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Investigating the Impact of Spatial Reasoning on Construction Hazard Recognition

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This study examines the relationship between spatial reasoning abilities and hazard recognition performance within virtual reality (VR) simulations of construction environments. Despite the construction industry's high-risk nature and the critical role of hazard identification in preventing accidents, the impact of spatial cognitive skills on hazard recognition remains underexplored. Utilizing VR technology, the study created immersive construction site scenarios incorporating common hazards. Participants' spatial reasoning abilities were assessed using the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R), followed by evaluations of their hazard recognition performance within the VR environments. Statistical analysis revealed no significant correlation between spatial reasoning scores and hazard recognition performance, although the results indicate a slight upward trend in hazard recognition index (HRI) with increasing spatial reasoning ability. These findings indicate that other factors, such as attention distribution, experience, and training methodologies, may play more substantial roles in enhancing hazard recognition. The study underscores the potential of VR-based training programs to improve safety outcomes by providing realistic and controlled environments for hazard identification practice. Future research should adopt a larger, more diverse, and experienced population.

Keywords: Hazard Recognition, Spatial Reasoning, Construction, Worker Safety, Virtual Reality

Introduction

The construction sector plays a crucial role in North America's economy, contributing $958.8 billion to the United States GDP in 2021 (Xiao et al., 2022). Nevertheless, it faces persistent challenges such as labor shortages, low productivity, elevated safety risks, and limited automation on a global scale (Golparvar-Fard et al., 2015). Furthermore, the industry is characterized by inherently high-risk work environments that are both complex and dynamic. In 2022, the construction sector experienced 1,056 fatal work injuries—an 11% increase from the previous year—making it the occupation with the second-highest fatality rate (BLS, 2022). The fatality rate for construction workers rose from 12.3 to 13.0 deaths per 100,000 full-time equivalent workers between 2021 and 2022 (BLS, 2022).

Despite ongoing efforts to enhance safety protocols, construction remains one of the most hazardous industries, with a persistently high incidence of workplace injuries and fatalities (Bohm & Harris, 2010). Research indicates that 80–90% of safety incidents are linked to workers' unsafe behaviors, often resulting from their inability to detect hazards (Choi & Lee, 2018). This underscores the critical importance of addressing hazard detection failures to improve construction site safety (Fang et al., 2016; Xiang et al., 2023). Hazard detection entails the processes of scanning, identifying, and recognizing potential risks in the surrounding environment (Fang et al., 2016; Khan et al., 2024). Consequently, enhancing hazard control and advancing safety management have become urgent priorities for the construction sector. Hazard detection is a critical component of construction safety management. However, traditional approaches to hazard recognition training often rely on two-dimensional (2D) drawings or in-person site walkthroughs, which may not fully replicate the complexity and dynamism of real-world construction environments (Jeelani et al., 2019). These methods fail to provide workers with the interactive and immersive experiences needed to prepare them for the unpredictable nature of construction sites.

Numerous studies in mathematics and geometry have demonstrated a positive correlation between individuals' spatial cognitive abilities and their problem-solving skill (Battiste & Bortolussi, 1988; Fennema & Tartre, 1985). However, more recent findings suggest that spatial cognitive skills may not significantly impact hazard recognition abilities, especially in the context of prevention through design (PtD) in construction (Hardison et al., 2022). Previous studies have explored the relationship between spatial reasoning and hazard identification, focusing primarily on identifying potential hazards from design drawings (Hardison et al., 2019, 2022). However, this approach may not fully capture the complexities of real-world construction environments. While spatial reasoning abilities are often linked to visual-spatial tasks, hazard recognition in dynamic construction environments likely involves a broader interplay of cognitive and situational factors. These include attention distribution, prior experience, and familiarity with construction activities, which may collectively influence a worker’s ability to detect hazards. Furthermore, the potential of VR to simulate dynamic construction scenarios and evaluate hazard recognition in real time has not been fully leveraged. To address this gap, this study investigated how spatial reasoning abilities influence hazard recognition in dynamic construction site simulations. A virtual reality (VR) environment was utilized in this study to provide a controlled and immersive setting for assessing the impact of spatial reasoning ability on hazard recognition.

Literature Review

Identifying hazards is the first step in accident prevention. Hazard identification is crucial in the construction industry to ensure safety on construction sites. Particularly as the industry is increasingly becoming more complex and dynamics and hazard identification continue to grow. Identifying hazards before they lead to incidents is important for improving construction safety, and this remains a widely studied area in construction safety research (Ouyang & Luo, 2022). Hazard identification and recognition in construction is a visual search task, whereas the adopted visual search patterns during hazard identification are demonstrated to impact identification performances (Jeelani et al., 2019).

