5th International/11th Construction Specialty Conference
5e International/11e Conférence spécialisée sur la construction

Vancouver, British Columbia
June 8 to June 10, 2015 / *8 juin au 10 juin 2015*

MEASURING CONSTRUCTION WORKERS' ATTENTION USING EYE-TRACKING TECHNOLOGY

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Abstract: Although there are several studies that have highlighted the importance of attention in reducing the number of injures in the construction industry, few studies have attempted to empirically measure the attention of construction workers. One of the techniques that can be used to measure workers' attention is eye-tracking. Eye-tracking is widely accepted as the most direct and continuous measure of attention given that where one looks is highly correlated with where a person is focusing his/her attention. Thus, with the fundamental objective of investigating hazard identification abilities and the visual attention of construction workers, this study pioneers the application of eye-tracking technology to the realm of construction-safety practices. The study conducts a pilot test to examine the pattern of participants' eye movement and attention distribution when shown a hazardous situation in a construction site. To achieve this objective, thirty-five pictures that include multiple areas of interest were shown to ten participants, and their eye movements were recorded using a head mounted EyeLink-II system (SR Research). Then, the absolute duration heat maps were generated and the fixation/gaze-related and saccade-related metrics were calculated for each area of interest. The results of the analysis revealed that some people failed to fixate on hidden hazards or even a danger sign. The findings of the study exhibit the immense potential of using eye-tracking technology for improving construction site safety.

1 INTRODUCTION

The U.S Bureau of Labor Statistics reported 845 fatalities within the construction industry in 2013 (U.S Bureau of Labor Statistics 2015). Even though the number of injuries have decreased significantly in the past couple of decades (Esmaeili and Hallowell 2012), accidents continue to take place. One of the main causes of accidents is the lack of attention and the failure of workers to identify hazards. If workers are distracted, they cannot identify and properly respond to a hazard. Therefore, it is rewarding to study attention and to identify ways for improving it. Although there are several studies that have highlighted the importance of attention in reducing the number of injures in the construction industry, few studies have attempted to empirically measure the attention of construction workers.

One of the scientific ways for studying attention is to use eye-tracking technology. Eye-tracking is widely accepted as the most direct and continuous measure of attention given that where one looks is highly correlated with where a person is focusing his or her attention (Hoffman and Subramaniam 1995). In the past decade, use of eye-tracking has been flourishing in studies related to human computer interaction (Jacob and Karn 2003, Jaimes and Sebe 2007), usability research (Poole and Ball 2006), advertisement

(Pieters and Wedel 2004), visual design (Jacob 1995), driving (Recarte et al. 2008), and sports (Land and McLeod 2000). Although eye-tracking exhibits the immense potential to provide deeper insights into construction workers' hazard-identification patterns, there is no previous study in the construction industry that uses eye-tracking technology to measure workers' attention.

To address this knowledge gap, the present study employs eye-tracking technology to investigate the visual attention of workers. The objective of the study is to identify the hazard identification patterns that participants demonstrate while performing a task-based search. To achieve this objective, a pilot test was conducted wherein eye movements were recorded using a head mounted Eye Link-II system (SR Research) and eye movement patterns were generated using the EyeLink® Data Viewer tool. The paper is organized into four sections. In the first part, the study presents the relationship between eye movement and attention, followed by a brief history of eye-tracking research, its application areas, and eye-tracking metrics. The second part explains the research method employed to conduct the pilot test. The third section includes findings of the study that are presented using absolute-duration heat maps and various eye-tracking metrics. Finally, the study concludes by providing a list of suggestions for using eye-tracking technology in future research.

