), most of these studies have been conducted in laboratory settings, which limits their extension to a real construction environment.

To respond to these lingering gaps in knowledge, this study makes two distinct advances. First, this paper presents an early investigation into the relationship between situation awareness and attention in fall-to-same-level accidents in the construction industry. Second, this paper pioneers applications of real-time eye-tracking technologies to questions of worker safety in dynamic construction environments. Combined, these innovations signify the advent of applying eye-tracking technologies to complex environments to document and analyze workers' situation awareness of hazardous situations.

To accomplish these advances, the current study determines how workers with different levels of situation awareness distribute their attention while walking on construction sites with potential tripping hazards. In particular, we use mobile eye tracking to document how participants with high and low situation awareness distribute attention when exposed to fall-to-same-level hazards in a live construction environment. This study builds a fixation-count heat map to better compare the visual attention of construction workers across the scene, and we aggregate additional fixation-related metrics to garner data regarding attentional allocation [specifically, the mobile eye tracker provides four fixation-related metrics: (1) fixation time [how quickly an individual fixates an area of interest (AOI) relative to the onset of the trial/scenario]; (2) fixation count (the number of fixations within each AOI); (3) run count (the number of visits to each AOI), with a visit being defined as a single fixation or series of fixations on an AOI without fixating anywhere else outside of that AOI (e.g., if an individual makes four fixations on an AOI and then fixates elsewhere, later returning to make three additional fixations on that same AOI, the run count would be 2); and (4) dwell time (the total time each participant fixated each AOI over the course of the experiment)]. This study additionally applies statistical analysis to these outputs and uses scan paths to study the visual search strategies and cognitive processes of workers in each scene. Together, these data and analyses enable the test of a general hypothesis that workers with low and high situation awareness levels will allocate their attention differently when exposed to fall-to-same-level hazards. To investigate this hypothesis, this study tests the following three null hypotheses:

- Null $H_1$: There is no difference between the attentional allocation of workers with low and high situation awareness in obtaining feedforward information;
- Null $H_2$: There is no difference between the attentional allocation of workers with low and high situation awareness toward immediate tripping hazards; and

- Null $H_3$: There is no difference between the attentional allocation of workers with low and high situation awareness toward environmental hazards.

Results from these tests signal whether eye movement patterns relate to workers' situation awareness levels and whether eye tracking can be used as a direct measure of situation awareness in uncontrolled and complex environments, including construction sites. Therefore, the theoretical knowledge created in this study establishes whether eye movements can serve as objective measures of situation awareness—information that will in turn subsequently help determine which construction workers are at greater risk.

## Research Methods

To test the research hypotheses, the researchers designed and implemented an eye-tracking experiment. Fig. 2 shows the data collection and analysis processes.

### *Data Collection*

#### Participants and Experimental Environment

Fourteen undergraduate and graduate students (12 males, 2 females) were recruited to participate in this study. To ensure that participants were familiar with safety hazards, all subjects were required to have more than 1 year of experience working for a construction company; participants' experience ranged from 1 to 6 years. All participants had normal or corrected-to-normal vision.

The experiment was conducted in a single day on one construction site (240,000-square-foot facility) located at the University of Nebraska–Lincoln campus; each subject participated in a single 30-min session (Fig. 3). Five different subcontractors were working simultaneously on the site, and the site included different hazards that varied in safety risk. An institutional review board approved all experimental processes prior to initiation of research, and participants were compensated with gift cards.

#### Eye-Tracking Experiment

**Design and Measures.** Before the eye-tracking experiment, the participants filled out a demographic survey, including questions about age, gender, working experience, and safety training. Then, during the experiment, subjects walked along a path in the presence of other workers who were conducting their normal activities on the jobsite (see Fig. 4 for a schematic model of the experiment path). Participants received specific instructions as to where to start and finish their walk through the jobsite; however, they were free to choose their own path and had to cope with potential causes of hazards on their way to the end point. Additionally, the potential causes of tripping and the environmental hazards within these paths were fixed. Although the authors did not control the participants' walking strategy during the experiment, they knew that the deviation of stepping locations from the hypothetical path would be very small, because there was limited flexibility for the subjects to reach the end point. To prevent test subjects from becoming unnaturally cautious because they were being watched during the experiment or were feeling pressured to complete the scenario faster than comfortable, the researchers simulated the experiment in advance to measure the time it would take to walk through the scenario's path. As a result of the research team's pilot testing, participants were allotted 45 s to complete the scenario while choosing their own walking strategy.

**Apparatus.** This study used a wearable mobile eye tracker (Tobii Pro glasses 2, Tobii Technology, Falls Church, Virginia) to track workers' natural behavior and to follow their attentional focus in real time. This device consisted of four eye cameras (directed toward the subject's eyes) with a sampling rate of 100 Hz and a wide-angle, full-scene camera directed toward the scene. The Tobii Pro wireless eye tracker is ultra-lightweight (45 g) and unobtrusive, which helped to ensure that study participants felt comfortable wearing it and could act naturally in the scenario. The mobile eye tracker also included a tablet that ran controller software to allow researchers to control the eye tracker and observe in both recorded and real time what the subjects were seeing. The device was set up and calibrated for each participant prior to the experiment, a process requiring between 2 and 5 min.

#### Subjective Situation Awareness Measurement

SART was used to measure the levels of situation awareness of the test subjects after they completed the scenario. The SART, developed by Taylor (1990), provided a subjective measure of each subject's situation awareness. SART is one of the most popular and easy-to-use situation awareness measurements and is applicable in a wide range of task types (Taylor 1990; Endsley 1995). It is easy to administer, low in cost, and applicable to multiple domains. Furthermore, it has high ecological validity, is nonintrusive to task performance, and accounts for attentional supply and demands. In terms of experimental design, SART is administered post-trial and asks subjects to self-rate three main dimensions of situation awareness on a 7-point Likert scale (1 = low, 7 = high; Taylor 1990), including demand on attentional resources (instability, complexity, and variability of the situation); supply of attentional resources (arousal, spare mental capacity, concentration, and division of attention); and understanding of the situation (information quantity and quality, and familiarity with the situation). The definition of each dimension is provided in Table 2. For each subject, the overall SART score was calculated using Eq. (1) as follows:

$$\mathrm{SA} = \mathrm{Understanding} - (\mathrm{Demand} - \mathrm{Supply}) \tag{1}$$

SART was the most appropriate technique for this study, as it does not necessitate interruptions during the scenario and thereby prevents test subjects from becoming unnaturally cautious. Consequently, the authors were able to study the subjects' natural behavior during the scenario. Using the SART outcomes, this study grouped subjects based on their opinions of the scenario's attentional demands, their attentional supply, and their understanding of the situation. These groupings were then used to examine differences in the subjects' attentional distribution.

