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USING EYE MOVEMENTS TO IDENTIFY HAZARDS MISSED BY AT-RISK WORKERS

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Identifying hazardous situations is a complex and multidimensional cognitive process that requires the proper allocation of workers' attention. Eye-tracking technologies provide a viable option for studying construction workers' attentional allocation and for linking attention to their hazard-identification capabilities. The objective of the study is to use eye-movement measures to determine which types of hazards construction workers miss, ignore, or perceive to be insignificant. In order to achieve this goal, 31 construction workers participated in a controlled laboratory experiment in which they searched for hazards in images of 35 real construction-site scenarios while a head-mounted EyeLink II tracked their eye movements. The results showed differences in the participants' attentional distributions and that the hazard identification of workers with low and high hazard-identification skills stems from the types of hazard - not the number of hazards - within the scenarios. Further investigation on five images revealed that at-risk workers dwelt on imminent danger (*e.g.*, workers in dangerous areas) rather than spreading their attentional efforts searching for sources of non-obvious hazards, including electrical hazards, housekeeping hazards and fall-protection-system-related hazards. The results of this experiment can thus support personalized safety training that targets at-risk workers.

Keywords: Hazard identification, Construction safety, Safety training, Eye-tracking, Visual attention.

1 INTRODUCTION

Construction accidents are one of the major concerns in construction projects worldwide (Esmaeili and Hallowell 2012, Zhang and Fang 2013, Pellicer *et al.* 2014), so project stakeholders often invest in various injury-prevention practices (Lu *et al.* 2016) to curb incidents. Since two of the main underlying causes of accidents in construction projects are skill-based errors (*e.g.*, lapsed attention) and perceptual-based errors (*e.g.*, failure to identify or misperceptions) (Garrett and Teizer 2009, Lopez *et al.* 2010), substantial amounts of funding have been invested in providing training to improve workers' hazard-identification skills. While the objectives of these training sessions are to enable workers to identify and manage hazards on-site, return on investment in training is very low as it relates to transferring skills (Baldwin and Ford 1994, Cromwell and Kolb 2004). One of the reasons for such a low efficiency is that, traditionally, similar trainings are provided to workers without considering their differences in knowledge, skill, national culture, and personality (Esmaeili *et al.* 2014, Lin *et al.* 2014). Therefore, devising techniques to provide safety trainings based on the individual needs of workers would help to save money and time.

An early step in developing personalized safety-training materials is to identify at-risk workers who need training regarding a specific type of hazard. A simple method to determine if a worker is not well-suited to identify a certain type of hazard is to ask him/her subjectively; however, there are some limitations related to this approach. First, self-report questionnaires are subject to bias, and it is possible that some workers will exaggerate the number of hazards that they can identify in order to impress their supervisors. Second, while one can conduct more in-depth interviews with a worker to see what hazards he/she has identified correctly, such subjective methods still do not provide any information about the amount of attention that a worker has paid to a hazard.

Given that where one looks is highly correlated with where that person is focusing his or her attention (Jacob and Karn 2003), eye movement monitoring is the most direct measure of the number and types of hazard that a worker can identify and. Eye-tracking technology is one of the most common techniques for measuring oculomotor behavior and visual attention (Popa *et al.* 2015), and several recent studies have shown practical applications of this technology to detecting at-risk workers, measuring situation awareness, and understanding the role of safety knowledge in workers' hazard identification skills (Hasanzadeh *et al.* 2016). However, no study has yet investigated the applicability of using eye-tracking technology to detect training requirements for a specific worker. To address this knowledge gap, the objective of this study is to provide a proof of concept that eye-tracking technology can be used to determine skill-based errors among at-risk workers and to identify the need for training a worker about a specific type of hazard.

2 METHODOLOGY

Thirty-one construction laborers from construction sites in Lincoln and Omaha, Nebraska, were recruited to participate in an eye-tracking experiment. All participants viewed 35 randomly ordered construction-scenario images, each of which displayed multiple hazards varying in safety risk. Each image appeared on the screen for a maximum of 20 seconds. To track and record subjects' eye movements, participants wore a head-mounted eye-tracking device (EyeLink II: SR Research Ltd) with a high spatial resolution and a sampling rate of 500 Hz. Participants then scanned each picture to look for potential or active hazards. After the image disappeared from the screen, subjects were asked about the number, types, likelihood, and severity of the safety issues they found in each scenario's image. In addition, participants took a short demographic survey addressing their age, gender, nationality, years of experience, obtained certifications, and safety training.