2 LITERATURE REVIEW

2.1 Eye movement and attention

Humans eyes have finite capabilities and cannot attend to everything in their surroundings at once (Nilsson 1989). To be able to focus our vision on an area of interest, we have to move our eyes continuously, inspecting the field of view using brief fixations. Very often, our attention is directed toward the point we are looking at. This inextricable link between perception and attention was found by Yarbus in 1967. In a series of experiments that provided evidence for the relationship between human eyes and cognitive goals, Yarbus demonstrated that human eyes fixate longer on elements that project more information of interest to the observer. The experiments also implied that the analysis pattern (or eye movement path) of the scene under observation differs depending on the purpose of the observer (Yarbus 1967). The relationship between eye movement and attention mechanisms led to the vast use of eye-tracking research in the fields of neuroscience, psychology, ergonomics, advertising, and design (Richardson and Spivey 2004). By observing eye movements and the proportion of time spent looking at areas of interest, researchers attempt to infer which portions of a scene capture the participant's visual attention and which portions are ignored.

2.2 History of Eye-Tracking Research

Historically, eye-tracking research was conducted to reveal *what* individuals look at, *where* they are look, or *how* they investigate an object of interest. Throughout the past century, several other concepts have emerged regarding the evolution of the eye-tracking technology, all of which have led to a wider scope for application areas (Duchowski 2007). Richardson and Spivey (2004) presented a commendable chronological account of various eye-tracking methods developed in the past century. They traced the history of eye-tracking back to the study of Louis Emile Javal in 1879. Javal (1879) used mirrors to observe the reader's eye movements and was the first to observe that eye movements were not smooth. Later, to gain more insights about eye movements, Delabare (1898) simultaneously succeeded in inventing the first eye-trackers. Although the first eye-trackers provided valuable information for conducting reading studies, these tools were criticized for being invasive. To provide a non-invasive approach, Dodge and Cline (1901) invented a device that used photography for recording eye movements. With advancements in technology, researchers such as Buswell (1922) were able to use the reflection of light for recording eye movements on a film that enabled the production of some of the first two-dimensional scan paths.

The early 1970's marked the onset of digital technology and image processing, which enabled Young (1970) to suggest scanning the image of the eye for the limbus. Due to the difficulty faced in scanning the limbus and vertical eye movements with Young's technique, an alternative approach of scanning for the lack of reflectance from the pupil ("dark-pupil" tracking) was proposed. The limitation to dark pupil tracking was the low contrast between the black circle and brown irises. Therefore, Merchant et al. (1974)

suggested the bright-pupil tracking technique, wherein the pupil is lit directly from the front so that the light bounces off the back of the retina and appears very bright and is easily detected while scanning. The same technique was used to find the smaller, brighter corneal reflection that is seen in the contemporary systems. Over years, eye-tracking devices have been improved to achieve higher-precision records of observers' points of regard, which allow for natural head and body movements (Richardson and Spivey 2004). Currently, eye-tracking technology exhibits a robust capability to aid in visual attention studies related to construction safety and can provide invaluable insights for further improvement.

2.3 Application Areas of Eye-Tracking

Although early eye-tracking research mainly focused on investigating the process of reading, the relationship between cognitive goals and eye movements opened gates for the use of eye-tracking in neuroscience, psychology, and behavioral research (Richardson and Spivey 2004). The application areas of eye-tracking research include diagnostic as well as interactive purposes. Considering the research objective of this study to be diagnostic in nature, we will limit the discussion of related eye-tracking research to diagnostic purposes only.

In the past decade, the use of eye-tracking has been flourishing in studies related to human-computer interactions and usability research (Jacob and Karn 2003, Poole and Ball 2006) and it has also been applied to transportation (Suh et al. 2006, Yao et al. 2011), driving (Recarte et al. 2008, Palinko et al. 2010), aviation (Sarter et al. 2007), marketing (Pieters 2008), nuclear power control rooms (Ha and Seong 2009), medicine (Zheng et al. 2011) and petrochemical control rooms (Ikuma et al., 2014). The use of eye-tracking in the above listed fields has been mostly related to estimating cognitive loads, analyzing user behavior, revealing differences in aptitude and expertise, and diagnosing neurological disorders. Even though eye-tracking is being applied in an increasing number of fields, it remains unexplored in the field of construction safety.

