Investigating the Neural Correlates of Different Levels of Situation Awareness and Work Experience

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Abstract

Maintaining good situation awareness is crucial for workers' safety on the dynamic and complex construction site, and workers with more experience may contribute to better performance in safety. However, little research has investigated the cognitive differences between experienced and novice workers regarding different levels of situation awareness (Level 1: perception, Level 2: comprehension, Level 3: projection). To address this gap, this study investigated the cognitive processes of hazard recognition behaviors among experienced and novice participants using functional near-infrared spectroscopy (fNIRS) across 12 virtual reality scenarios. The results revealed that novice participants showed higher activation in the left prefrontal cortex across all three levels of situation awareness, indicating their tendency to focus on detailed information when faced with unfamiliar environments. In contrast, more experienced workers exhibited increased activation in the right prefrontal cortex, particularly in hazard comprehension and projection (Level 2 and Level 3). This suggests that experienced participants prioritize global control mechanisms by activating the right prefrontal cortex associated with spatial awareness. These results highlight cognitive differences at different levels of situation awareness between experienced and novice participants, providing insights into following behavioral patterns and decisions. Furthermore, these findings offer a theoretical foundation for tailoring safety interventions to address the cognitive deficiencies in each level of situation awareness.

Keywords

Situation awareness, fNIRS, Work experience, Neural, Cognitive process

1 Introduction

Construction sites include various potential and active hazards, necessitating workers to maintain proper spatial awareness to prevent accidents and injuries [1–3]. Situation awareness, encompassing three Levels as proposed by Endsley (perception, comprehension, and projection), is a pivotal factor in successfully recognizing hazards within construction environments [4,5]. Various factors, including sensitivity to stimuli, limitation in attention resources, constraints in working memory, and possession of experience in construction sites, affect situation awareness [4,6,7]. Previous literature argued that experienced workers exhibit a heightened capacity to tackle the challenges inherent in complex construction sites as they are familiar with the construction environment and better allocate their limited cognitive resources to potentially hazardous cues [8,9]. Despite the pivotal role of situation awareness in shaping safety behaviors, few studies have an in-depth understanding of the intricate cognitive mechanisms at each level of situation awareness, particularly regarding the differences between experienced and novice workers. Dzeng et al. used an eye-tracker to investigate the search patterns between experienced and novice workers in site hazard identification but did not measure the situation awareness [8]. Hasanzadeh et al explored the worker's situation awareness under fall and tripping hazard conditions but did not probe into each level of situation awareness [5]. A deeper exploration of the cognitive processes underlying situation awareness may help unveil the cognitive mechanisms behind successful hazard recognition among more experienced workers [10].

Achieving higher levels of situation awareness (i.e., comprehension, and projection) represents a complex cognitive process with neural activation in different regions of the brain cortex [11]. Existing research has illustrated a strong association between the prefrontal cortex, and planning and decision-making [12]. Activation in this region, reflected by oxygen concentration, can be a reliable indicator of attaining higher levels of situation awareness [11,12]. Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive and portable device capable of measuring changes in the concentration of oxygenated and deoxyhemoglobin (oxyHb, deoxy-Hb) in brain tissue [13]. Examining oxygen consumption in the prefrontal regions at various levels of situation awareness between novice and experienced participants may provide insights into cognitive limitations that impede higher levels of situation awareness. However, previous studies predominantly focused on the overall hazard recognition performance (i.e., recognized or not) and the corresponding neural activity, neglecting to explore the differential neural mechanism across various levels of situation awareness.

To bridge this gap, this study examined the cognitive disparities within each level of situation awareness between more experienced and novice participants, employing fNIRS technology within multiple virtual reality (VR) scenarios. These findings offer insights into potential training strategies to address cognitive deficiencies during situation awareness, ultimately contributing to reduced injury rates at construction sites.

2 Background

2.1 Effect of Work Experience on Situation Awareness

The construction site is a multifaceted and dynamic environment with diverse stimuli [14,15]. Hazard recognition abilities are essential for ensuring safety on construction sites [3]. Situation awareness, i.e., comprehensive perception, comprehension, and anticipation of environmental stimuli [4], is crucial for successful hazard recognition [16]. The attainment of higher levels of situation awareness primarily depends on developing mental models in long-term memory shaped by practical experience [17].

