Developing a Computational Spatial Attention Metric to Examine Workers' Visual Search Efficiency at Hazardous Construction Jobsites

Kyeongsuk Lee[1]; Yugandhar Shinde[2]; Sogand Hasanzadeh, Ph.D.[3]; and Behzad Esmaeili, Ph.D.[4]

[1]Ph.D. Student, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN. Email: lee2490@purdue.edu
[2]M.S. Student, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN. Email: yshinde@purdue.edu
[3]Assistant Professor, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN (corresponding author). Email: sogandm@purdue.edu
[4]Associate Professor, Lyles School of Civil Engineering and School of Industrial Engineering, Purdue Univ., West Lafayette, IN. Email: besmaei@purdue.edu

ABSTRACT

Workers are required to efficiently distribute their limited attentional resources to the surrounding environment to maintain their situational awareness at hazardous jobsites. While previous studies have argued that the hazard identification performance of workers is significantly affected by their attentional allocation, no study empirically investigated the spatial attentional distribution for a successful search strategy. To address this gap, this study monitored 30 workers' visual search patterns within immersive 360° construction scenarios using eye-tracking technology. Incorporating a computer vision technique, a new spatial attention metric regarding effective search strategy was developed based on workers' visual search data. The results indicated that workers tended to distribute their attention to the narrow area limited to their field of view, and often, around 80% of 360° surroundings remained unattended, including behind and overhead areas. These findings highlighted the importance of designing a proper training program to improve workers' search efficiency and hazard identification performance.

INTRODUCTION

Despite numerous efforts to enhance workplace safety, the construction industry has continuously shown a large number of fatal injuries (U.S. Bureau of Labor Statistics (BLS) 2020). Among various causal factors, unidentified hazards are recognized as one of the main factors leading to construction accidents (Lee et al. 2022b). Under dynamic and complex construction jobsite, workers are required to continuously scan surrounding environments to maintain their situational awareness and avoid unsafe behavior. Recently, advanced eye-tracking technology has been used to investigate workers' attentional allocation abilities to understand how workers distribute their limited attentional resources toward the hazardous area in the construction scenario (e.g., Hasanzadeh et al. 2016; Lee et al. 2022a). Various eye-tracking-related metrics (e.g., fixation duration, fixation count, and first time to fixation), indicating when or how often workers attended hazards, have been widely used. Although previous studies have shown promising results using those eye-tracking metrics, one critical limitation has been identified.

To effectively recognize and remain aware of potential hazards which can be materialized anytime and anywhere, it is essential to prioritize a broader distribution of attention toward the surrounding environment. This allows for a more comprehensive understanding of the surroundings and enables the identification of potential risks, thus maintaining situational awareness. While the preferential attentional allocation to 360° surrounding is critical, existing eye-tracking metrics have primarily focused on attentional distribution to predefined hazardous areas. As a result, these metrics have failed to effectively capture workers' ability regarding 360° spatial attention, which is a key capability in maintaining situational awareness in a real-world construction environment. Thus, this study develops a novel eye-tracking metric using computer vision techniques to measure workers' 360° spatial attention and situational awareness. This study contributes to the body of knowledge and practice by proposing a new metric to help understand workers' fundamental visual search abilities at the jobsite, which can be used to develop personalized visual scanning training. The outcomes of this paper will lay the essential foundations needed to understand workers' situational awareness ability to enhance workplace safety.

BACKGROUND

Among varied cognitive stages that play a key role in the situational awareness process, proper attentional distribution is the first primary stage for maintaining situational awareness (Endsley 1995). According to Lee and his colleagues' study, approximately 35% of hazards remained unidentified due to attentional failure (Lee et al. 2022c). To maintain situational awareness under dynamic construction environments, workers must properly allocate their attention across the 360° surroundings to correctly process the scene and identify the potential risks. Hence, diagnosing workers' visual search ability and providing appropriate training strategies to mitigate attentional failure cases is important. Due to the recent advancement of eye-tracking technologies, it became available to examine workers' objective visual scanning patterns (e.g., Hasanzadeh et al. 2016; Lee et al. 2022b). For example, one study examined the impact of experimental environments (i.e., image vs. video) on workers' visual search strategies using an eye-tracker and five eye-movement metrics, which can show how workers distribute their visual attention on predefined hazardous areas (Lee et al. 2022a). While several eye-tracking metrics have been widely used in hazard identification-related studies, they are mainly area-of-interest (AOI) related factors, and could not provide vital information regarding how the limited attentional resources must be properly and efficiently distributed across the scene.