### *Determining Areas of Interest*

To extract eye-tracking metrics, AOIs should be defined first. This process requires experts in the subject matter to evaluate a scene and determine which areas represent hazardous situations or objects to which participants must attend, to maintain situational awareness during the scenario. Defining AOIs when using eye tracking in a controlled laboratory environment is easy, as objects and elements are static. However, defining AOIs while studying the visual behavior of subjects in a natural setting is challenging, because some stimuli in the environment are dynamic (e.g., a moving crane). Even if the stimulus is static, it may be seen from different angles by different participants. To address these problems, AOIs should be defined based on multiple snapshots taken from the eye-tracking recordings of participants' eye movements. Selected scenes must cover all path perspectives, be seen by most of the subjects, and include potential hazards. Therefore, the video recordings of the eye movements were examined and three safety managers with at least 10 years of experience helped select scenes for further investigation.

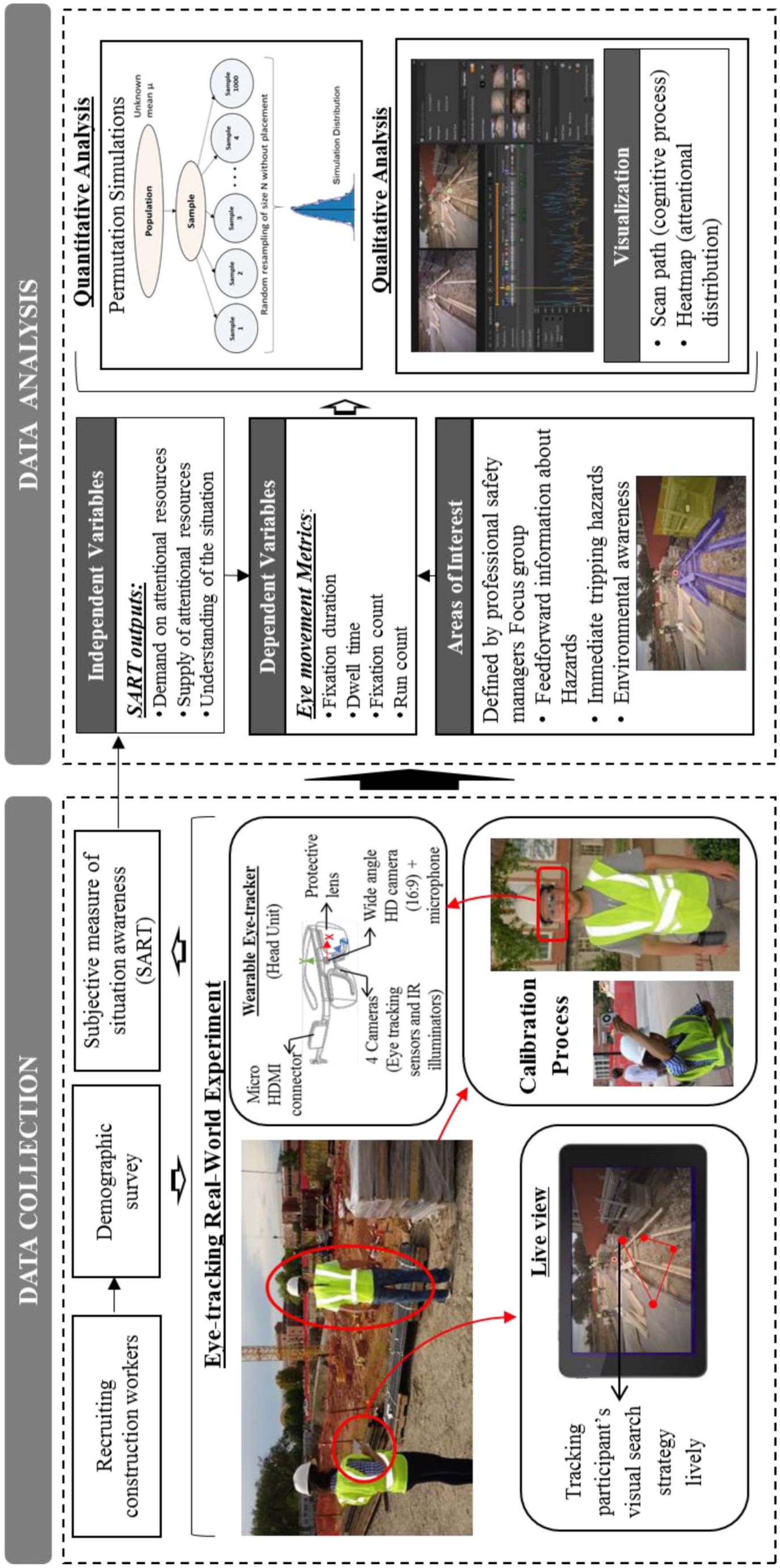



**Fig. 2.** Research framework.

**Fig. 3.** Images from the construction site that was used as the experimental setting.

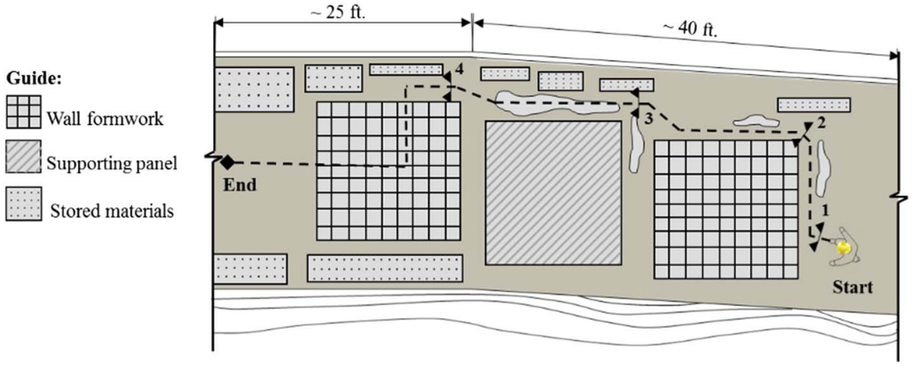



**Fig. 4.** Schematic model of the experiment path.

**Table 2.** SART dimensions and their definitions

| Dimension | Construct | Definition |
|---|---|---|
| Attentional demands | Instability of situation | Likelihood of situation to change suddenly |
| | Variability of situation | Number of variables that need attention |
| | Complexity of situation | Degree of complication within the situation |
| Attentional supply | Arousal | Degree that one is ready for activity |
| | Spare mental capacity | Amount of mental ability available to spare for new variables in the situation |
| | Concentration | Degree that thoughts are brought to bear on the situation |
| | Division of attention | Amount of division of attention in the situation |
| Understanding of the situation | Information quantity | Amount of information received and understood |
| | Information quality | Accuracy and value of information |
| | Familiarity with the situation | Degree of prior experience and knowledge |

The research team and the safety managers chose four representative scenes from the experiment's path for further investigation. The selected scenes consisted of various potential tripping hazards, navigation alternatives, and potential hazardous areas in the surrounding environment. Fig. 5 shows the four scenes in addition to examples of the three categories of AOIs identified for analysis; these three categories correspond to the types of information that workers must process to maintain situation awareness.

