Working-Memory Load as a Factor Determining the Safety Performance of Construction Workers

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ABSTRACT

Cognitive processes have been found to contribute substantially to the human errors that lead to construction accidents. Working memory—a cognitive system with a limited capacity that is responsible for temporarily holding information available for processing—plays an important role in reasoning and decision-making. Since eye movements indicate where a worker directs his/her attention, tracking such movements provides a practical way to measure workers' attention and comprehension of construction hazards. As a departure in construction industry research, this study correlates attentional allocation with working memory to assess workers' situation awareness under different scenarios that expose workers to various hazards. To achieve this goal, this study merges research linking eye movements and workers' attention with research focused on working-memory load and decision making and evaluates what, how, and where a worker distributes his/her attention while performing a task under different working-memory loads. Path analysis models then examined the direct and indirect effect of different working-memory loads on hazard identification performance. The independent variable (working-memory load) is linked to the dependent variable (hazard identification) through the set of mediators (attention metrics). The results showed that the high-memory load condition delayed workers' hazard identification. The findings of this study emphasize the important role working memory plays in determining how and why workers in dynamic work environments fail to detect, comprehend, and/or respond to physical risks.

INTRODUCTION

Many consider the construction industry one of the most hazardous industries in which to work, and construction accidents are one of the major concerns challenging construction projects worldwide (Esmaeili and Hallowell 2012). Such characteristics may be attributed to the industry's dynamic nature and diverse environments, especially given that construction jobs often must be performed at heights and in complex work environments, which inherently embeds risks to workers' health and safety (NIOSH 2004). Furthermore, construction activities usually involve physically demanding tasks executed in adverse environmental conditions, which can lead to poor judgment, poor work quality, decline in productivity, and increased risk of accidents (Cheng et al. 2013). Compounding such challenges is the fact that unlike other industries, construction jobs are more labor-intensive, increasingly complex, and often demand that construction workers surpass their natural physical capability (Nath et al. 2017). These considerations shed light on why 971 out of the 5,147 fatalities (18.9%) in 2017 occurred in the construction industry alone (BLS 2018), and such statistics justify the need to identify innovative techniques and practices to reduce workers' risks.

Workers' unsafe behaviors resulting from human errors represent the causal factor for up to 80% of accidents in the construction industry (Li et al. 2015). Such errors manifest because, apart from the industry's physical demands, construction tasks require a high level of cognitive activity. Goal-directed, these tasks are associated with the processes of attention and working memory, which place cognitive stress on the worker alongside physical effort. Consequently, analyzing the working memory and attention functions in workers' unsafe behaviors is an essential step in understanding and thereby preventing injuries on construction jobsites (Hasanzadeh et al. 2017b).

An increasing number of studies in psychology and neuropsychology have indicated that cognitive processes and eye movements are interrelated (Sun et al. 2008, Mele and Federici 2012), so eye-tracking technology has been harnessed to measure cognitive processes in construction safety (Hasanzadeh et al. 2019). Previous research used eye-tracking technologies to evaluate the impact of attentional and environmental factors (injury exposure, work experience, and training) on construction workers' awareness allocation and hazard identification (Hasanzadeh et al. 2016). However, only one study has investigated the interaction between attention and working memory (Hasanzadeh et al. 2017b). Consequently, knowledge about working memory in construction is limited.

This study addresses this knowledge gap by investigating the role of working-memory load on the awareness allocation of construction workers when they are exposed to fall hazards. Here, and for the first time, a meditation path model defines the direct and indirect impacts of working memory on hazard identification, using eye metrics as mediators. The findings of this study contribute to the construction industry by enhancing the knowledge of how working memory impacts the safety performance of construction workers, which in turn reveals opportunities for preventing or interrupting the human errors at play in construction accidents.

Working Memory

"Working memory" is described as the significant system or systems involved in maintaining and temporarily storing information in mind while performing complex tasks such as reasoning, learning, and comprehension (Baddeley, 2010). Working memory is associated with information-processing functions, and it facilitates awareness, reasoning, planning, and problem solving (Cowan, 2014). The model of how working memory functions appears in Figure 1.