Minimizing exposure to hazards is essential for preventing injuries and illnesses in construction. Recognizing safety hazards is a critical first step in managing or avoiding them effectively. If hazards go unnoticed, they are unlikely to be addressed, which can elevate the risk of workplace incidents and injuries. A study emphasized that effective hazard identification is essential for improving construction safety management, especially regarding non-fatal fall injuries, which are prevalent in the industry (Antwi-Afari et al., 2020). Similarly, another study investigated the mechanism of construction workers' visual attention on their ability to identify hazards, suggesting that enhanced visual attention can lead to better hazard recognition and avoidance behaviors (Hasanzadeh et al., 2018). These studies show that workers must distribute their portion of attention to effectively maintain situational awareness and prevent potential incidents during construction tasks (Hasanzadeh et al., 2017, 2018). Therefore, hazard identification and attentional distribution must be considered to understand and investigate the impact of spatial reasoning ability on construction workers.

Spatial reasoning abilities are generally regarded as inherent traits that precede any activity and remain relatively stable over time. In the construction industry, these abilities are crucial for interpreting and visualizing complex structures, especially when utilizing advanced technologies such as Virtual Reality (VR) simulations. Unlike traditional reliance on two-dimensional (2D) blueprints, VR provides immersive, three-dimensional environments that require workers to encode, transform, retain, and match design information in real time. This dynamic interaction enhances the retention, manipulation, and generation of precise visual representations, enabling workers to proactively identify and address potential safety hazards on construction sites. Employing VR technology allows the construction industry to improve safety outcomes and reduce the ambiguities often associated with traditional methods. Spatial orientation encompasses the processes of encoding, retaining, transforming, and aligning design information. These processes can sometimes result in omissions and ambiguities (Hardison et al., 2019).

Methodology

This study aimed to examine the relationship between spatial reasoning abilities and hazard recognition performance (HRP) within a virtual reality (VR) construction environment.
VR has been extensively used to educate and train construction workers on safety management (Wolf et al., 2022) such as hazard recognition (Noghabaei et al., 2020; Guo et al., 2024). VR environments replicate dynamic construction scenarios with high fidelity, enabling workers to experience realistic hazards in a controlled, safe setting (Eiris et al., 2021). VR also facilitates real-time data collection, enabling researchers to track participants' interactions with hazards, analyze their decision-making processes, and evaluate their performance quantitatively. These capabilities make VR an ideal tool for studying the cognitive and behavioral factors that influence hazard recognition (Guo et al., 2024). The research design consisted of three key phases: participant recruitment and training, spatial reasoning assessment, and hazard recognition evaluation in VR simulations. The virtual reality (VR) environments simulating a construction site populated with heavy equipment and workers were created to provide the ground for the study. The VR scene included OSHA's "Fatal Four" hazards, along with other significant hazards that frequently lead to injuries and fatalities on construction sites. Participants were recruited from construction-related, and engineering disciplines and screened to ensure they met the study's inclusion criteria, which required basic familiarity with construction site operations. In this environment, participants encountered scenarios involving working at height, a leading cause of construction-related fatalities (Zhao et al., 2014). The experiment involved three phases: (1) a safety training session that included OSHA's Fatal Four hazards, followed by a safety quiz to ensure comprehension (minimum score of 80% to proceed); (2) a spatial reasoning assessment using the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R); and (3) hazard recognition tasks within a VR-simulated construction environment. During the VR scenario development, construction site elements, such as 3D models of workers and heavy machinery, including cranes, trucks, and forklifts, were integrated into Unity®. These models were then animated and programmed to simulate real construction activities. To enhance the VR experience, a drone sound effect was added to accompany the drone's movements. The completed VR scenes were reviewed by five experts with experience in construction, VR, and robotics to identify potential hazards in the environment. The VR environment included 26 pre-identified hazards, such as fall risks, struck-by incidents, and equipment-related hazards. Participants' hazard recognition

performance was measured using the Hazard Recognition Index (HRI), calculated as the percentage of correctly identified hazards relative to the total hazards present in the simulation.