The first step in extracting eye-movement metrics and establishing dependent measures is to define areas of interest (AOI) in each image. AOIs are visual environments of interest that members of the research team define (Jacob and Karn 2003); in this study, a focus group consisting of five safety managers with more than 10 years of experience designated the AOIs. The AOIs included hazards related to ladders, falls to lower levels, fall-protection systems, housekeeping, struck-by risks, caught-in/between risks, and electricity. The EyeLink® Data Viewer then gathered and analyzed the two-dimensional eye-movement patterns of construction workers. The selection of eye-movement metrics depends on the cognitive processes investigated in each study. In this study, three fixation-related metrics per AOI were chosen: fixation count (*i.e.*, the number of times the observer fixated on the specific area), the dwell-time percentage (*i.e.*, relative to the duration of the trial, what proportion of time was spent fixating on each AOI), and run count (*i.e.*, the average number of times each participant returned his/her gaze to a specific AOI). These metrics have been used frequently in previous eye-tracking work as dependent variables (*e.g.*, Bhoir *et al.* 2015, Hasanzadeh *et al.* 2016) to determine which stimuli workers attended to.

To evaluate the hazard-identification skills of workers, the hazard-identification index (HII) suggested by Carter and Smith (2006) was calculated for each worker for each picture. Then, based on the participants' average performance in identifying hazards across 35 images (*i.e*., HII), they were divided into three groups—namely low, medium, and high HII groups. Eye-movement metrics were calculated for each group across the various types of hazards (AOIs). The primary hypothesis was that the complexity of the scenario would impact workers' performance in identifying hazards. To analyze this hypothesis, the scenario images were first ordered based on the number of hazards (AOIs) within them, with the three eye-movement metrics on the vertical axis. The results showed no specific trend between the number of hazards in the image and the performance of HII groups; however, considerable differences between HII-group performance appeared in some images. Accordingly, using a set of criteria to select scenarios for further analysis—specifically, images with more than one standard deviation's worth of difference in eye-movement metrics among workers with high and low hazard-identification skills—five images were chosen for further investigation. To determine which types of hazards workers with different hazard-identification skills missed or perceived to be less significant, the research team then performed a permutation simulation on the actual eye-movement measures.

3 RESULTS AND DISCUSSIONS

As mentioned earlier, five pictures were selected for further analysis. These pictures, along with their permutation results for eye-movement metrics, are shown in Figure 1. Image "a" contains three hazardous situations (AOIs) that can lead to accidents: two ladders in an unsafe position and trip hazards on the ground due to improper housekeeping. Conducting permutation analysis revealed that while participants with high hazard-identification skills dwelt less on ladder-related hazards, they had higher dwell percent, fixation count, and run count on trip hazards. This result indicates that at-risk workers who had low hazard-identification skills failed to identify housekeeping hazards (or perceived them as insignificant), which signals that workers with low hazard-identification skill need to be trained more proactively about the risk of slips, trips, and fall to same level hazards and how to respond to them properly. This finding concurs with previous literature that also recognized slip and trip hazards as significant sources of injury (*e.g.*, Layne and Pollack 2004, Lipscomb *et al.* 2006); in most of the reported injuries, the victim was not performing a task but rather moving from one place to another when the slip or trip occurred (Lipscomb *et al.* 2006). Outcomes from image "a" highlight the fact that human factors are important contributing causes to slip and trip injuries; thus, it is important to provide proactive and effective training for workers with low hazard-identification skill to address safe walking areas.