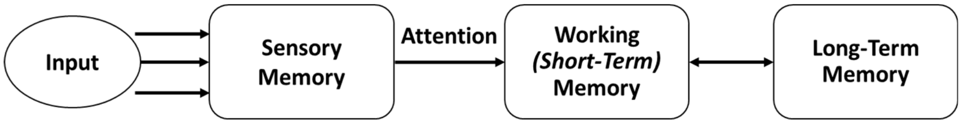


Figure 1. The Working Memory Model (Adapted from Hitch and Baddeley, 1976)

The use of the theoretical concepts "Short-Term Memory" and "Working Memory" in literature is not always rigorous, even though these terms differ from each other in the cognitive functions they are presumed to reflect. Correlational studies have not been able to divide both concepts consistently and there is evidence for a large or even complete overlap between these two concepts (Aben et al. 2012). Moreover, cognitive processes are viewed as a sequence of persistent conditions representing end products of processing. In skilled activities, obtained memory skills allow these end products to be transferred to long-term memory storage and kept directly accessible by means of retrieval signals in short-term memory (Ericsson and Kintsch 1995). The current study uses these concepts to manipulate the working memory load and further examine the correlation between attentional allocation and working memory in construction safety.

POINT OF DEPARTURE

Although some previous studies have been conducted using eye-movement data to measure attention in the field of construction safety (Hasanzadeh et al. 2016, 2017a, Hasanzadeh et al. 2018, 2019, Sun and Liao 2019), a limited number of studies have focused on the connection between working memory and eye movements (Hasanzadeh et al. 2017b, Li et al. 2019) or have studied the mediating effect of eye movements on hazard identification (Hasanzadeh et al. 2018, Sun and Liao 2019). Given that working-memory load is one of the important—and yet unexplored—attentional factors impacting the situation awareness of construction workers, manipulating working memory provides an opportunity to determine the safety performance of construction workers under different working-memory loads. This project will examine the link between working-memory load and hazard-identification performance using eye metrics as mediators. Specifically, we will use path analysis to describe the directed dependencies among the independent variable (working-memory load), dependent variable (hazard identification), and the set of eye metrics variables serving as mediators.

RESEARCH METHODS

Apparatus

Participants' eye movements during the experiment were tracked using EyeLink II, a system produced by SR Research Ltd. out of Kanata, ON, Canada. The EyeLink II is a video-based eye-tracking system that consists of three miniature cameras mounted on a comfortable padded headband. One head-tracking camera detects infrared markers in the world, while two eye cameras focus on the left and right eyes respectively. An optional scene camera allows eye movement recordings to be integrated into the worldview of the subject in a scene-camera mode. This system operates with a high spatial resolution and a sampling rate of 500 Hz to track and record the subjects' eye movements and to determine the path of their focus.

Participants

Thirty-eight students *(30 male, 8 female)* participated in this study. To assure the familiarity of the subjects with construction-site safety hazards, the participants were selected from their respective schools' civil engineering department. The vision of the selected participants was normal or corrected to normal, which allowed for the proper calibration of the eye-tracking device.

Experiment Modeling

The experiment in this research consisted of two main tasks: (1) identifying potential or active hazards *(primary tasks)*, and (2) memorizing a three-digit or six-digit string, used to impose low- and high-working-memory loads, respectively *(secondary task)*. The intention of the experiment was to combine both tasks in order to measure subjects' efficiency in identifying safety hazards while experiencing low- and high-working-memory loads.

The primary task was introduced to the subjects as an assignment to identify the potential hazards in 35 construction-scenario images. Before the start of each test, participants received a full briefing about the procedures of the experiment. The subjects' performance in hazard identification was then monitored via their eye movements using the SR Research Eyelink II system and by the verbal reporting of the subjects, recorded by the research team during the experiment. The tests were conducted in the Safety, Risk Management, and Decision-Making (SARMAD) lab at George Mason University and at the Center of Brain, Biology and Behavior at the University of Nebraska-Lincoln.

The images used in the experiment involved different types of construction activities (erecting structures, roofing, etc.) from various private residential and commercial construction sites across the United States. Moreover, they contained one or multiple different hazard types, including those most likely to lead to accidents, such as fall-protection systems, fall-to-lower-level, struck-by, ladders, and housekeeping. Hazardous situations in all the pictures were defined in previous study (Hasanzadeh et al. 2016) where the assistance of certified safety managers, who had at least ten years of experience was used.