2.4 Heat Maps

A heat map is one of the most frequently used techniques for the visualization of data in eye-tracking studies. Heat maps can be described as graphical representations of eye movements over a scene. Major advantages of using heat maps include that they are easy to create and interpret because they graphically represent data using a color scale that relates to temperature, they provide a quick view of existing patterns, and they reveal a huge amount of data that would otherwise require more mental effort if presented in numerical formats (Bojko 2009). Therefore, heat maps are found to be widely used in web usability studies (Cutrell and Guan 2007, Buscher et al. 2009). Heat maps are limited in their representation of data—i.e. they only show density-based representation and heat maps lack information about the sequential order of eye movements. Thus, understanding the different types of heat maps, their limitations, and their purpose of use is necessary prior to their implementation (Bojko 2009).

2.5 Eye-Tracking Metrics

A large number of eye-tracking metrics have been used in previous studies to analyze human cognitive processes. The most common measurements used in eye-tracking research are “fixations” (relatively stationary eye positions over minimum duration) and “saccades” (quick eye movements). In order to explore the determinants of ocular behavior, a multitude of derived metrics that stem from these basic measures are incorporated into eye-tracking studies as dependent variables. Fixation-related and saccade-related metrics identified from literature are described in Table 1.

3 POINT OF DEPARTURE

Eye-tracking research has been flourishing widely in various fields of study. Even though the key characteristic of eye-tracking research—namely, that eye-tracking is the only direct measure of attention—provides immense potential for investigating, understanding, and improving construction workers' attention, eye-tracking remains unexplored in the field of construction safety. This study addresses this gap in knowledge and pioneers the application of a widely developed technology to the realm of construction-safety practices.

Table 1: Summary of eye movement metrics

	Metrics	Description
Fixation/gaze-related	Time to the first fixation on target	This measure is useful when there are specific targets of interest in a scene. This metric is measured by calculating the time in milliseconds that it took for each participant to reach a specific area of interest while viewing a picture (Thiessen et al. 2014)
	Gaze % on each area of interest	Cumulative duration of consecutive fixation and relatively small saccades time between them describe gaze duration within an area of interest. The proportion of gaze duration looking at a particular element indicates possible importance of that element (Jacob and Karn 2003).
	Number of fixations per area of interest	More frequent fixations on the specific area reflect the importance of that element (Jacob and Karn 2003).
	Run count	This metrics indicate the total number of runs, where a run is two consecutive fixations within same area of interest in a particular scene (Uzzaman and Joordens 2011)
	Fixation-duration mean	This metric is widely used in eye-tracking studies and is an indication of task difficulty and complexity (Pan et al. 2004). The higher values mean that the participant needed further investigation to complete a task.
	Number of fixations	In most of the previous studies, a larger number of fixations indicates the complex situation that decreased efficiency in searching for the desired targets (Ehmke and Wilson 2007).
Saccade-related	Saccade amplitude	This metrics can be computed by dividing the distances between consecutive fixations by the number of saccades (Goldberg and Kotval 1999). In computer-interface and -usability studies, larger saccade amplitudes indicate well designed interfaces with sufficient cues that users can find the desired targets rapidly (Goldberg et al. 2002).
	Number of saccades	More saccades reflect that participants spend more time searching for important targets (Jacob and Karn 2003). This measure can be computed from the number of fixations minus one (Goldberg and Kotval 1999).
	Saccade/ fixation ratio	A larger ratio indicates that participants spend more time searching and less time processing and comprehending targets (Ehmke and Wilson 2007).