Hasanzadeh et al. [16] utilized eye-tracking technology to investigate hazard recognition on real construction sites, noting that levels of work experience influenced situation awareness and attentional allocation during hazard searches. More experienced workers demonstrated a greater ability to detect relevant hazard-related changes in the construction environment [18]. This was consistent with Aroke et al. [9], who found work experience and dwell time positively correlated with hazard identification. In the realm of driving, Kass et al. [19] observed that experienced drivers exhibited better performance following traffic regulations and greater situation awareness. This aligns with Wright et al. [20], which illustrated that middle-aged drivers with more experience were found to have higher levels of situation awareness and were better at anticipating hazards. Conversely, research by Zhou and her colleagues, [11] indicated that novice workers with higher sensitivity achieved a higher hazard recognition rate, coupled with a stronger electroencephalogram signal than experienced workers in a hazard recognition task involving a series of construction photos. While many studies suggest a positive relationship between experience and situation awareness, a consensus remains unclear. Most previous literature focused on the overall hazard recognition rate rather than delving into the cognitive processes at each level of situation awareness. Therefore, exploring the intricate mechanisms of each level of situation awareness is crucial to understanding the differences between novices and experienced individuals in hazard recognition.

2.2 fNIRS Application in Construction-Related Research

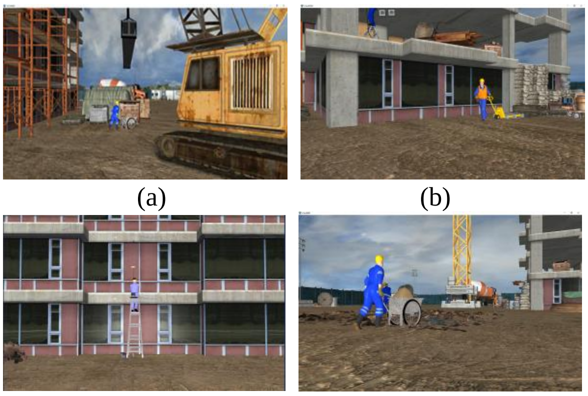
The consumption of glucose and oxygen drives neuronal activity, so active nerves represent increased consumption of glucose and oxygen in local brain regions [13]. Functional Near Infrared spectroscopy (fNIRS) is a non-invasive, safe, and reliable device to measure changes in the concentration of oxygenated and deoxyhemoglobin (oxy-Hb, deoxy-Hb) in the brain [21]. This concentration change was detected by emitting NIR light from 760nm to 850 nm into the head [13]. When NIR light enters the brain, it is absorbed, scattered, or reflected. Intensity changes of scattered or reflected light can be quantified using the modified Beer-Lambert law, which is essentially an empirical description of the attenuation of light in a highly scattering medium [13,21].

fNIRS, an emerging neuroimaging technology, has not yet seen widespread application in the construction sector. While some researchers have explored its application in architectural design [22], wayfinding [23], and hazard perception [24], its application remains limited. For instance, Hu et al. [22] experimented with design brainstorming, comparing outcomes with and without real-time neurocognitive feedback of brainstorming for students. Results indicated that when feedback was provided, a higher percentage of right-hemispheric dominance, associated with increased design idea fluency, was observed. Zhu et al. [23] modeled the relationship between fNIRS features and cognitive load by extracting hemodynamic response features in the prefrontal cortex during a building wayfinding information memory test. Pooladvand et al. [24] investigated individual decision-making and cognitive demand changes under normal or stressful conditions in VR scenarios. Findings suggested that limited cognitive resources led to a failure in comprehensively processing environmental information. By analyzing pupil responses and cerebral oxyhemoglobin signals, Liao et al. [22] demonstrated that different hazard types can induce varying cognitive demands. Despite these efforts, research focusing on situation awareness has been relatively scarce. This study seeks to bridge this gap by employing fNIRS technology to investigate the neural correlates of different levels of situation awareness in the hazard recognition process.

3 Research Method

The virtual reality (VR) experiment was designed, covering four common hazard types identified by the Occupational Safety and Health Administration (OSHA), which included: (a) Struck by an equipment: The crane was moving toward a worker, and the worker may be hit by this equipment. (b) Struck by objects: Some materials were stacked on the edge of the upper floors, and a worker passing by may be hit by the falling materials). (c) Fall to a lower level: A painting worker was standing on a ladder without fall protection and may fall from the ladder. (d) Electrocution: A worker was navigating an uneven floor cluttered with electrical wires and may be hit by electricity. These hazards were visually represented in Figure 1.

Twelve VR scenarios were developed, and 33 civil engineering participants from Purdue University were recruited to identify hazards within these scenarios. Participants with two or more years of work experience were classified as experienced participants, while those with less than six months of work experience were categorized as novice participants. Equipped with an HTC VIVE Pro Eye VR headset and Artinis fNIRS Brite II devices (Figure 2), they could freely scan the VR scenarios to identify hazards. Two regions of interest (RoIs) were selected in the fNIRS device, which were the left prefrontal cortex (LPFC) and right prefrontal cortex (RPFC), as shown in Figure 3. Both RoIs contained six transmitters and six receivers, instrumenting 14 channels covering the prefrontal cortex.