The secondary task consisted of memorizing a three- (low load) or six- (high load) digit string that displayed in white font on a black background screen before each hazard-scenario image appeared. The participants had 2 seconds to memorize the string. The participants were then instructed to remember the string because they would be tested about it at the end of the trial. After the string disappeared from the screen, a randomly ordered construction scenario image appeared for 12 seconds, during which time the eye-movement tracker recorded the participant's eye movements while he/she searched for hazards. Next, the working-memory test displayed two strings of numbers: the original, correct string shown at the start of the trial and an incorrect string that had two digits out of order. The subjects were required to press either "z" indicating that the string shown on the left was the original or "/" to indicate the string on the right was the original one. Each subject performed 18 trials under the high-working-memory load and 17 trials under the low-load conditions. The reporting of the number and types of hazards identified for each trial and the reasons for defining the situations as hazardous took place after the working memory test. The steps of the working memory / hazard identification trial and data analysis are demonstrated in Figure 2.

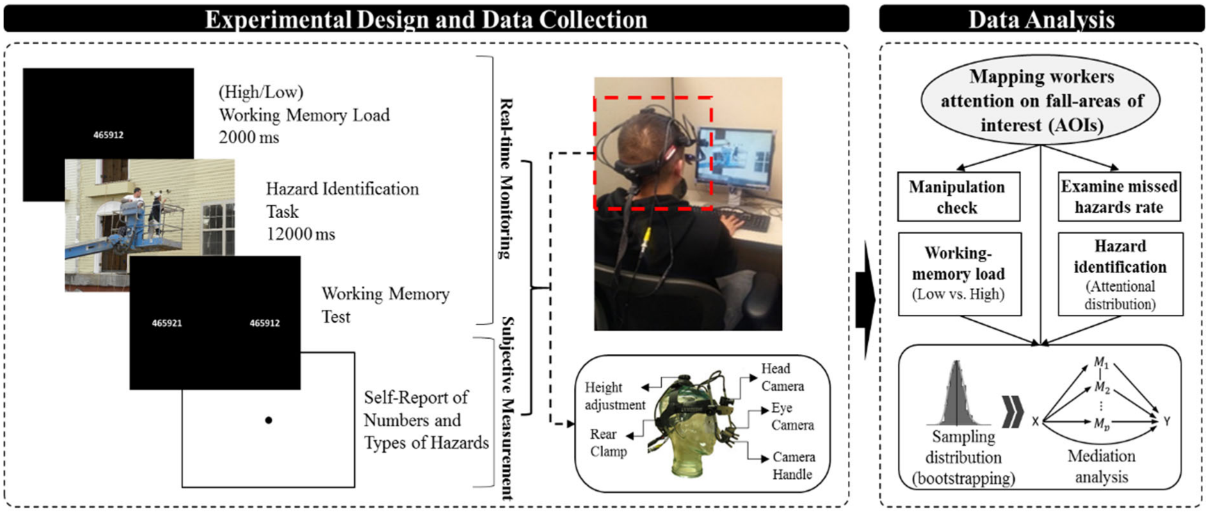


Figure 2. Research methods overview

Analysis

To evaluate participants' effectiveness in identifying hazards while undergoing working-memory load, the research team first categorized areas of interest within the images to subsequently compare with eye-tracking data. To map these areas, certified safety managers identified which hazard scenarios contained active fall-protection systems and potential fall-to-lower-level hazards and classified these hazards as areas of interest (AOI). Hazards categorized as "fall-protection systems" included all scenarios of improper use of lanyards or other related fall-protection equipment and systems. Missing guardrails, floor openings, workers in the vicinity of an unprotected roof or building edge, unguarded roof, improper scaffolding, or skylights were categorized under "fall-to-lower-level" hazards. These AOI's were then used in the analysis to compare hazard identification rates among participants under low- and high-working-memory load situations.