Construction job sites are remarkably dynamic and complex due to changes in physical structures, coinciding tasks, and overlapping teams (Sacks et al. 2009). In other words, workers are encircled by their 360° surroundings, such as underneath, behind, and overhead, and each direction may include various potential or active hazard sources. Under this situation, humans have a limited functional field of view (FOV) that distributes on a radius of 60° around the fixation point (Park and Reed 2015). Accordingly, workers must preferentially have a high ability to broadly allocate their visual attention and properly identify hazards in the surrounding environment (Harada and Ohyama 2019). For instance, if there is an overhead crane operation and workers do not provide attention to the associated orientation, they will completely miss the chance to recognize the active hazard and may be struck by the crane. This fact highlights the necessity for a new numerical metric to indicate workers' 360° spatial attentional distribution capability.

METHODOLOGY

Experimental Design and Data Collection. This study adopted twelve 360° video panoramas to mimic realistic construction scenarios with the dynamic nature of the construction environment and to examine workers' attentional distribution capabilities. These scenarios consisted of several construction tasks (e.g., welding, installing HVAC, erecting, and crane operation) captured at commercial construction sites in Washington, D.C., and northern Virginia. Each contains three to five static and dynamic hazards. Then, thirty construction workers with normal or corrected-to-normal vision (aged 34.5±10.6 years and 8.5±7.2 years of work experience) were recruited to obtain their naturalistic behavior when immersed in 360° construction scenarios. The selected construction scenarios were presented via the HTC VIVE Pro Eye head-mounted display with an embedded eye-tracking sensor offering millisecond synchronization and a seamless eye-tracking integration at 120 Hz during the experiment. The headset includes Hi-Res-certified headphones and a dual OLED 3.5" diagonal screen providing a resolution of 1,440 × 1,600 pixels per eye and a 110° field of view. Participants were asked to view twelve scenarios for thirty seconds, then report the number and types of hazards they recognized in each scenario (Figure 1). While subjects were scanning the scenarios to identify the hazards, their visual search strategies were continuously monitored.