These identified hazards were used to establish the ground truth to measure the participants' Hazard Recognition Performance (HRP). The Hazard Recognition Index (HRI) was used to evaluate each participant's HRP, following the methodology outlined in the study by Namian et al. (2021). The HRI is calculated by dividing the number of hazards identified by the participant (HI) by the total number of hazards present in the VR scene (TH) and multiplying the result by 100. This equation quantifies the participant's ability to recognize hazards as a percentage of the total hazards in the virtual environment, providing a standardized measure of their hazard recognition performance. The total number of hazards designed in the scene was 26.

$$HRI = \frac{HI}{TH} \times 100$$

The Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) was utilized to measure the spatial reasoning ability of each participant. The PSVT:R, a validated assessment tool, evaluates participants' mental rotation skills by requiring them to visualize and predict the appearance of two- and three-dimensional objects after specific rotations (Maeda & Yoon, 2013). This test is a critical tool for assessing spatial visualization capabilities, which are essential for understanding and manipulating visual-spatial information, as well as for problem-solving and interpreting complex spatial relationships (Maeda & Yoon, 2013). Below (See Figure 1) is the research methodological process.

Participants were then grouped into three distinct spatial ability levels; Low, Medium, and High based on their PSVT:R scores. These groups were determined using the first quartile (Q1) and third quartile (Q3) of the scores as cutoffs. Participants scoring below Q1 were categorized as Low, those between Q1 and Q3 as Medium, and those above Q3 as High. This categorization facilitated a comparative analysis of hazard recognition performance across spatial ability levels.

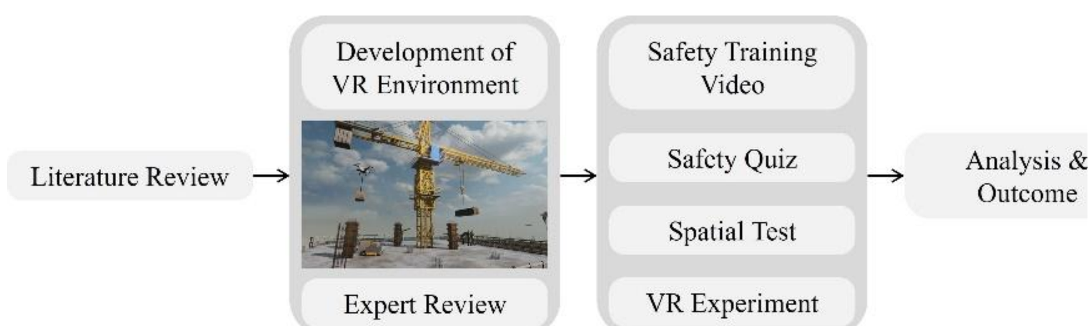

Figure 1. Research Methodology

A total of 29 participants were recruited for the study. Before starting the experiment, participants were required to watch a safety training video on construction safety, which includes OSHA's Fatal Four. After watching the video, participants completed a safety quiz to evaluate their understanding, with a minimum score of 80% necessary to proceed further. Following the quiz, participants took a spatial reasoning test to measure their spatial reasoning ability.

Statistical analysis

Data were analyzed using one-way ANOVA to compare mean HRI scores across the three spatial reasoning groups (Low, Medium, High). Assumptions for ANOVA were verified using the Shapiro-Wilk test for normality and Levene's test for homogeneity of variances. Post hoc Tukey HSD tests were conducted to explore pairwise group differences.

Result

The study aimed to investigate how the spatial reasoning ability of HRP in a virtual construction site. Table 1 presents the demographic details for the 29 participants who took part in the study. The participants' ages ranged from 18 to 44 years, with males comprising a substantial majority at 72.4%. Most participants had a background in construction, while others came from engineering and various other fields. In terms of construction experience, 44.8% of participants had 0 to 1 year of experience, while 55.2% had 1 to 5 years of experience as shown in Table 1.

Table 1. Demographic Information

Demographics		**Frequency**	**Percent (%)**
Age	18 – 24	11	37.9%
	25 – 34	17	58.6%
	35 – 44	1	3.4%
Gender	Female	8	27.6%
	Male	21	72.4%
Discipline or specialization	Construction related	22	75.9%
	Engineering	3	10.3%
	Others	4	13.8%
Construction experience	0 - 1 years	13	44.8%
	1 - 5 years	16	55.2%

Before performing the one-way ANOVA, the data were evaluated to ensure they met the required assumptions. The Shapiro-Wilk test was used to check for normality, and the results showed that the HRI was normally distributed across all groups ($p > 0.05$). Levene's test was also conducted to examine the equality of variances, confirming that the group variances were similar ($p > 0.05$). These findings verified that the data were suitable for one-way ANOVA analysis. Participants were then grouped into three distinct groups based on their spatial test scores. The grouping criteria were using the first quartile (Q1) and third quartile (Q3) of the spatial test scores as cutoff points. Participants with scores below Q1 were categorized as Low, those between Q1 and Q3 were categorized as Medium, and those above Q3 were categorized as High. Table 2 presents the mean and standard deviation of HRI for each group. The descriptive statistics in Table 2 indicate that the mean HRI values increased slightly across groups (low: M = 20.46, SD = 4.21; medium: M = 23.18; SD =10.59; high: M = 26.45, 10.72) but these differences were not sufficient to achieve statistical significance.