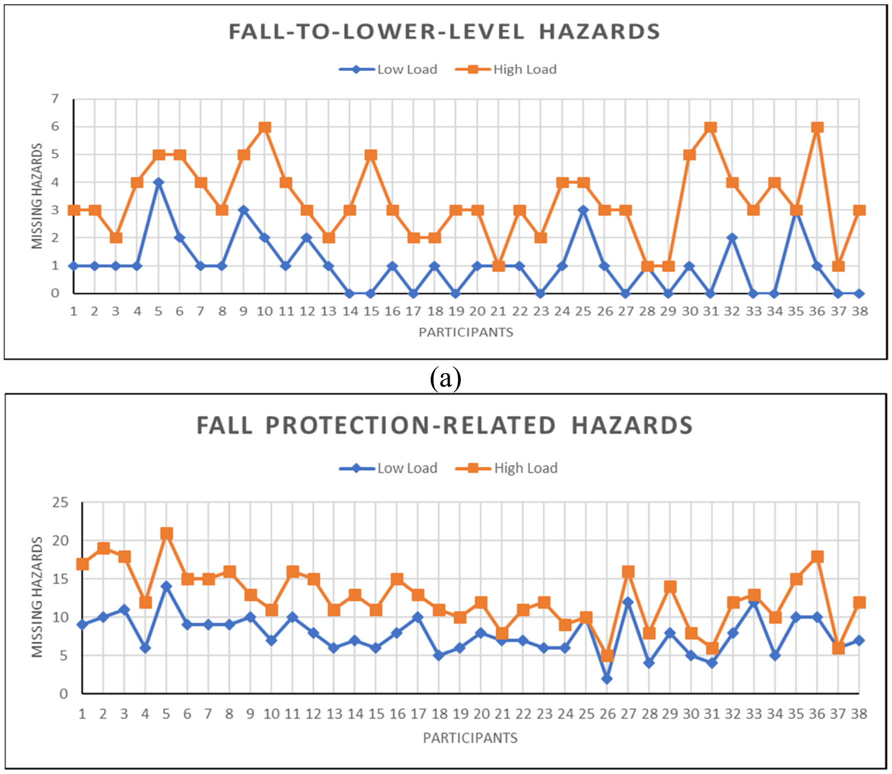
All relevant eye metrics were extracted for each subject using the EyeLink Data Viewer software. After cleaning the eye tracking data, eye metrics such as first fixation time *(the amount of time that it takes a subject to look at a specific AOI from the image's first appearance on the screen)*, run count *(total number of times that each subject returns attention to an AOI),* and dwell time percentage *(the percentage of time that the subject focuses on an AOI)* for each participant were then transferred to statistical software, MPLUS for mediation analysis.

RESULTS

Hazard Identification Performance Under Different Working-Memory Loads

To ensure that the working-memory assignment was effective, a comparison between the scores of the Working-Memory Load Test under low- and high-load conditions was performed. Subjects managed to score a higher hazard-identification accuracy rate during the Working-Memory Load Test under the low-load condition (mean = 87%) compared to the high-load condition (mean = 73%). This initial result bespeaks the fact that the secondary task introduced during the experiment to manipulate working-memory load was effective since the participants achieved different success under different conditions.

Moreover, the subjective, verbal reports of the participants as to their hazard identification proved that working-memory manipulation had a direct impact on how many hazards they could recognize. The score of each subject for both hazard categories (“fall-to-lower-level” and “fall protection-related” hazards) under low- and high-working-memory loads are graphically displayed in Figure 3. The curves in the graphs demonstrate that the participants skipped more hazards during high-load trials than they did during low-load trials.



(a)

(b)

Figure 3. Graphical presentation of missed hazards during low- and high-working-memory load trials; (a) Fall-to-lower-level, (b) Fall protection-related hazards

The summary of the hazards that participants missed during the trials for “fall-to-lower-level” and “fall protection-related” hazards are displayed in Table 1. Apparently, the high-working-memory load had a negative impact on the participants’ capability to identify potential and active hazards in the specific areas of interest.