Image "b" has three AOIs: a worker close to an open edge, improper guardrail installation, and loose materials on a roof. The permutation analysis showed that participants with high hazard-identification skill returned their attention to fall-related hazardous areas more frequently to check every dimension of the unprotected edge and its corresponding worker whereas subjects with low hazard-identification skills over-focused attention on imminent danger or workers in dangerous areas instead of spending their attentional efforts searching for the sources of hazards. These outcomes mean that workers with low hazard-identification skills should to be trained to gain more information about the requirements for providing proper and safe guardrails. Additionally, results from this experiment showed that the area given the least attention from both groups was the area associated with shingles laying up on the roof (housekeeping hazard). Expanded training would be warranted for such hazards.

There are two main hazards in image “c”: a burn risk due to welding, and working at height with improper use of a personal fall-arrest system—based on OSHA regulations, the retractable lanyard should be placed above the worker’s head and should have a sufficient length to prevent contact with a lower level; the anchorage connector in this image cannot prevent the worker’s contact with a lower level if a fall occurs since it is twisted up on his backside. As one can see, the permutation analysis demonstrated that workers with higher hazard-identification skills paid more attention (in terms of fixation count and run count) to both AOIs. The results of the analysis suggest that workers with low hazard-identification skills need to be trained regarding safety requirements of fall protection systems (*e.g.*, anchorage connectors, lanyards, body harnesses) and potential hazards related to welding activities.

Image “d” represents two workers who are working on the aerial lift with no fall-arrest system and inappropriate PPE. Fall protection is important for those who work on the aerial work platform: Based on OSHA regulations and ANSI standards, while the guardrail around a platform is considered a primary fall-protection system, a fall-arrest system with a short lanyard attached to the anchor point of the boom is required with all boom-supported elevated platforms to prevent the workers from being ejected or pulled from the basket (OSHA 1926.453(b)(2)(v) and ANSI/SIA A92.5 7.10(1)). Moreover, workers must wear appropriate PPE while working on the aerial work platforms. Statistical analysis showed that at-risk workers paid less attention to these safety issues. Such findings call for developing training materials detailing the safety requirements of working on aerial lifts and on other boom- supported platforms for these at-risk workers.

There are three main hazards in image “e”: fall to lower level, improper installation of lanyard, and electrocution. The two groups performed significantly differently in identifying the hazard associated with the fall-related hazard. In this picture, the worker wrapped the lanyard around the front side of his body meaning that, if he fell, he would likely spin around and strike against the I-beam and the metal handrail. The results from the eye-tracking experiment showed that at-risk workers placed less attentional effort on this area; consequently, this hazard appeared to not be important to them because they did not identify or assess its associated risk. However, the workers with higher hazard-identification skills checked the appropriateness of the fall-protection system and assessed the risk of fall by refocusing their attention and fixating their gaze more frequently to this area of interest. Furthermore, in this picture, the plug of the portable drill had been inserted into the receptacle of a very long extension cord lying on the ground and tied to a metal handrail. This situation has a high risk for an electrical hazard. The permutation simulation showed that workers with higher hazard-identification skills spent more time assessing the risk of this hazard by fixating their gaze on this area and also by returning their attention more frequently to evaluate the associated risk completely. This finding indicates that at-risk workers also need to be trained about the safety requirements of using electric portable equipment on the jobsite.

(a)

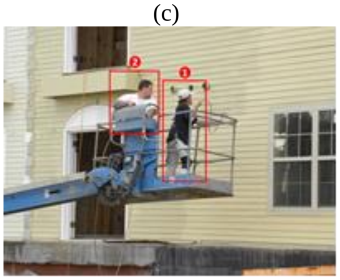
ET metrics - AOI	Welsh t-	*p*-value	Low HII Mean (SD)	High HII Mean(SD)
Dwell% - (1)	2.241	0.057*	0.264 (0.153)	0.129 (0.048)
Fixation count - (1)	0.340	0.783	8.429 (4.541)	7.714 (3.200)
Run count - (1)	-1.868	0.087**	3.143 (1.215)	4.571 (1.618)
Dwell% - (2)	1.751	0.111**	0.284 (0.084)	0.203 (0.090)
Fixation count - (2)	-0.511	0.629	11.000 (3.606)	12.429 (6.451)
Run count - (2)	-0.721	0.505	4.571 (1.718)	5.429(2.637)
Dwell% - (3)	-2.153	0.050*	0.163 (0.101)	0.289 (0.117)
Fixation count - (3)	-2.731	0.019*	6.571 (4.791)	17.714 (9.673)
Run count - (3)	-3.078	0.007*	2.714 (1.704)	6.429 (2.699)