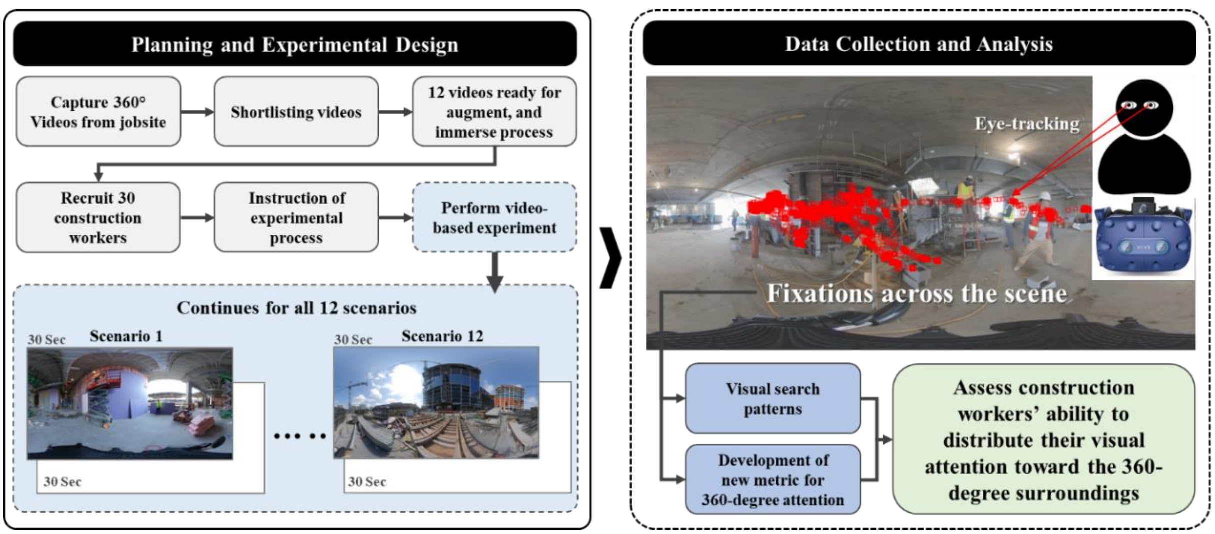

Figure 1. Research framework

Metric Development. Figure 2 illustrates the overall flow of calculating the spatial attention percentage as a measure of visual search efficiency. First, Tobii Pro Lab automatically transformed the 360° panoramic spherical video into a squared 2D video ranging from coordinates 0 to 1 and marking the real-time X and Y coordinates of the fixation points. To develop a new eye-tracking metric for 360° attention, fixation coordinates that provide spatial information about workers' eye movements were used. Accordingly, the scatterplots of participants' precise visual scanning patterns were developed. These plots were then converted into contour maps using a python data visualization library called 'Seaborn' widely used for visualizing informative statistical graphics. The contour map of fixation points was created using the Kernel density estimate approach, indicating a continuous probability density curve in two dimensions. Then, the Gaussian kernel was used as a smoothing algorithm to smoothen the curves and produce an interpretable contour map that covers all the fixation points and their connections, displaying the fixation area based on individuals' visual scanning path. The image processing algorithm named 'Open computer vision' was then adopted to calculate the proportion of the area of the outmost boundary of the contour map over the whole 360° scene (Bradski 2000). To do that, the contour maps were read at a singular pixel level, and all pixels outside of the contour boundary were cleaned to make them white-colored pixels (i.e., the pixel value of 255). Then, the value of each pixel was marked based on its color, ranging from 0 (black-colored pixel) to 255 (white-colored pixel). The number of pixels which did not have the pixel value of 255 (i.e., all non-white colored pixels) was extracted, and these pixels refer to the areas within the outermost boundary of the contour map. Lastly, the proportion of fixation area across the 360° scenario was calculated by the following equation:

$$spatial\ attention\ \% = \left(\frac{Number\ of\ Pixels\ within\ the\ boundary\ of\ contour\ map}{Total\ Number\ of\ Pixels}\right) * 100$$

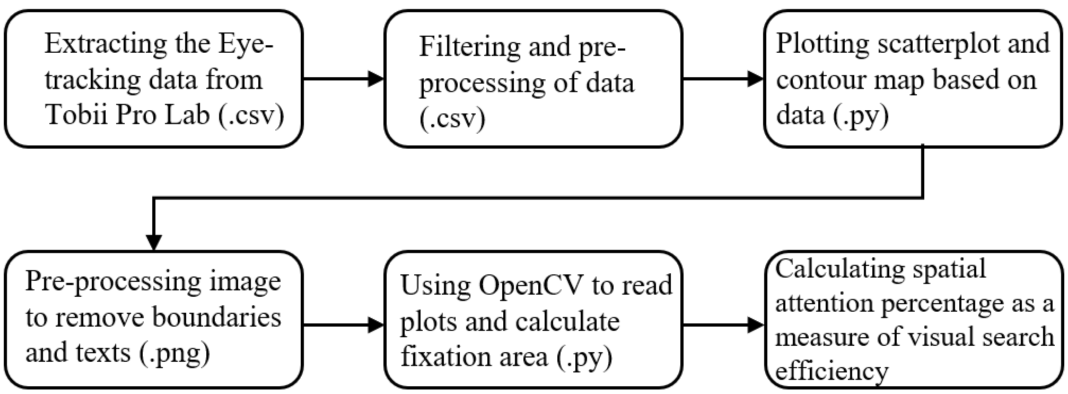

Figure 2. The flow of the new metric calculation

APPLICATION AND RESULTS

Figure 3 shows the example process to calculate the percentage of spatial attention of a worker searching for hazardous areas in the 30-sec scenario. Then, the scatterplot, which illustrates the worker's attentional distribution across the entire scene, was developed and used to create the corresponding contour map. Based on the described pixel color approach, the processed contour map was analyzed to determine the area within the final boundary of the contour map. The results revealed that the total number of colored pixels where the worker allocated his visual attention was 137,329, while the total number of pixels present in the scene was 541,314. As a result, the percentage of fixation area was 25.4%, which indicates that the worker scanned only one-fourth of the 360° surroundings, showing an inefficient visual search strategy.