4 METHODOLOGY

A pilot test was mandatory for this research since no study had previously investigated using eye-tracking technology to explore the hazard identification abilities of construction workers. The pilot test was designed to examine participants' viewing behaviors and attention distribution when shown a hazardous situation in a construction site. The experiment tested participants' search-efficiency skills when required to use cognitive processing to determine whether or not a hazard is present in a given situation.

Eight male and four female graduate students at the University of Nebraska–Lincoln participated in the experiment as paid volunteers. All of them had normal or corrected-to-normal vision and had been prohibited from drinking coffee on the day of the experiment. Participants were invited to the study by responding to an invitation flyer. Eye movements were recorded using a head mounted Eye Link-II system (SR Research) with a sampling rate of 500 Hz and an instrument spatial resolution of 0.01°. The construction site images were displayed on a square 19' computer screen. Participants used a video-game remote control to complete the task. The EyeLink® Data Viewer tool was used to generate eye movement patterns and variables.

Following the guidelines provided by Pernice and Nielson (2009), the experiment was performed in a lab setting. The lab was well lit and equipped with a dual screen setup, with the eye-tracking monitor placed behind the participant to avoid distracting him or her from the assigned task. The study strictly followed a well-drafted research protocol based on literature and expert advice. The experiment consisted of a single task wherein each participant was shown thirty-five construction site images ordered randomly on a computer screen while wearing the eye-tracker and was told to identify whether or not the situation in the image presented a hazard. Each image was displayed for a maximum of 20 seconds. The research assistant observed the participants' eye movements on the eye-tracking monitor. The participants had to answer whether or not they found any hazards with the use "A"—Yes—or "B"—No—buttons on a video-game remote control. No specific information was provided regarding the type of hazard to look for.

After conducting the experiment and collecting the data, the first step for analyzing the relationships between eye movement parameters and dependent measures was to define areas of interest (AOI) in each picture. AOI(s) are visual environments of interest defined by the research team (Jacob and Karn 2003). For example, in marketing-related studies, specialists might be interested to know about the total time each observer views the desired target (brand area) on home page (Goldberg et al. 2002). In this study, because we aim to find out how participants scan a picture to identify hazards, we defined AOI(s) as visual environments of interest in pictures that include a hazard. The research team specified areas in each picture, and two examples are shown in Figure 2.

(I) (II)

Figure 2: Picture I and II's Areas of Interests

After conducting the experiment, to graphically represent the data, an absolute fixation duration heat map was generated for each picture. The results were also analyzed using different eye movement metrics such as time to the first fixation on target, average gaze percent (time) on each AOI, average number of fixations per AOI, average run count, saccade/fixation ratio, and average saccade amplitude.

5 RESULTS

The experiment was conducted on twelve participants and data were collected according to the established protocol. The data of two participants were omitted from the analysis because acceptable levels of calibration on the eye-tracker could not be achieved. Then, the EyeLink® Data Viewer was used to extract data and perform the analysis. To compare visual representations of participants' eye movements with their hazard identification abilities, heat maps were created and compared with the number of hazards identified by each participant. Then eye movement metrics were analyzed to determine which areas of interest (areas that contain a hazard or a hint to identify a hazard) were identified fastest, which areas of interest were perceived more important, and how the participants searched and scanned pictures.

5.1 Hazard Identification and Heat Maps

The results of the pilot test conducted on ten students at the University of Nebraska-Lincoln confirmed that most of the hazards in a construction site can be easily missed or not considered to be a hazard by individuals. Although all of the thirty-five images shown to the participants had multiple hazards varying in safety risk, the number of hazards identified by participants for all pictures ranged from 11 to 29 with a median of 22.5. The results can be alarming because working in an environment with latent hazards drastically increases the risk of an incident (Laurence 2005, Sneddon et al. 2004).