(b)

ET metrics - AOI	Welsh t-	*p*-value	Low HII Mean (SD)	High HII Mean (SD)
Dwell% - (1)	0.791	0.434	0.149 (0.101)	0.112 (0.069)
Fixation count - (1)	-1.013	0.330	3.714 (2.870)	5.571 (3.910)
Run count - (1)	-1.477	0.184	1.286 (0.756)	1.857 (0.690)
Dwell% - (2)	-0.600	0.567	0.154 (0.106)	0.184 (0.075)
Fixation count - (2)	-3.644	0.009*	4.429 (2.507)	11.857 (4.776)
Run count - (2)	-1.789	0.104**	2.714 (1.604)	4.857 (2.734)
Dwell% - (3)	1.187	0.254	0.396 (0.107)	0.339 (0.070)
Fixation count - (3)	-1.703	0.116**	11.143 (3.185)	15.143 (5.336)
Run count - (3)	-1.444	0.171	4.429 (1.397)	6.000 (2.517)

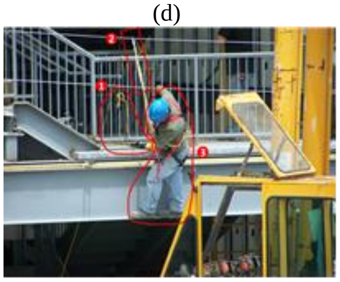
(c)

ET metrics - AOI	Welsh t-	*p*-value	Low HII Mean (SD)	High HII Mean (SD)
Dwell% - (1)	-1.299	0.210	0.075 (0.048)	0.096 (0.057)
Fixation count - (1)	-3.323	0.001*	3.143 (2.414)	6.619 (4.141)
Run count - (1)	-3.424	0.001*	1.952 (1.396)	3.714 (1.901)
Dwell% - (2)	-0.531	0.624	0.300 (0.108)	0.326 (0.072)
Fixation count- (2)	-2.658	0.018*	11.571 (4.928)	20.571 (7.480)
Run count- (2)	-3.258	0.010*	5.857 (2.410)	9.571 (1.813)



(d)

ET metrics - AOI	Welsh t-	*p*-value	Low HII Mean (SD)	High HII Mean (SD)
Dwell% - (1)	-0.135	0.900	0.124 (0.065)	0.129 (0.072)
Fixation count - (1)	-1.371	0.195	4.429 (4.036)	7.714 (4.889)
Run count - (1)	-1.492	0.156	2.571 (1.718)	4.571 (3.101)
Dwell% - (2)	0.322	0.754	0.403 (0.130)	0.385 (0.078)
Fixation count - (2)	-2.482	0.031*	15.000 (5.228)	24.714 (8.939)
Run count - (2)	-2.420	0.033*	4.857 (1.773)	8.000 (2.944)



(e)

ET metrics - AOI	Welsh t-	*p*-value	Low HII Mean (SD)	High HII Mean (SD)
Dwell% - (1)	-1.950	0.078**	0.052 (0.042)	0.109 (0.066)
Fixation count - (1)	-2.372	0.034*	2.571 (2.370)	6.571 (3.780)
Run count - (1)	-2.298	0.050*	1.571 (1.272)	3.429 (1.718)
Dwell% - (2)	0.175	0.871	0.056 (0.024)	0.053 (0.039)
Fixation count - (2)	-1.561	0.149	1.857 (1.215)	3.429 (2.370)
Run count - (2)	-0.816	0.362	1.571 (0.787)	2.143 (1.676)
Dwell% - (3)	0.358	0.704	0.406 (0.141)	0.383 (0.096)
Fixation count- (3)	-2.538	0.025*	15.714 (5.964)	26.714 (9.793)
Run count- (3)	-1.884	0.075**	5.714 (1.704)	8.429 (3.409)

Figure 1. Results of permutation simulation on each AOI across low and high hazard-identification index groups. ET metrics = eye-movement metrics; AOI = number of areas of interest in image.

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