(a) (b) (c) (d)

Figure 1. Hazard types in VR scenarios: (a) Struck by an equipment; (b) Struck by an object; (c) Fall to a lower level; (d) Electrocution.

After each scenario, participants were asked to answer three Situation Awareness Global Assessment Technique (SAGAT) questions by randomly freezing the scenarios. There are a few types of situation awareness measurement techniques such as SAGAT, Situational Awareness Assessment Technique (SART) [25] and Crew Awareness Rating Scale (CARS) [26]. SART and CARS are self-rating assessments that might be limited by an individual's ability to assess their situation awareness [27]. Conversely, SAGAT measures objective reflections regarding situation awareness and is the most widely used freeze-probe technique that aims to assess different levels of situation awareness [28]. Choi et al. used SAGAT to measure workers' situation awareness while operating the forklift at the construction site, where SAGAT assisted in accurately capturing situation awareness at every level [27].

Based on their response, participants were categorized based on the level of situation awareness they have achieved [Achieved Level 1 (AL1), Achieved Level 2 (AL2), Achieved Level 3 (AL3)]. Notably, to examine the changes in the cognitive processing of participants, fNIRS data was extracted during periods when participants specifically focused on the hazardous area within the scenarios. Homer 3, a MATLAB-based toolbox, assisted in processing the fNIRS data. Physiological noise, such as cardiac activities, respiration, and blood pressure, was addressed by a bandpass filter. The modified Beer-Lambert law with different partial pathlength factor (ppf) based on individuals' age (e.g., ppf = 6,6,6) was adopted to convert the optical intensity changes into variations of oxy-Hb and deoxy-Hb. The General Linear Model (GLM) was used to analyze fNIRS data and calculate the Hemodynamic Response Function (HRF), which was computed for all participants across multiple channels.

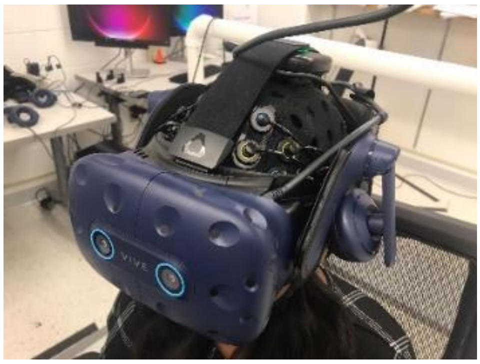


Figure 2. The participant with a VR headset and fNIRS device.

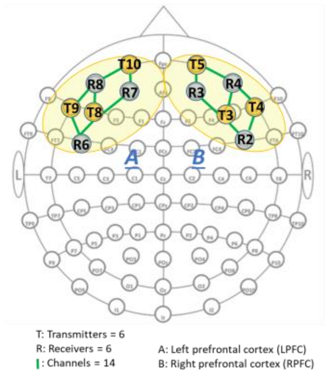


Figure 3. fNIRS layout: Region A is the Left Prefrontal Cortex (LPFC). It includes 3 Transmitters (T8, T9, T10), 3 receivers (R6, R7, R8), and 7 channels (green lines between transmitters and receivers). Region B is the Right Prefrontal Cortex (RPFC). It includes 3 Transmitters (T3, T4, T5), 3 receivers (R2, R3, R4), and 7 channels.

4 Results

Table 1 demonstrates the distribution of novice and experienced participants. 23 novice participants and 10 experienced participants were recruited for this research. The average age of novice participants was about 27 years while experienced participants exhibited an average age of around 30 years and an average work experience of 5.50 years.

Table 1 Age and work experience distribution.

Type of Participants	# of Participants	Age Mean (±SD)	Years of work experience Mean (±SD)
Novice	23	27.09 (±2.56)	-
Experienced	10	30.40 (±4.40)	5.50 (±3.13)

Note: Most novice participants had no work experience, and a few had less than or equal to six months of work experience.

To fully investigate the hazard recognition behaviors at construction sites, all participants performed hazard searches on 12 scenarios. Consequently, the study involved 23 novice participants with a total sample size of 276 and 10 experienced participants with a total sample size of 120, as shown in Table 2. It is noteworthy that 43 samples from novice participants and 12 from experienced participants were excluded due to the absence of recorded levels of situation awareness in these assessments. Therefore, 233 samples were selected from novice participants and 108 samples were selected from experienced participants.