As mentioned in the background section, to retain awareness while exposed to tripping hazards, a worker needs to obtain feedforward information about hazards, detect immediate tripping hazards, and visually scan surroundings for any additional potential environmental hazards. Thus, the categories of AOIs in Fig. 5 (AOI I indicates feedforward information, AOI II indicates immediate hazards, and AOI III indicates environmental hazards) were defined based on the following informative categories:

1. Feedforward information: The AOIs highlighted as AOI I (Fig. 5) in each scene include objects that need to be visually attended to in advance: (1) leftover lumber on the ground in Scene 1; and (2) wall formwork left on the ground and blocking the path in Scene 4;
2. Immediate tripping hazard: The AOIs highlighted as AOI II (Fig. 5) include potential causes of immediate tripping hazard: (1) vertically stacked panels left on the ground in Scene 1, (2) leftover lumber on the ground in Scene 2, and (3) pile of lumber scraps in Scene 3. What differentiates AOI I and from AOI II is the proximity to participants: the sources of hazards that require feedforward information become an immediate tripping hazard when the subject is in close proximity and needs to step over them; and
3. Environmental hazard: The AOIs highlighted as AOI III (Fig. 5) are related to environmental hazards consisting of potential struck-by hazards that would lead to falling to the same level:

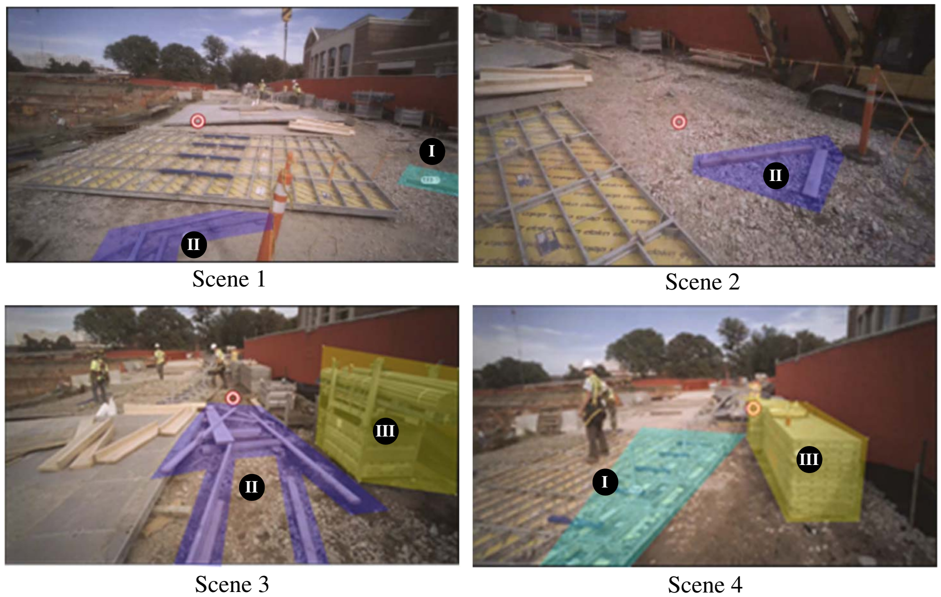



**Fig. 5.** AOIs in each scene.

(1) stored form ties and plumbing accessories in Scene 3 and (2) framed formworks that block the path in Scene 4. The delineation of these AOIs relates to what is beyond the subject's useful visual fields or what he or she would turn his or her head to attend to and identify.

### *Data Analysis*

The time required to analyze the data collected from the mobile eye-tracking apparatus was considerably reduced using state-of-the-art image-recognition technology (provided by Tobii Pro Glass Analyzer software). This technology superimposed real-world mapping data with eye-tracking data to build out images for our analysis. The raw eye-movement data are processed within a coordinate system using image-recognition technology to map the areas of interest onto the four scenes. These resulting images streamlined the analysis process by saving the research team the task of manually coding each frame. Data were analyzed for 11 of the 14 participants; three participants were removed due to difficulties with the eye tracker's calibration. To compensate for a small sample size, the statistical technique used in this study generated a reference distribution by recalculating data statistics using resampling (10,000 samples), which increased the power of the analysis.

To establish the analysis, after the subjects participated in the experiment, the research team gathered each participant's SART scores for situation awareness dimensions (i.e., supply, demand, and understanding) in addition to their total SART scores. This first step allowed the research team to then test the research hypotheses by dividing the participants into two groups based on their levels of situation awareness as determined by their SART score: high situation awareness (above average SART score—7 of 11 participants) and low situation awareness (below average SART score—4 of 11 participants). Although these delineations are broad, the segregation of high from low situation awareness based on above-average versus below-average scores helps to offset the subjectivity of the SART technique. Next, the eye-movement data of these situation awareness groups were analyzed with respect to the AOIs within each scene to determine which objects the participants attended to while performing the walking activity. The Tobii Pro Glass Analyzer software was then used to extract eye-movement metrics for each participant across the identified AOIs for quantitative analysis, and to create visualization diagrams for qualitative analysis.

#### Qualitative Analysis

The research team was able to garner qualitative data by observing the participants live during the experiment and by watching recordings of the subjects' perspectives of the scene. Then, by aggregating and visualizing multiple subjects' visual behaviors—both in terms of their attentional distributions and scanning strategies—the researchers were able to compare the overall strategies of the different situation-awareness groups.

To visualize the eye-movement behaviors of an individual (or group of people), the research team created heat maps and scan paths. According to the approach described in the "Background" section, this study's fixation-count heat maps used colors to represent how much the individual (or group of people) attended to different objects in a scene; additionally, the scan paths showed the visual search strategy of the individual (or group of people). The Tobii Pro Glass Analyzer software was used to map the subjects' eye-movement data on the AOIs' scene images (snapshots) to create these fixation-count heat maps and scan paths. These visualization outputs and analyses of recorded eye movements helped the authors to interpret the results qualitatively to better understand quantitative findings.

#### Quantitative Analysis

Although qualitative analysis and visualization techniques allow for analysis of the eye-tracking data in an explorative way, a statistical analysis had to be conducted to determine significant differences in attention due to variations in situation awareness. The mobile eye-tracker software obtained four fixation-related metrics, including fixation count, run count, dwell time, and first fixation time. The research team excluded the first fixation time metric from the analysis because the real-world construction site could not be controlled during the experiment, so sudden sounds, the light's direction, or any sharp color may have attracted first attention and thereby rendered the information from this metric not useful for our current real-world study. The eye movement metrics were calculated for individuals in each situation awareness group (high and low) within the four scenes and across the AOIs.