The absolute duration heat maps were generated by combining data from all ten participants to provide a quick view of average existing viewing patterns. To demonstrate the potential application of eye-tracking technology for measuring construction workers' attention, a heat map for one of the images is shown in Figure 3. By looking at heat maps, one can visually understand which objects captured participants' attention in a scene. While the absolute duration heat maps generated by combining data from all ten participants illustrates existing viewing patterns on average, the heat maps developed per participant for each image shed light on another aspect of the individual's visual attention. In one of the pictures, five out of ten participants did not fixate on a person standing at a height without any fall-arrest protection systems. In another example, participants missed a danger sign, raising doubts as to the effectiveness of the signboards in catching peoples' attention.

(a) (b)

Figure 3: Heat maps for Pic I - (a) Original picture, (b) Heat map

5.2 Eye-Tracking Metrics

The metrics provided in Table 1 are calculated by analyzing the two-dimensional eye movement patterns of participants. The two-dimensional eye movement analysis starts by measuring the visual angle of pairs (or more) of data points in a time series—i.e., (x_i, y_i)—and also, the distance between successive data points—i.e., (x_{i+1}, y_{i+1})— (Duchowski et al. 2002). Using this concept, the following eye-tracking metrics were calculated for all AOI(s) in each image: the time to the first fixation on an AOI; the average proportion of gaze duration on each AOI based on time; the average number of fixations per AOI; and the average run count. The results for two pictures (out of 35 pictures) are shown in Table 2. Using these metrics, one can answer the following questions: How long does it take for a participant to see an AOI for the first time? On average, how long does a participant fixate on an AOI? In a given time, how many times does a participant fixate on an AOI? How many times does a participant come back to an AOI?

Table 2: Mean values of eye movement variables per area of interest

Picture(s)	AOI(s)	Time to the first fixation on target (ms)	Gaze % (time) on each AOI-Avg	Number of fixations per AOI_Avg	Run count _Avg
Pic I	AOI 1	1336.57	9.05	2.1	1.5
	AOI 2	2337.5	13.58	2.5	1.4
	AOI 3	1789.6	25.97	3.5	2.4
Pic II	AOI 1	2953.33	5.84	2.1	0.8
	AOI 2	260	37.16	6.4	3.7
	AOI 3	1318.8	19.52	3.8	2.5

In picture I, the time of the first fixation in three areas of interests shows that the lack of guardrails placing around walking/working surface (AOI 1) captured people's attention quicker than other areas of interest. This is an important finding, as previous studies related to graphical user interfaces showed that a lower first-fixation time indicates that the target better captured one's attention (Byrne et al. 1999). In addition, the results of the analysis illustrate that participants spent more time on the AOI 3 (larger gaze proportion, number of fixations, and run count). In the AOI 3, a person is looking down a third floor of a building without any fall protection. This is against OSHA regulations as an employer has to provide some type of fall protection for workers who are working more than six feet above the lower surface. The highest run-count and proportion of gaze duration looking at the AOI 3 indicate the importance of this hazardous situation for participants.

In picture II, the AOI 1 was a danger sign that received only 5.84% of the proportion of gaze duration. This means that, on average, participants paid little attention to this part. Further analysis revealed that seven out of 10 participants did not even look at the sign. On the other hand, the AOI 2, which included a human figure, grabbed more attention (37.16% of proportion of gaze duration). This was expected as previous studies found that participants mostly tend to fixate preferentially and rapidly on human figures (Wilkinson and Light 2011, Thiessen et al. 2014). In the construction safety domain, it can be concluded that participants can identify areas with an imminent danger to a person faster than those areas that include a dormant hazard. The AOI 3 was also important because it showed that the worker standing on an elevated lift did not use the personal fall-arrest system properly: while he was wearing the body harness with attached lanyard, he anchored himself to the elevated lift in way that created a swing-fall hazard. According to the OSHA regulations, the anchorage point must support the force of a person falling and the worker should be tied off to an anchor in such a way that if he fell, he would not swing into an obstruction. The AOI 3 was the second most important area viewed by participants.