Table 2 Sample distribution.

Types of Participants	# of VR scenes	Total sample size	Selected	Excluded[a]
Novice participant	12	276	233	43
Experienced participant	12	120	108	12

[a] means the participant did not achieve any level of situation awareness.

Figure 4 shows the percentages of participants who achieved each level of situation awareness to better understand hazard recognition behaviors across novice and experienced groups. In AL1, 84.42% of novice participants and 90% of more experienced participants were recorded, while in AL2, 71.38% of novice participants and 80% of experienced participants were observed. Ultimately, 63.41% of novice participants and 65.83% of experienced participants attained AL3. Notably, a declining trend from AL1 to AL3 was evident in both participant groups. The data indicates that irrespective of work experience, fewer participants achieved AL2 and AL3 compared to AL1. Analyzing the percentages of participants reaching each level of situation awareness across all 12 VR scenarios, it becomes apparent that more experienced participants exhibited slightly higher percentages than novice participants. However, the difference between the two groups was not substantial.

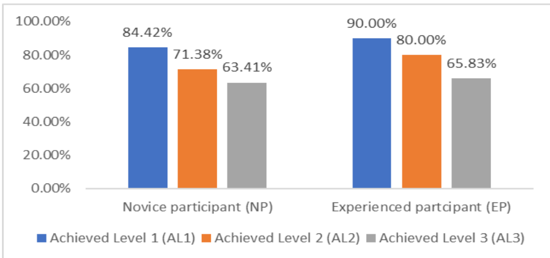


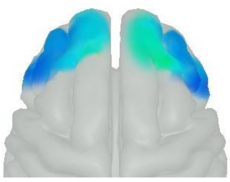
Figure 4. Percentages of participants achieved each level of situation awareness across two groups (Novice and Experienced)

Under observation of Oxy-Hb Concentration across levels of situation awareness, novice participants demonstrated a positive Oxy-Hb concentration in all situations. Specifically, the activation in the LPFC of novice participants was moderately higher than experienced participants in the perception level of situation awareness (AL1) ($p=0.06<0.1$) and significantly higher in the comprehension level of situation awareness (AL2) ($p=0.02<0.05$), as shown in Table 3. Experienced participants exhibited a negative value of Oxy-Hb in LPFC across all levels of situation awareness. However, experienced participants did have a higher Oxy-Hb concentration value in the RPFC in the comprehension level of situation awareness AL2 (Oxy-Hb = 4.11E-07) and in the projection level of situation awareness AL3 (Oxy-Hb = 2.41E-06). The brain activation examples of selective experienced participants with higher activation in AL3 were shown in Figure 5. As can be seen, experienced participants exhibited lower activations during the initial stage of situation awareness (AL1). As the stimuli increased, the activations in the brain became more pronounced. Significantly, during AL3, RPFC demonstrated the highest activation compared to other levels of situation awareness in experienced participants.

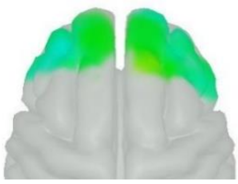
Table 3 Oxy-Hb Concentration across two groups.

RoIs	Cat.	Oxy-Hb Concentration across Levels of Situation Awareness		
		Achieved Level 1 (AL1)	Achieved Level 2 (AL2)	Achieved Level 3 (AL3)
L-PFC	NP	1.65E-06	3.37E-06	3.31E-06
	EP	-2.34E-06	-1.94E-06	-1.32E-06
	NP-EP	3.99E-06	5.31E-06	4.63E-06
	p-value	**0.06***	**0.02****	0.13
R-PFC	NP	1.92E-08	4.55E-08	7.55E-08
	EP	-5.28E-07	**4.11E-07**	**2.41E-06**
	NP-EP	5.47E-07	-3.65E-07	-2.33E-06
	p-value	0.82	0.89	0.44

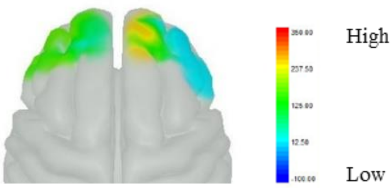
Note: RoIs: Regions of interest; LPFC: Left prefrontal cortex; RPFC: Right prefrontal cortex; NP: Novice participant; EP: Experienced participant. * $p<0.1$; ** $p<0.05$.



(a) AL1



(b) AL2



(c) AL3

Figure 5. Brain activation of representative experienced participants in each level of situation awareness. The color red represents a higher activation level, whereas blue indicates a lower activation level.