To test the research hypotheses, the research team then compared the average value of eye-movement metrics among participants with low and high levels of situation awareness. There are three main approaches to statistically measure significant differences between means of two independent groups: (1) parametric tests (e.g., t-test); (2) nonparametric tests (e.g., Mann-Whitney U test); and (3) simulation (e.g., permutation). Parametric methods could not be used for the statistical analysis in this study because the eye-tracking data did not meet the distributional requirements and assumptions for using a parametric test (LaFleur and Greevy 2009). Furthermore, because simulation techniques use the actual data rather than ranking it—as would be the case when using nonparametric techniques—simulations can provide higher statistical power than other nonparametric techniques (Gleason 2013). Therefore, in this study, the statistical analysis used a permutation to evaluate the eye-tracking data for each category of AOI. Permutation simulation generates a reference distribution by resampling the data and recalculating data statistics, omitting the resampling bias found in randomization and bootstrapping techniques. With permutation, we could use a calculated t-value as a measure of the group's difference and test it against an empirical sampling distribution. We then could determine how the new t-value was extreme or smaller than our observed value. If $X$ of 10,000 shuffles produces a t-value larger than our observed value, we could conclude that the probability of such an extreme outcome is only about $X/10{,}000$, two-tailed. It must be emphasized that t-value is used as a measure of the difference between the groups, not as a statistic to be compared with the parametric t distribution. To conduct the permutation test, the research team used the Deducer package in the Java Graphical User Interface for R 1.7-9 of the open-source statistical package R (version R2.15.0). This study considered a 95% confidence level ($p < 0.05$) as significant and a 90% confidence level ($p < 0.1$) as moderately significant.

## Results

As mentioned previously, this study measured test subjects' SART scores and recorded their eye movements during a real-world experiment to study how construction workers with various situation-awareness levels distribute their attention on a construction site. The mean SART score for demand on attentional resources was 9.82 (standard deviation = 3.97), for supply of attentional resources was 19.82 (standard deviation = 3.37), and for understanding of the situation was 9.45 (standard deviation = 2.30). The mean overall SART score of the test subjects was 19.17 (standard deviation = 5.93, median = 20.00; SART score mean for low SA group = 12.5; SART score mean for high SA group = 23.4). After conducting the experiment, as described in the "Research Methods" section, participants were classified into two groups based on their SART-based situation-awareness level (low and high), and the eye-movement data for each group were extracted for the four scenes in the scenario. Each scene included multiple AOIs (hazardous situations) that were used to test the research hypotheses.

To visually compare the attentional allocation of individuals in each situation-awareness group, the scan paths for a scene were developed for each situation-awareness group; these appear in Fig. 6. The image in the leftmost panel in each row shows the path the participants followed in that scene, whereas the center panel shows the scan paths of the high SA group, and the right panel shows the scan paths of the low SA group. Dots in the scan paths indicate the locations at which the eyes paused for periods of fixation, and lines indicate the eye movements (saccades) that brought the eyes to each location. The different dot colors in the group scan paths represent individual participants, and the dot sizes indicate the fixation duration.

For each of the four scenes, the fixation point data for each subject (as shown in the dots in Fig. 6) were assigned to one of the three categories of information necessary for situation awareness (shown in Fig. 5 as AOIs): feedforward information about tripping hazards, immediate tripping hazards, and environmental hazards. Eye-tracking metrics were then calculated to determine the proportion of time that the subject's gaze was directed to each AOI—this time corresponded to the subject's attention directed toward the AOI. Fig. 7 depicts the mean proportion of viewing time that each situation-awareness group spent looking at each category of AOI in the scenes. The dark bars show the viewing behavior of participants with high situation-awareness levels and the gray bars show the viewing behavior of participants with low situation-awareness levels. Generally, those with higher situation-awareness levels looked at all areas of interest within the scenarios far more than those with lower situation-awareness levels (Fig. 7). The differences between the attentional allocations of participants with different situation-awareness levels for each category of AOI are described in the following subsections.

### Feedforward Information about Hazards

In the four scenes that were selected for the analysis, two AOIs were related to feedforward information (AOI I in Fig. 5): leftover lumber on the ground in Scene 1 and wall formwork left on the ground and blocking the path in Scene 4. Qualitatively exploring the visual attention of workers while they were walking suggested that a person with high situation awareness did not simply look down at the exact landing area of his or her steps. Instead, while moving in a natural and dynamic environment such as a construction site, the test subjects with high situation-awareness levels visually scanned the entire environment to obtain the feedforward information necessary to maintain situation awareness and did not look down at the exact landing area of steps. Scenes 1 and 4 in Fig. 6 visually demonstrate this concept: In both scenes, the fixation points of the high SA subjects appear in greater profusion beyond the immediate walking path of the subjects as compared with the low SA subjects. Another tool that can be used to compare participants' visual behavior is a heat map that represents how much members of each situation-awareness group attended to different objects in Scenes 1 and 4 (Fig. 8). The attentional distributions of low and high SA groups confirm that participants with higher situation-awareness levels allocated their attentional resources across the scene, specifically to the horizon, to obtain necessary information about potential and active hazardous situations. In contrast, those with low situation-awareness levels allocated most of their attention to the areas under their feet, with minimal allocation of attentional resources to other potential hazardous areas in Scenes 1 and 4.

In terms of quantitative analysis, the descriptive statistics of four eye-movement metrics (i.e., run count, fixation count, and dwell time) for groups with high and low situation awareness are summarized in Table 3. The descriptive data show that participants who had higher situation-awareness levels were more cautious about identifying tripping hazards beforehand; they fixated and returned their attention more frequently to these hazardous areas and spent more time processing the information obtained from these tripping areas. One interesting observation in Scene 1 is that only workers with high situation awareness levels gazed in advance toward the leftover lumber on the ground to obtain feedforward