In addition to metrics per image, one can calculate mean value of eye-movement variables per participants to further investigate each person's search strategy. These values are summarized in Table 3. Larger saccade/fixation ratios reflect that a person was more careful to scan pictures and search for hazards. Also, larger average saccade amplitudes indicate that a person could find the hazards more rapidly according to his/her experience. These values can help a researcher divide participants into multiple groups based on certain characteristics (e.g., age, gender, hazard-identification ability, risk perception, previous training, etc.) and test related hypothesises to compare their visual attention. Due to the low number of participants in this pilot test, the results of this analysis are not shown here.

5.3 Scanpath

Scanpath is a compelling visualization of eye movements that shows the sequence of saccade-fixate-saccade. Figure 4 depicts a scanpath obtained from one of the participants for Picture II. An optimal scanpath is a straight line eye movement to desired targets and a short fixation on targets (Jacob and Karn 2003, Pole and Ball 2005). Different quantitative measures and statistical analyses are used to analyze scanpaths—these analyses are outside of the scope of this study. Previous studies investigated scanpath variability between multiple webpage designs and found that visual complexity contributes to eye movement behavior. Similar studies can be conducted in the construction industry to measure the impact of crowded jobsites in distracting workers.

6 CONCLUSION

One of the root causes of accidents is human error (Abdelhamid and Everett 2000), i.e., the lack of attention and failure of workers to identify hazards. Given that hazard identification plays a crucial role in construction safety (Holt and Lampl 2006), the use of eye-tracking technology to investigate hazard identification abilities can aid in reducing construction worksite injuries. This paper presents a novel approach to improving construction-site safety by employing the eye-tracking technology that has been widely accepted as the most direct and continuous measure of attention. As a first step towards exploring the use of eye-tracking technology for construction safety, this study conducted a pilot test aimed at investigating patterns of participants' eye movements when performing a task-based search. To analyze the results, heat maps were created for data visualization, and gaze/fixation-related and saccade-related metrics were calculated.

Figure 4: Pic II Scanpath

Table 3: Mean values of eye movement variables per person

Pictures	Participants	Fixation duration mean	Saccade amplitude-Avg	Number of fixations	Number of saccades	Saccade/ fixation ratio
Pic I	P #1	233.89	5.39	55	54	1.24
	P #2	293.00	4.25	12	11	0.16
	P #3	334.95	3.75	19	19	0.21
	P #4	220.33	2.54	12	11	0.13
	P #5	292.00	4.27	18	17	0.25
	P #6	324.00	2.03	11	10	0.06
	P #7	386.46	3.22	13	12	0.10
	P #8	312.00	3.23	6	5	0.05
	P #9	134.67	3.83	21	20	0.57
	P #10	325.79	2.94	38	38	0.34
Pic II	P #1	199.48	3.18	31	30	0.48
	P #2	306.42	3.16	43	43	0.44
	P #3	287.81	4.10	21	21	0.3
	P #4	240.00	2.44	5	5	0.05
	P #5	300.23	3.89	35	34	0.44
	P #6	229.07	3.35	15	14	0.20
	P #7	418.53	1.93	19	18	0.08
	P #8	286.29	5.57	7	6	0.12
	P #9	185.33	2.73	15	14	0.21
	P #10	255.6	4.26	30	29	0.48

The findings of this study provide a proof-of-concept and indicate the immense potential for using eye-tracking technology to improve construction-site safety and to attempt to facilitate more detailed investigations in future research. As implied above, eye-tracking can be utilized for innumerable purposes inclined towards achieving safer working conditions, such as identifying hidden hazards, measuring situational awareness of workers, and improving the effectiveness of safety-training programs. With advancements in technology, eye-tracking equipment is available at lower costs, allowing for higher flexibility in use and providing a higher precision record for observer's eye movements. There is no doubt that investments in eye-tracking technology will prove beneficial in academic as well as professional fields, thereby unveiling invaluable findings for improving construction-site safety.

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