5 Discussion

The findings revealed distinct patterns of brain activation representations associated with various situation awareness levels among novice and experienced participants. Novice participants exhibited positive neural activity in both the left and right prefrontal cortex across the three levels of situation awareness (AL1, AL2, AL3). These outcomes are consistent with Zhou et al. [11], where increased neural activation was observed in novice participants during a hazard-searching task, suggesting heightened cognitive effort in novices aiming for higher levels of situation awareness. It must be noted that higher neural activity in novices in the left prefrontal cortex compared to the right is associated with recognizing specific features of objects, particularly in terms of remembering what an object is [29,30]. Within the hazard recognition process, the left prefrontal cortex plays a more important role compared to the right prefrontal cortex for the novices [30]. Given their lower familiarity with the work environment, they tend to allocate more attention to the details and exert more cognitive efforts from Level 1 to Level 3 situation awareness. Moreover, the diminished activation in the right forehead of novices could be linked to the absence of corresponding experience or knowledge, which serve as important factors that assist in forming mental models in their long-term memory [31].

Experienced participants consistently exhibited reduced activation in the left prefrontal cortex, a region crucial for detail recognition, across all three levels of situation awareness (AL1, AL2, AL3). This suggests a reduced cerebral cortex stimulation due to the familiarity with the construction site. However, this familiarity among experienced individuals also contributes to developing intrinsic mental representations that enhance hazard recognition. The positive changes in Oxy-Hb concentration in the right prefrontal cortex among more experienced participants were observed in higher levels of situation awareness (AL2 and AL3). These may link to the activation of mental models innated in the RPFC when they achieved higher levels of situation awareness [31]. In addition, given that the right prefrontal cortex is responsible for spatial processing and awareness rather than detailed information [29–31], this suggests that experienced individuals were inclined towards employing a global searching strategy to obtain a comprehensive understanding of the construction site. It is noteworthy that, despite these distinctions, the percentages of achieving each level of situation awareness were similar between novices and experienced individuals in this study. This implies that experienced individuals may underestimate risks due to familiarity, whereas novices exhibit a more cautious approach.

This paper provided a new perspective to investigate hazard recognition behaviors by comparing different situation awareness levels. Employing neuroimage techniques helped gain insights into the cognitive mechanism at different situation awareness levels among individuals with various experience levels. Findings revealed that novices had different neural reactions across three levels of situation awareness compared to the experienced, calling for customized training to address the specific weaknesses among novice workers. In addition, the phenomenon of diminished neural activations in experienced participants warrants careful consideration and attention. Injuries may occur when experienced workers underestimate or do not adequately acknowledge potential hazards. More effective safety training can be developed based on recognizing the deficiencies in brain activity during hazard recognition, aiming for enhanced hazard identification and overall safety performance.

While this paper offers valuable insights into the interplay between neural activation across various levels of situation awareness, some limitations should be noted. First, a few types of hazards have been considered in this study, and only one main hazard exists in each scenario, limiting the generalizability of the findings. Second, although the experienced group comprised over 100 samples, the participant count was limited to ten individuals, future research can consider recruiting more experienced participants. Third, it's noteworthy that the more experienced participants with five years of work experience were also students in the civil engineering domain, potentially limiting the generalizability of the findings to real-world construction scenarios. Future studies could benefit from a larger and more diverse worker pool. Last, the experiment was conducted with VR scenarios, replicating it in actual dynamic construction sites using portable fNIRS devices can enhance ecological validity.

6 Conclusion

Maintaining situation awareness is pivotal for worker safety in the dynamic and hazardous environments of construction sites. A detailed examination of various levels of situation awareness between novice and experienced individuals unveils insights into the cognitive neural correlates affecting the attainment of higher awareness levels. The findings indicated that novice participants exhibit higher neural activations in the left prefrontal cortex, which is linked to detailed object information, particularly in Level 1 perception and Level 2 comprehension. In contrast, more experienced participants showed increased activations in the right prefrontal cortex, associated with global comprehension and mental representation, particularly in achieving Level 2 comprehension and Level 3 projection. These results underscore distinct cognitive patterns of hazard recognition in novice and experienced participants facing the same hazardous scenarios. Greater activation in the left prefrontal cortex among novices is mainly due to their lower familiarity with the dynamics of construction sites, which may demand more attention to identify the related hazards in the scene. Simultaneously, the lack of mental representation in the right prefrontal cortex weakens hazard recognition ability, leading to lower neuron activations. These results highlight the potential of fNIRS data to differentiate the status of situation awareness between novice and experienced individuals, offering valuable insights for tailoring training strategies to address these cognitive deficiencies.

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