As specified in the Methodology section, all participants completed scanning and reporting hazards within 12 scenarios. Figure 4 illustrates each participant's average spatial attention percentage across the twelve construction scenarios. On average, workers only allocated their attention to 21.1% of the 360° surroundings. In other words, almost 80% of areas of scenarios were missed to be scanned by participants, while the scenarios include various static and dynamic hazards across the whole 360°. Additionally, only 7% (2 out of 30) participants generally scanned more than 30% of the entire area of the scene, and surprisingly, 43% (13 out of 30) workers only viewed less than 20% of the whole surroundings. These results indicate that all workers have significantly poor 360° attentional distribution abilities.

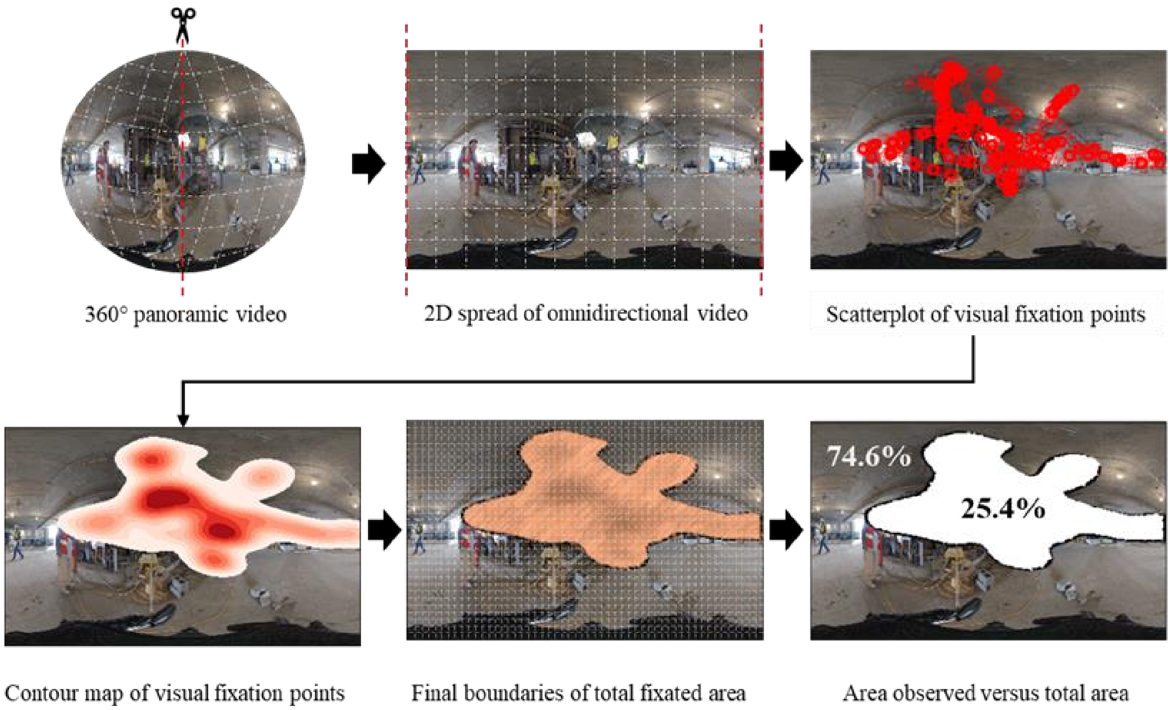

Figure 3. Examplespatial attention percentage metric calculation process

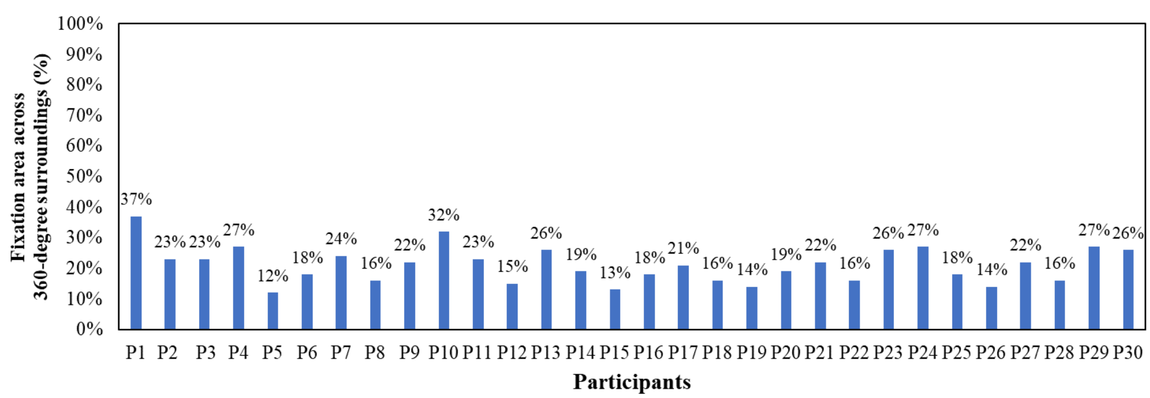

Figure 4. Grand average of spatial attention percentage of participants across twelve construction scenarios

During the experiment, workers were asked to review twelve construction scenarios, including different activities (e.g., indoor or outdoor tasks) and hazard types (e.g., fall and struck-by hazards). As shown in Figure 5, while participants generally scanned around 25% of each 360° scenario, three scenarios (i.e., s7, s9, and s11) showed relatively lower average spatial attention percentage with an average of 16%., However, these results demonstrated that workers' 360° attentional distribution abilities are not significantly influenced by hazard types or environments and may be more connected to the human factor (e.g., individual's visual scanning strategies).

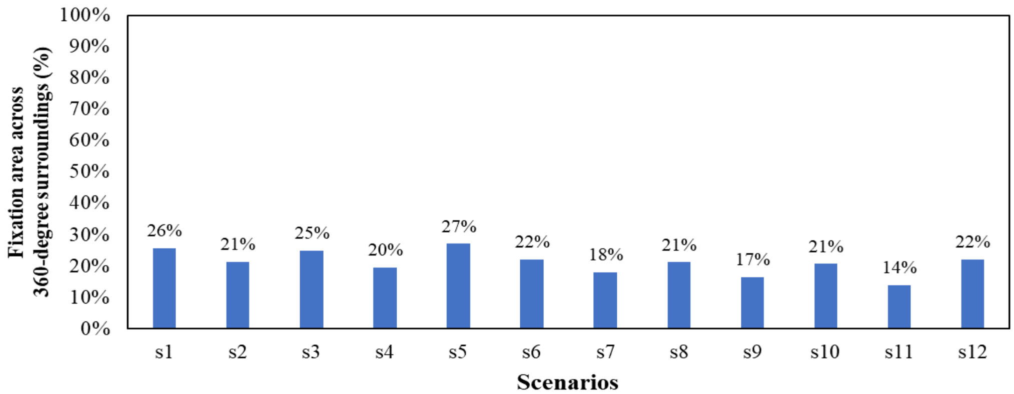

Figure 5. Average spatial attention percentage of all participants across twelve construction scenarios

DISCUSSION

Workers in hazardous construction environments must properly distribute their selective attention (i.e., have an efficient visual search strategy) across the entire surroundings to identify the potential and active hazards. This study aimed to propose a new numerical metric of spatial attention that can illustrate workers' visual search performances.