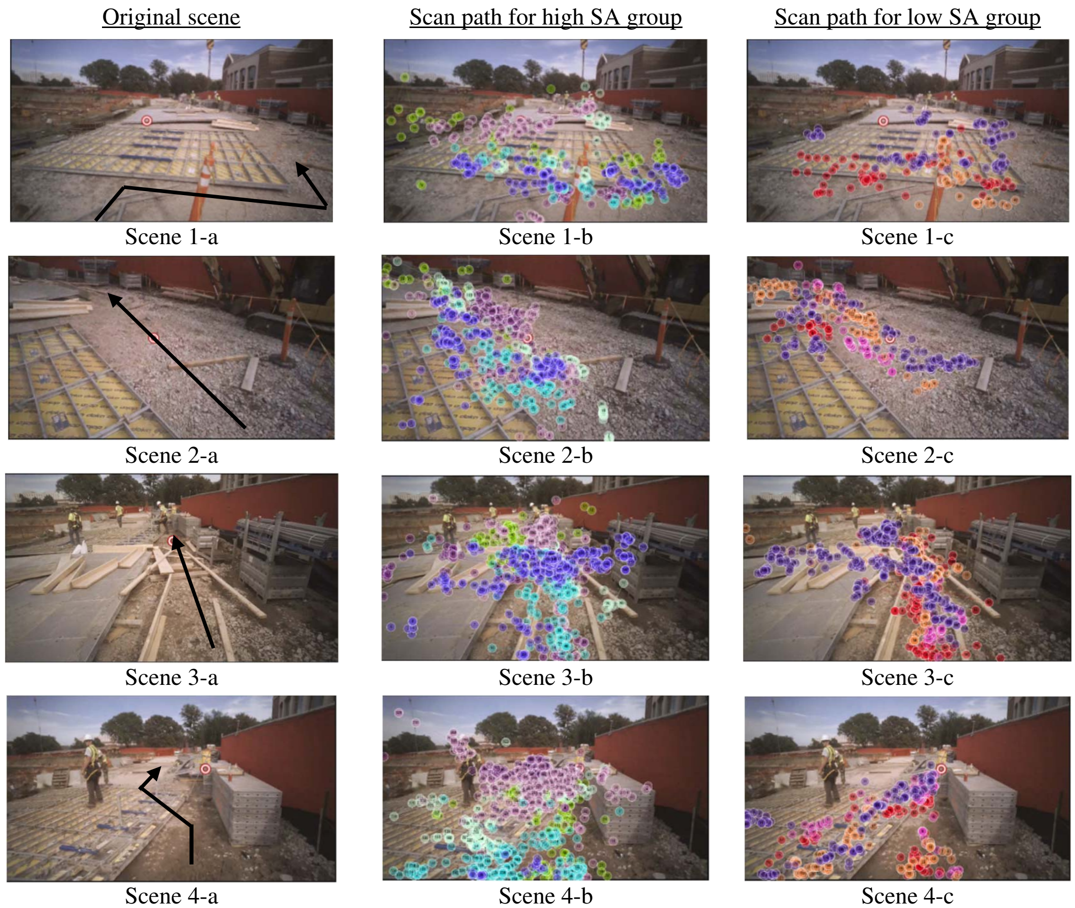



**Fig. 6.** Aggregated SA group scan paths in each scene indicating visual search strategy within each SA group. Dots represent individual participants. The search patterns of each group illustrate differences between the SA groups in terms of cognitive process (search strategy) and attentional allocation.

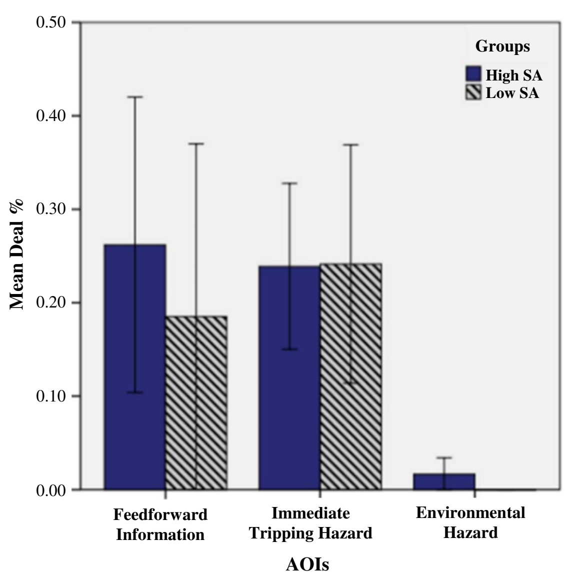



**Fig. 7.** Mean proportion of viewing time that each SA group spent looking at each category of AOI in the scenario. Error bars show one standard error of the mean.

information; workers with low situation awareness levels paid no attention to the potential tripping hazard beforehand (i.e., did not fixate on this AOI). Consequently, people with such lower situation awareness would be at greater risk of exposure to tripping hazards.

To determine whether these differences are statistically significant, the averages of the eye-tracking metrics for each group were compared across AOIs using the permutation simulation technique. The statistical analysis shows that three eye-tracking metrics significantly signaled high SA workers' abilities to obtain the necessary feedforward information to identify tripping hazards (Table 3): run count ($p_{\mathrm{Scene\,1}} = 0.10 \leq 0.1$); and dwell time ($p_{\mathrm{Scene\,1}} = 0.10 \leq 0.1$). These outcomes demonstrate that high SA workers allocated more attentional resources on the AOIs related to feedforward information across the two scenes.

In Scene 4, the walkway was blocked by stored materials and wall formwork, as shown in Fig. 8 (Scene 4-d). Thus, participants were required to scan the scene, obtain any necessary feedforward information about an alternative path, and then navigate through the path while paying attention to stored materials. The descriptive statistics related to Scene 4 show that participants with higher situation awareness had a higher mean on all attention metrics, demonstrating that they obtained more feedforward information (Table 3).

The results of the permutation simulation of participants' visual behavior while passing through this scene also show significant differences between the high and low SA groups. In terms of their visual behavior, to obtain feedforward information about an alternative path, those with higher situation awareness levels dwelt significantly longer ($p_{Scene\,4\text{-}dwell\,time} = 0.05 \leq 0.05$) and fixated more ($p_{Scene\,4\text{-}fixationcount} = 0.05 \leq 0.05$) on the AOIs related to feedforward information across scenes. The group with low situation awareness spent less time and attentional effort detecting and perceiving the risks to formulate an alternative path.

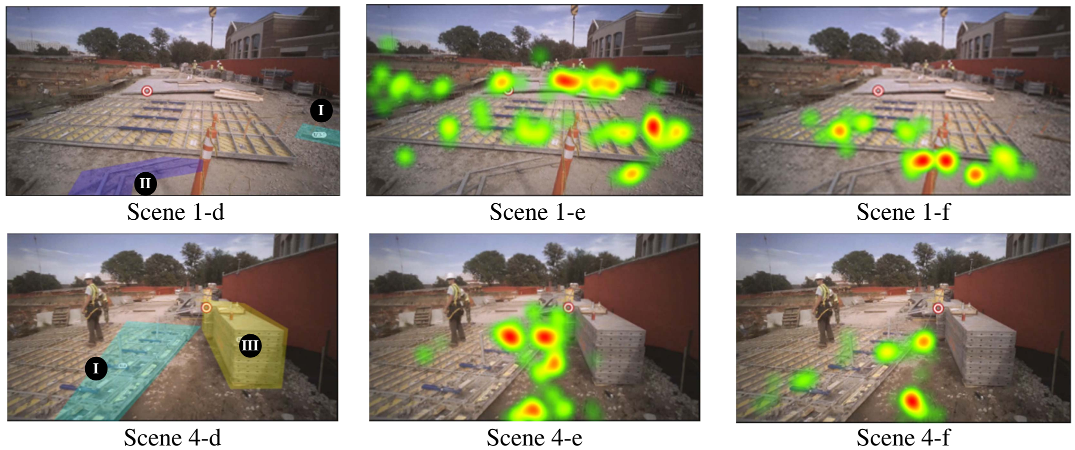



**Fig. 8.** Differences in attentional allocations of SA groups in Scenes 1 and 4.1-d and 4-d: original scene with AOIs; 1-e and 4-e: heat map for a participant with high SA level; and 1-f and 4-f: heat map for a participant with low SA level. Darker colors indicate areas that attracted more fixations and attention.

**Table 3.** Eye-tracking metrics acquired for the feedforward-information AOIs across Scenes 1 and 4

| | | High SA | | Low SA | | Permutation results | |
|---|---|---|---|---|---|---|---|
| Eye-tracking metrics | AOI | Mean | Standard deviation | Mean | Standard deviation | Welch's t | $p$ value |
| Run count | Scene 1 | 2.167 | 1.941 | 0.000 | 0.000 | 2.735 | 0.10[a] |
| | Scene 4 | 8.000 | 4.099 | 4.500 | 2.887 | 1.584 | 0.15 |
| Fixation count | Scene 1 | 2.000 | 2.898 | 0.000 | 0.000 | 1.690 | 0.25 |
| | Scene 4 | 42.667 | 29.248 | 11.000 | 9.764 | 2.455 | 0.05[b] |
| Dwell time | Scene 1 | 0.143 | 0.186 | 0.000 | 0.000 | 1.891 | 0.10[a] |
| | Scene 4 | 0.857 | 0.583 | 0.220 | 0.195 | 2.475 | 0.05[b] |

[a] $p < 0.1$.
[b] $p < 0.05$.