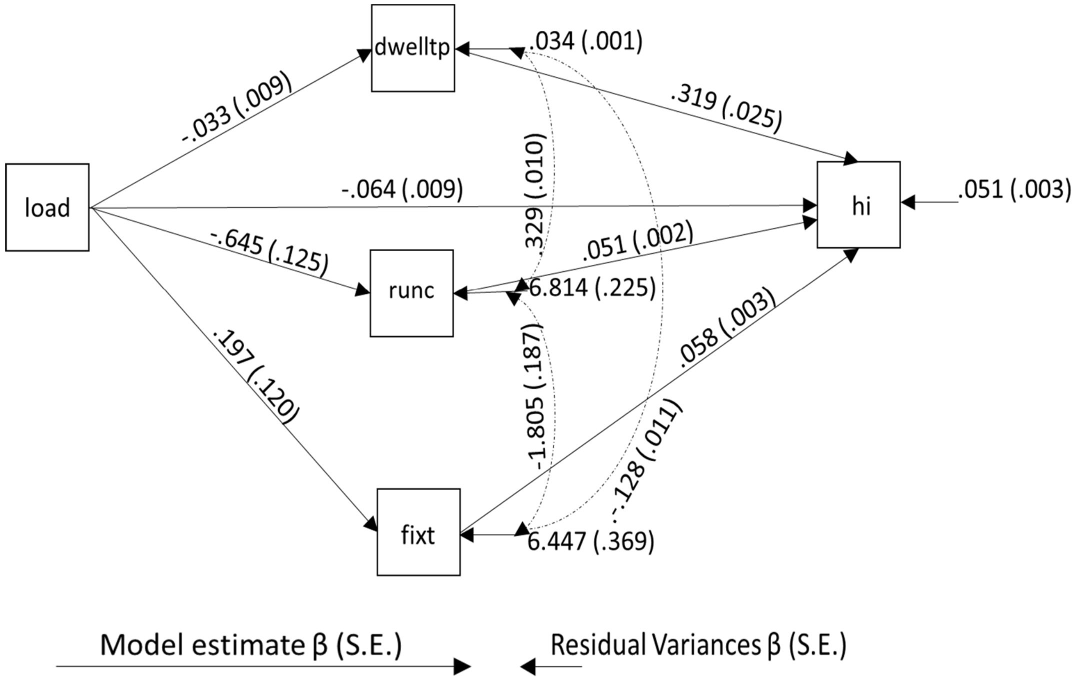
Table 1. Missed hazards for different memory-load conditions

Hazards NOT Identified	Low Memory Load	High Memory Load
Fall-to-lower-level hazards	4.3%	13.9%
Fall protection-related hazards	35.5%	44.8%

Participants identifying “fall-to-lower-level” hazards performed 3.2 times poorer during high-load compared to low-load trials. Concurrently, the participants’ performance for “fall protection-related” hazards identification deteriorated 1.3 times under the high-load working-memory condition.

Impact of Working-Memory Load on Eye-Movement Metrics

To investigate the correlation between eye-movement metrics (dwell time percentage, first fixation time, run count) and working-memory load, a mediation model was created in the statistical software MPLUS, and 5,000 bootstrap draws were compiled with the data extracted from the eye-tracking experiments. The eye-metric parameters were assigned as mediators between the independent variable—working-memory load—and the dependent variable—hazard identification. The residuals of parallel mediators (dwell time percentage, first fixation time, run count) were properly covaried and a unified path analysis in MPLUS using full information maximum likelihood estimation and bootstrapping was conducted. The diagram for fall-to-lower-level hazards appears in Figure 4.



Legend of the labels used in the model		
load = Working-memory load	*fixt = First fixation time*	*SE = Model standard error*
dwelltp = Dwell time %	*hi = Hazard identification*	*β* = Standardized model estimate*
runc = Run Count	*β = Model estimate*	*p = Model two-tailed p-value*

Figure 4. Diagrams for statistical analysis for Fall-to-lower-level hazards

Mediators were screened for multicollinearity and the following correlations (less than .70) were received as shown in Table 2.