The results showed that participants had significantly limited attentional spans and failed to broadly distribute their visual attention across the surrounding conditions. On average, almost 80% of areas of each construction scenario were not scanned by subjects which means if there are any hazards within these unattended areas, they were missed by the worker. These results also indicated that workers tended to over-fixate on small regions within their field of view instead of comprehensively scanning the entire surroundings. Figure 6 shows the representative worker's visual search patterns for one of the scenarios (scenario #11) that most participants had poor visual search efficiency, with an average fixation area of 14%. When the scenario was delivered via VR headset, participants could initially see the scene in the yellow box (Figure 6a) based on the human field of view and experimental setting (i.e., orientation). In this scene, there was a worker who was standing on the ladder without proper fall protection. As this hazardous situation was already activated and it was in the initial FOV, on average, there were highly concentrated fixation points within this area (Figure 6b), while relatively lower fixation points were outside the initial FOV. Over fixating on this area, the workers rarely recognized any potential or active hazards in the unattended areas, increasing the likelihood of being involved in any injuries or fatalities.

Considering that previous studies reported that workers' hazard identification performance was still under the desired level even after receiving the safety training (Jeelani et al. 2021), the results of this study call for developing visual search training for workers focusing on how to efficiently and effectively allocate limited attentional resources toward the whole 360° surrounding to enhance hazard identification skills. To address this need, the authors' recent study highlighted the need for improving workers' 360° spatial attention ability to help them properly tune attention to anticipate risks relying on incoming visual cues while having an effective attentional orienting (e.g., maintaining attention across a large field of view) (Lee et al. 2022c; b).