Combined, these results regarding the differences between the high and low SA groups' approach to gathering feedforward information enable this analysis to reject the null hypothesis $H_1$—that there is no difference between the attentional allocation of workers with low and high situation awareness in obtaining feedforward information. We will further explore the importance of this finding in the "Discussion" section.

### *Immediate Tripping Hazards*

The underfoot surface in a construction site can be relatively uncontrollable and can occasionally include multiple tripping hazards, including unexpected housekeeping hazards. Therefore, construction workers are required to divide their attention throughout the scene to identify potential causes of tripping hazards while walking at a jobsite. In this study, three AOIs related to immediate tripping hazards appear in three scenes: vertically stacked panels left on the ground in Scene 1; leftover lumber on the ground in Scene 2; and a pile of lumber scraps in Scene 3. A heat map (attentional distribution map) created for one representative subject from each situation awareness group (Fig. 9) shows that the participant with high situation awareness distributed attention across the scene to identify potential and active hazards, whereas the person with a lower situation-awareness level overfocused on some areas that presented insignificant hazards.

Table 4 lists the means, standard deviations, and results of the permutation analysis for the three eye-tracking metrics related to the scenes' three tripping AOIs. Except for the pile of lumber scraps in Scene 3, participants with higher situation awareness had a greater run count, fixation count, and dwell time on tripping AOIs.

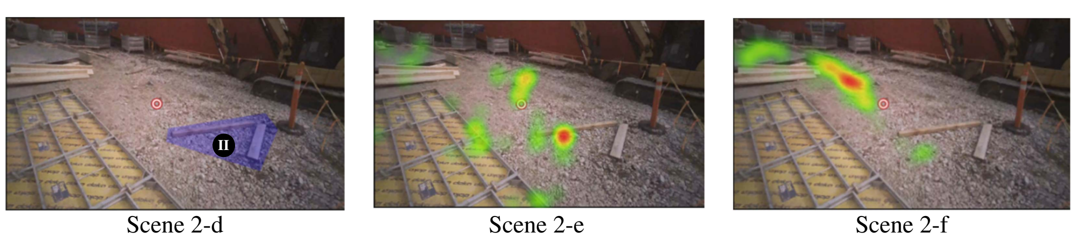



**Fig. 9.** Differences in attentional allocations of SA groups in Scene 2. 2-d: original scene with AOIs; 2-e: heat map for an individual with high SA level; and 2-f: heat map for an individual with low SA level.

**Table 4.** Eye-tracking metrics acquired for the immediate-tripping AOIs across Scenes 1–3

| | | High SA | | Low SA | | Permutation results | |
|---|---|---|---|---|---|---|---|
| Eye-tracking metrics | AOI | Mean | Standard deviation | Mean | Standard deviation | Welch's t | $p$ value |
| Run count | Scene 1 | 1.333 | 1.751 | 1.000 | 1.000 | 0.363 | 0.72 |
| | Scene 2 | 2.667 | 1.751 | 1.000 | 1.155 | 1.814 | 0.11 |
| | Scene 3 | 9.143 | 1.773 | 10.000 | 6.683 | −0.251 | 0.75 |
| Fixation count | Scene 1 | 5.833 | 6.646 | 1.333 | 1.528 | 1.577 | 0.43 |
| | Scene 2 | 24.667 | 20.820 | 14.750 | 27.536 | 0.613 | 0.52 |
| | Scene 3 | 191.000 | 91.258 | 205.250 | 62.994 | −0.305 | 0.79 |
| Dwell time | Scene 1 | 0.127 | 0.144 | 0.027 | 0.031 | 1.629 | 0.42 |
| | Scene 2 | 0.506 | 0.423 | 0.295 | 0.551 | 0.650 | 0.49 |
| | Scene 3 | 4.105 | 1.798 | 4.354 | 1.232 | −0.161 | 0.88 |



However, the inferential analysis of the subjects' eye movements showed that, overall, we cannot reject null hypothesis $H_2$—that there is no difference between the attentional allocation of workers with low and high situation awareness toward immediate tripping hazards (Table 4). Thus, the research team had to accept null hypothesis $H_2$. This finding is justifiable, because no falls or near misses were observed during the experiment.

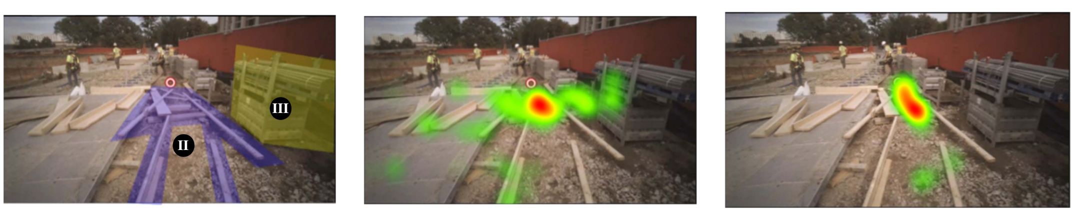
### Environmental Awareness

In addition to the objects that are directly related to tripping hazards, workers who are walking through a construction site should allocate attention to other sources of hazards in the surrounding environment, including stored materials, moving heavy equipment, or a moving crane boom. In fact, if a worker wants to pass through a walkway while maintaining environmental awareness, he or she must find a balance between focusing on tripping hazards and distributing attention to the surrounding environment. Without distributed attention, errors may occur that will lead to accidents.

During the experiment, the only environment-related hazardous situations that the safety managers identified within the scenes were the potential hazards of striking against stored materials in Scenes 3 and 4. The heat maps in Fig. 10 provide an sample comparison between the attentional allocation of participants with low and high situation awareness. The participant with low situation awareness focused primarily on tripping hazards and did not pay that much attention to the stored material. To observe attentional distribution for a member from each situation awareness group when exposed to Scene 4, see the heat map in Fig. 8 (Scenes 4-e and 4-f).

Table 5 provides the means, standard deviations, and results of the permutation analysis associated with the eye-tracking metrics focusing on environment-related AOIs. Participants from the high situation-awareness group had higher attentional allocations on all environment-related hazards; the value of eye-tracking metrics for people with low situation awareness was zero for these AOIs.

Descriptive statistics for visual attention metrics for Scene 3 demonstrate that participants with low situation-awareness levels devoted most of their attentional resources to tripping hazards and paid minimal attention to the potential hazard of striking against stored material on the right-hand side of the scene (Fig. 10). The permutation simulation of visual attention metrics related to Scene 3 reveal that participants with high situation awareness fixated for a longer time on stored materials ($p_{Scene\,3-dwell\,time} = 0.00 < 0.05$). Such outcomes imply that workers with high situation awareness would likely avoid hazardous areas after initially perceiving them. Inversely, workers with low situation awareness would be at greater




Scene 3-d Scene 3-e Scene 3-f

**Fig. 10.** Differences in attentional allocations of SA groups in Scene 3. 3-d: original scene with AOIs; 3-e: heat map for an individual with high SA level; and 3-f: heat map for an individual with low SA level.