Table 2. Correlations among the Mediators

Mediators		Correlation
Dwell time %	Run count	0.683
Run count	First fixation time	0.275
Dwell time %	First fixation time	0.273

First, it was found that working-memory load was negatively associated with dwell time percentage *("fall-to-lower-level" values:* $\beta = -.033$*, 95% CI[-.051, -.016], S.E. = .009,* $\beta^* = -.089$*).* Results indicated that working-memory load significantly and negatively affected run count as well *("fall-to-lower-level" values:* $\beta = -.645$*, 95% CI[-.886, -.394], S.E. = .125,* $\beta^* = -.123$*).* However, working-memory load was not significantly related to first fixation time *("fall-to-lower-level" values:* $\beta = .197$*, 95% CI[-.032, .440], S.E. = .120,* $\beta^* = .039$*).* As would be expected from these results, the direct effect of working-memory load on hazard identification was significant by generating a negative impact, which was confirmed by the following values: *"fall-to-lower-level" values:* $\beta = -.064$*, SE = .009,* $\beta^* = -.112$*,* $p < .005$*.*

DISCUSSIONS

The experimental results indicated that subjects under lower working-memory load were able to detect hazards in "fall-protection systems" and "fall-to-lower level" categories significantly at a higher rate compared to the subjects under high-working-memory loads. Also, increasing working-memory loads impacted negatively workers' search effectiveness as the workers under high-working-memory loads dedicated less time to looking for hazards in unsafe areas. The results of this study also revealed that participants under low working-memory loads focused attention more often on hazardous areas, which suggests that access to more cognitive resources strengthens hazard identification. Therefore, working memory load can have an impact on the hazard-detection skills of workers. This conclusion is in parallel with the findings of previous studies stating that the increment of working memory load can cause failure to detect relevant items even when they are right in the field of view, which can lead to a considerably higher accidents probability (Fang et al. 2016, Hasanzadeh et al. 2017b).

Such findings offer significant considerations for both academia and construction industry: For academics, this study is one of the first attempts to measure the correlation between working memory and situation awareness using eye metrics as mediators. In this study, eye metrics were used as the bridge to examine the effect of working memory load on situation awareness which was identified through hazard identification capability. Understanding how people under different working-memory loads distribute their attention has practical implications for safety managers and project managers in construction industry as establishing a link between working-memory load and situation awareness reveals controllable considerations for managers attempting to decrease the risks workers face.

Although, the contributions of this study are substantial, there are some limitations that should be stated. First, the experiments were conducted in the laboratory using static images, which cannot fully embody all the real-world specificities of a construction site. Construction jobsites are dynamic and complex, so substantial differences exist between laboratory premises and real construction sites. Future studies should be conducted on construction workers using a mobile eye-tracker in real-world construction sites. Second, the subjects used in this research were undergraduate students and not real construction workers. However, while their lack of practical experience might have an impact on the overall success of their hazards identification, the main target of this study was to recognize the impact of different working-memory loads on safety performance; accordingly, the inter-subject comparison between working-memory loads would not be significantly influenced by subjects' past experience. Future work could target professional construction workers as test subjects to determine what, if any, difference individuals' experience has on the outcomes of this experiment.

CONCLUSION

Working memory is one of the cognitive processes influencing accidents caused by human errors. As working memory involves storing information, focusing attention, and manipulating information over a relatively short period of time, and as awareness allocation impacts construction workers' hazard-identification success, comprehending the correlation between working memory and awareness allocation presents an opportunity to improve safety performance on construction jobsites.

This research presents an experimental method for studying the effect of working-memory load on construction workers' safety performance. Subjects identified fall-related hazards while under low and high working memory loads to determine what mediating impact working-memory load has on hazard identification. Both, hazard-identification and working-memory tasks were monitored by tracking eye movements, which has been proven in previous studies to be effective in detecting construction workers' awareness allocation (Hasanzadeh et al. 2017, 2018, Sun and Liao 2019). The results of this study indicate that subjects showed different performance capabilities when identifying fall hazards under low- and high-working-memory loads. While under high-working-memory loads, subjects focused less on the hazardous conditions and were unable to identify as many safety hazards as they were able to identify during lower working-memory load tests. Therefore, the ability of the subjects to detect and determine potential hazards appears to have been negatively affected by increases in their working-memory loads. These results suggest that the safety performance of construction workers deteriorates with increasing working-memory loads, which raises considerations for future analyses assessing opportunities to increase the safety performance—and subsequently the safety in general—of construction workers on construction sites.

ACKNOWLEDGMENTS

The National Science Foundation is thanked for supporting the research reported in this paper through the Decision, Risk and Management Sciences (DRMS) program (Grant Nos. 1824238 and 1824224). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the writers and do not necessarily reflect the views of the National Science Foundation.

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