(a) **(b)**

Figure 6. Inefficient search strategy example of a worker for scenario #11

Although the findings offered a unique perspective on measuring the visual search efficiency of workers as a primary step of situational awareness, due to the page and space limit, the current paper only examined workers' visual search abilities with the proposed metric. So, future research requires investigating the relationship between the spatial attention percentage and workers' hazard recognition results.

CONCLUSION

Workers must work in dynamic construction environments, where active or potential hazards may exist anywhere behind and overhead. Thus, an efficient visual scanning strategy is vital in maintaining worker safety because they have a limited functional field of view (i.e., on a radius of 60° around the fixation point). Accordingly, it is critical to examine workers' 360° spatial attention capabilities. As an initial study in such direction, this study developed a new metric related to 360° spatial attention using computer vision techniques. The results of this study indicated that workers had significantly poor visual scanning ability under dynamic construction environments and missed large areas of surroundings, which may include various hazards. The findings of this study emphasized the necessity of new safety training programs which help workers develop efficient search skills to comprehensively and effectively allocate their visual attention toward the whole 360° surrounding environments and to maintain their situational awareness. The results of this paper are expected to motivate future construction safety studies to consider more advanced eye-tracking metrics required for effective attentional orienting ability and efficient search strategy to monitor workers' hazard identification performances.

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REFERENCES

Bradski, G. (2000). “The openCV library.” *Dr. Dobb’s Journal: Software Tools for the Professional Programmer*, Miller Freeman Inc., 25(11), 120–123.

Endsley, M. R. (1995). “Toward a Theory of Situation Awareness in Dynamic Systems.” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1), 32–64.

Harada, Y., and Ohyama, J. (2019). “Spatiotemporal Characteristics of 360-Degree Basic Attention.” *Scientific Reports*, 9(1), 16083.

Hasanzadeh, S., Esmaeili, B., and Dodd, M. D. (2016). “Measuring Construction Workers’ Real-Time Situation Awareness Using Mobile Eye-Tracking.” *Construction Research Congress 2016*, American Society of Civil Engineers, Reston, VA, 2894–2904.

Jeelani, I., Asadi, K., Ramshankar, H., Han, K., and Albert, A. (2021). “Real-time vision-based worker localization & hazard detection for construction.” *Automation in Construction*, 121, 103448.

Lee, K., Hasanzadeh, S., and Esmaeili, B. (2022a). “Spatial Exposure to Dynamic Safety Hazards in Construction Sites through 360-Degree Augmented Panoramas: Ecological Validity in Safety Research.” *Construction Research Congress 2022*, American Society of Civil Engineers, Reston, VA, 715–725.

Lee, K., Hasanzadeh, S., and Esmaeili, B. (2022b). “Assessing Hazard Anticipation in Dynamic Construction Environments Using Multimodal 360-Degree Panorama Videos.” *Journal of Management in Engineering*, 38(5).

Lee, K., Shinde, Y., Hasanzadeh, S., and Esmaeili, B. (2022c). “Toward Personalized Safety Training: Automating the Classification of Construction Workers’ Cognitive Failures.” *Proceedings of the International Symposium on Automation and Robotics in Construction*, 268–275.

Park, G. D., and Reed, C. L. (2015). “Nonuniform Changes in the Distribution of Visual Attention from Visual Complexity and Action: A Driving Simulation Study.” *Perception*, 44(2), 129–144.

Sacks, R., Rozenfeld, O., and Rosenfeld, Y. (2009). “Spatial and Temporal Exposure to Safety Hazards in Construction.” *Journal of Construction Engineering and Management*, 135(8), 726–736.

Soret, R., Hurter, C., and Peysakhovich, V. (2019). “Attentional orienting in real and virtual 360-degree environments.” *Proceedings of the 11th ACM Symposium on Eye Tracking Research & Applications*, ACM, New York, NY, USA, 1–3.

BLS (US Bureau of Labor Statistics). (2020). “Table 4. Fatal occupational injuries for selected industries, 2016-20 - 2020 A01 Results.” <https://www.bls.gov/news.release/cfoi.t04.htm>(Oct. 16, 2022).