**Table 5.** Eye-tracking metrics acquired for the environment-related AOIs across Scenes 3 and 4

| | | High SA | | Low SA | | Permutation results | |
|---|---|---|---|---|---|---|---|
| Eye-tracking metrics | AOI | Mean | Standard deviation | Mean | Standard deviation | Welch's t | $p$ value |
| Run count | Scene 3 | 0.571 | 0.787 | 0.000 | 0.000 | 1.922 | 0.21 |
| | Scene 4 | 3.167 | 4.579 | 0.000 | 0.000 | 1.694 | 0.07[a] |
| Fixation count | Scene 3 | 5.571 | 13.867 | 0.000 | 0.000 | 1.063 | 0.21 |
| | Scene 4 | 9.667 | 15.921 | 0.000 | 0.000 | 1.487 | 0.07[a] |
| Dwell time | Scene 3 | 0.111 | 0.277 | 0.000 | 0.000 | 1.063 | 0.00[b] |
| | Scene 4 | 0.197 | 0.326 | 0.000 | 0.000 | 1.476 | 0.07[a] |

[a] $p < 0.1$.
[b] $p < 0.05$.

risk of being struck by such stored materials because their eye-tracking metrics indicate that they failed to attend to and identify this hazard.

The permutation simulation run on the eye-movement metrics of the two situation-awareness groups in Scene 4 indicate that participants with high situation-awareness levels significantly (moderately; $p < 0.1$) fixated more, dwelt longer upon, and returned their attention to stored materials (Scene 4) ($p_{Scene\,4\text{-}fixation\ count} = 0.07 < 0.1$; $p_{Scene\,4\text{-}run\ count} = 0.07 < 0.1$; $p_{Scene\,4\text{-}dwell\ time} = 0.07 < 0.1$) than did those with low situation-awareness levels. Again, such a finding indicates that these participants attended to environmental hazards more often, which would foreseeably enable these workers to avoid the hazards more than their less situationally aware counterparts.

Based on the results of this analysis, we can reject null hypothesis $H_3$—that there is no difference between the attentional allocation of workers with low and high situation awareness toward environmental hazards, for several eye-tracking metrics.

## Discussion

Skills to allocate limited attentional resources properly and in a balanced way are important for detecting hazards, perceiving them, and making proper decisions to avoid potential accidents. Therefore, this study investigated whether differences in workers' attentional distribution—and in particular, their focus on tripping hazards—relate to their situation awareness. Given the main hypothesis, this paper puts forth that attentional allocations relate to workers' situation awareness. Moreover, given that this study limited its scope to workers' detection of tripping hazards, the research team tested this hypothesis using three categories of AOIs: obtaining feedforward information, detecting immediate tripping hazards, and maintaining environmental awareness (i.e., detecting adjacent hazards such as stored materials). Qualitative analyses of the eye-movement patterns and attentional distributions of subjects in high and low situation-awareness groups revealed that those with higher situation awareness periodically looked down and scanned ahead while they walked along the jobsite path; these workers also repeated these motions frequently to remain fully aware of the environment and its associated hazards. Quantitative analysis using permutation simulation also indicated that workers did not allocate their attention equally to all hazardous areas, and—notably—these differences in attentional distribution were modulated by the workers' situation awareness.

Two categories of AOIs yielded statistically significant eye-movement metrics between the subject groups: feedforward information about hazards and environmental hazards. As far as obtaining feedforward information is concerned, our inferential statistics enabled this study to reject the null hypothesis $H_1$. Rather, the findings of this study show that workers with high situation awareness not only look where they are stepping, but also direct their gaze forward toward their intended path so they can gain feedforward information to detect potential hazards. Receiving feedforward visual information about the path ahead allows workers to proactively adjust their gait and safety to accommodate obstacles and other potential tripping hazards. Members of the higher situation awareness group who are equipped with this information are subsequently able to adjust their step length and foot placement to avoid exposure to tripping hazards. These results align with the findings of Hasanzadeh et al. (2016), who provided evidence that to maintain situation awareness and identify hazards on a construction site, workers need to allocate their attentional resources in both distributed and focused ways and not overfocus on a single source of hazard. The results of our study also coincide with previous studies that have implied that visual attention plays an important role in sensory proactive response to hazards (Patla 2003; Sheik-Nainar et al. 2015). Gathering and using feedforward information enables workers with high situation awareness to avoid hazards before immediately encountering them.

Regarding environmental hazards, the results of this study also showed that workers with higher situation-awareness levels balance their attentional allocation between looking for tripping hazards and maintaining awareness about other potential hazards in the surrounding environment (e.g., stored materials); thus, this study could reject null hypothesis $H_3$. Our results show that those who have a lower level of situation awareness erroneously tend to direct their attentional resources solely to the task that they are performing (i.e., walking); however, workers with higher levels of situation awareness distribute their attention in a more balanced way to not only detect the tripping-related hazards ahead but also to maintain awareness of the surrounding construction environment. This finding reasonably relates to the limited capacity of attentional resources: maintaining gait and scanning the environment demand attention; therefore, performing both tasks simultaneously may deteriorate performance in one of the tasks (Segev-Jacubovski et al. 2014). This study's eye-tracking data revealed that most of the environment-related hazards did not come within the effective visual field of subjects with low situation awareness, because their cognitive resources were occupied with their primary activity, leaving fewer attentional resources available for scanning beyond the subjects' effective visual field. Therefore, to increase the likelihood of detecting hazards, safety managers need to be proactive about teaching broader SA skills to workers, to distribute their attention to the surrounding environment and the path workers are traveling, even beyond their effective visual field.

This study found no statistically significant difference between the attentional allocation of workers with low and high situation awareness when exposed to immediate tripping hazards. This finding can be explained by the fact that during the experiment, there were no tripping accidents or near misses. Nonetheless, identifying hazards by obtaining feedforward information would relieve the cognitive load for workers with higher situation awareness, making more cognitive resources available to detect other potential hazards (i.e., environmental hazards).

With regard to situation awareness and eye-movement metrics, the results demonstrated that greater situation awareness is associated with increased run count, fixation count, and dwell time on related AOIs. Apart from a minor exception, these findings affirm many previous laboratory-based eye-tracking studies. However, some previous construction safety studies that used eye tracking in the laboratory found that workers with higher hazard-identification skills dwelt less on hazards (Hasanzadeh et al. 2017a, b), a finding that diverges from the results obtained with the mobile eye tracker used in the current study. This discrepancy can be explained by comparing the experimental conditions in the laboratory and real world. In studies conducted by Hasanzadeh et al. (2017a, b), workers were given a limited amount of time (20 s) to scan each scenario image and identify hazards. Such time pressure indirectly affected safety behavior, because subjects tended to scan over the scene quickly to detect hazards and report the number of identified hazards. In other words, in the laboratory setting, there was no need to focus on a single central hazard. Furthermore, in the laboratory studies, the participants were certain that they were not going to be injured even if they had missed a hazard. In contrast, in the mobile eye-tracking experiment conducted in this study, participants were given 45 s to move from one point to another while choosing their own walking strategy. Because participants were responsible for their own safety while being exposed to hazards in a dynamic environment, fear of getting injured would have affected the way they distributed their attention; therefore, they tended to dwell longer on potential hazards. This outcome indicates that workers who dwell longer on potential safety risks while returning attention to potential causes of hazards more often are more likely to develop higher situation awareness.

In summary, although the results of this study validate findings of previous laboratory eye-tracking experiments, they also push the frontiers of our knowledge about the differences between attentional allocation in a laboratory setting versus natural behavior on a real construction site. These findings further highlight the importance of conducting eye-tracking experiments in real-life settings using mobile devices.

## Contributions to Theory and Practice

The findings of this study have significant implications for both theory and practice. For academics, this study is one of the first attempts to measure the relationship between attention and situation awareness using eye movements. Because past studies reveal that it is feasible to track eye movements as an indicator of meta-cognitive processes such as attention, and this study demonstrates that eye-tracking metrics separate low situationally aware workers from high, this study opens the door to further examinations of the effect of a wide range of variables (e.g., stress, fatigue, work load, risk perception, risk-taking behavior, and personality) on situation awareness and, consequently, on the likelihood of accidents occurring in a real construction setting. In fact, using mobile eye-tracking technology, researchers can better understand root causes of safety incidents by studying the natural behavior of workers on a real-world construction site. Such an opportunity for study will advance our fundamental knowledge about the role of cognitive processes in human error and occupational accidents. Furthermore, the results of the current study demonstrate the utility of using mobile eye trackers for determining the relationship between situation awareness and attention. Therefore, this approach can be used in conducting studies related to cognitive ergonomics in improved construction safety.

Understanding how people with high situation awareness distribute their attention (e.g., obtaining more feedforward information) also has practical implications for safety managers and project managers. Considering that proper division of attention is a skill that can be learned (Damos and Wickens 1980), limitations on attentional resources may be circumvented by providing effective training and safety guidelines to people whose eye-tracking metrics reveal a low situation awareness level. For example, training programs can be developed to emphasize the importance of obtaining feedforward information and detecting environmental hazards while walking on a construction site. Consequently, workers will learn to use an efficient process of information sampling to compensate for attention limits and to attend to potential objects with relative priorities and frequency, thus maximizing their performance and increasing situation awareness.

Furthermore, because participants reported that the mobile eye tracker did not affect their effective visual field and was a relatively unobtrusive tool (much like safety glasses), this study demonstrates the feasibility of using mobile eye tracking to assess situation awareness and attentional allocation of subjects in real time. As technology advancements proceed and the cost of eye trackers decreases, practitioners can use mobile eye trackers on sites to identify at-risk workers (e.g., workers with low hazard identification skills and fatigued or distracted workers), provide personalized training for them based on the hazards they missed or ignored, measure training effectiveness, and foreseeably aggregate data to detect hidden hazards on site. Furthermore, the feedback provided from tracking eye movements can lead to the development of metacognitive practices to help workers become aware of their strengths and weaknesses in detecting hazards and distributing their attention.

## Limitations and Future Studies

There are some limitations related to this study that need to be mentioned. First, the research team aimed to conduct an experiment on a live construction site while other activities were going on. Because the construction site is dynamic (and thus the scenario would change over extended amounts of time), the research team had a short amount of time to test subjects, which limited the potential number of participants. We therefore suggest conducting similar experiments with larger sample sizes. Second, the mobile eye tracker used in the current study functions for those who wear contact lenses, but not those who wear eye glasses; the authors were forced to remove subjects with corrective eye glasses due to calibration difficulties. Foreseeably, as technology advances, the new versions of mobile eye trackers address this limitation by providing prescription lens packages for participants with vision impairments. Such advancements will allow for a larger variety of subjects in real-life settings such as those involving construction sites. Third, in this study the authors only examined attention and did not measure other influential cognitive processes, such as working memory. Because working memory capacity is limited, conducting multiple tasks at the same time may lead to poor performance (e.g., Hasanzadeh et al. 2017c; Sheik-Nainar et al. 2015). We suggest that future studies use mobile eye trackers to study the safety performance of construction workers by manipulating working memory (e.g., task complexity) or time pressure and then by comparing the results with the baseline awareness level of individuals before manipulation. Moreover, the researchers suggest that future studies collect more qualitative data through structured interviews that accompany quantitative data to obtain more information about the causes of missed or unattended hazards. Fourth, because the scope of this study was limited to tripping hazards, we suggest that future studies explore the relationship between attention and situation awareness in other construction activities such as roofing. Despite these limitations, the results of this study advance our knowledge and understanding of the role of attention and situation awareness in tripping-related hazards and provide a framework for objectively differentiating less situationally aware workers from more situationally aware workers.

## Conclusion

Tripping hazards are among the most common incidents on construction sites (Lim et al. 2015). Beyond the cost and loss of productivity resulting from these injuries, tripping accidents can lead to a lifetime of pain for injured workers. Although walking is a somewhat automated process and can be completed with little conscious thought, for construction workers to walk safely at a jobsite, they must exert some conscious input, specifically through visual cues. Information about where and how a worker distributes his or her attention while moving through a construction site thus helps to identify the causes of tripping injuries. Although a few studies have used eye trackers to assess the visual attention of construction workers in laboratory settings (Bhoir et al. 2015; Hasanzadeh et al. 2017a, b, c), one may argue that workers behave differently when they are in a live construction site due to the complexity and



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existence of multiple attentional targets in a real-world setting. To address this knowledge gap, this study evaluated the utility of tracking and analyzing the eye movements of construction workers moving through a natural and dynamic construction environment to determine whether eye movement patterns can differentiate workers with high and low situation-awareness levels. Qualitative results (presented in scan paths and heat maps) and quantitative analysis (executed via permutation simulation) of eye-movement metrics in potential hazardous areas allowed this study to evaluate differences in attentional allocations among construction workers with varying levels of situation awareness. This study revealed that individuals in the high SA group allocated a substantial percentage of their attention to potential causes of tripping hazards in advance to obtain required information. These situationally aware workers also tended to allocate more attentional resources to potential peripheral hazards, such as stored materials, than those with low SA. However, there was no significant statistical difference between the attention allocations of participants with high and low situation awareness regarding immediate tripping hazards.

The outcomes of this study provide valuable insights both to practice and theory, as the ability to objectively differentiate workers' level of situation awareness using their attention metrics will facilitate rapid and accurate detection of at-risk workers in addition to opportunities for evaluating variables that influence workers' safety risk. Furthermore, safety managers will be better able to assess and identify workers' situation awareness levels, which will enable such safety managers to train workers to distribute their attentional resources properly to achieve higher situation awareness. Thus, this study yields both immediate benefits in connecting eye-tracking metrics to workers' attentional allocation and situation awareness and long-term benefits in opening new avenues for safety-risk research and mitigation.

## Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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