Table 2. Descriptive Statistics for HRI

Spatial Ability Group	**M**	**SD**
Low	20.46	4.21
Medium	23.18	10.59
High	26.45	10.72

Descriptive statistics indicated a slight upward trend in mean HRI values (Low: M = 20.46, SD = 4.21; Medium: M = 23.18, SD = 10.59; High: M = 26.45, SD = 10.72); however, these differences were not sufficient to achieve statistical significance. A post hoc Tukey HSD test confirmed no significant pairwise differences between groups (all $p > 0.05$). A one-way ANOVA was conducted to assess the effect of spatial reasoning ability (categorized as Low, Medium, and High based on PSVT:R quartiles) on hazard recognition performance (HRI). The results showed no statistically significant differences in HRI across the three groups, $F(2, 26) = 0.967$, $p = 0.394$. To further explore potential pairwise differences, a post hoc Tukey HSD test was performed, which also revealed no statistically significant differences between any of the groups (all $p > 0.05$). Specifically, the differences between the Low and Medium groups ($p = 0.814$), the Low and High groups ($p = 0.368$), and the Medium and High groups (p =0.708) were not statistically significant. These results indicate that, while there is a slight upward trend in HRI with increasing spatial reasoning ability, this trend does not reach statistical significance (see Figure 2).

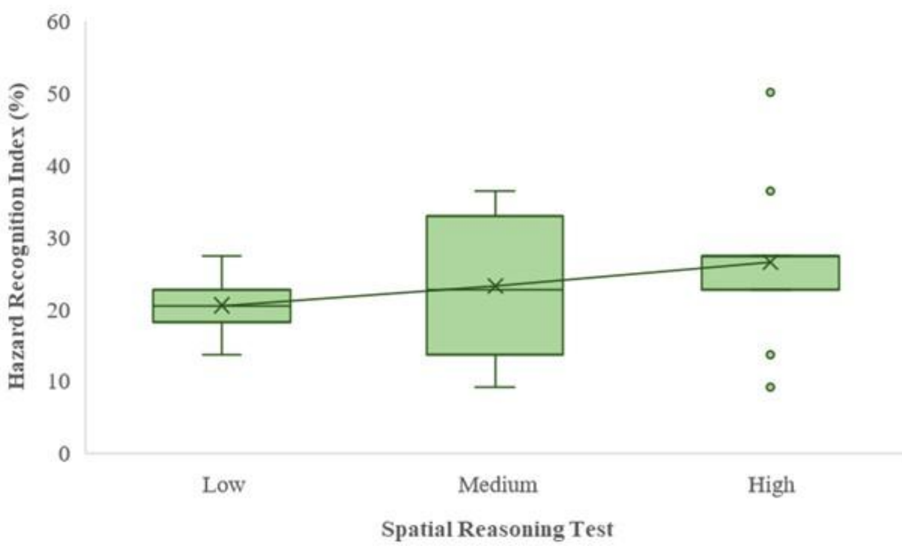

Figure 2. Hazard Recognition Performance of Each Group

Discussion

This study explored the relationship between spatial reasoning abilities and HRP within a VR-simulated construction environment. Interestingly, the mean HRI values increased across the groups (low: M = 20.46, medium: M = 23.18; high: M = 26.45); however, this increase was not statistically significant relation to spatial reasoning scores contrary to previous studies in other fields, such as mathematics and geometry, Although there was an observed upward trend in mean hazard recognition scores corresponding with higher spatial reasoning scores, these differences did not reach statistical significance. Although spatial reasoning ability has a positive relationship with HRP, other factors such as experience, and training should be considered. This aligns with previous research indicating that spatial cognitive skills may not significantly impact hazard recognition abilities, particularly in prevention through design contexts (Hardison et al., 2022). The absence of a significant correlation highlights the need to explore other cognitive or perceptual factors that may impact hazard recognition, such as attention, distractions, and prior experience. While spatial reasoning ability alone did not emerge as a strong determinant of HRP, it is important to note the variability observed in the Medium (SD =10.59) AND high (SD =10.72) groups compared to the low group (SD =4.21). This suggests that individual differences, potentially linked to other cognitive or situational factors, may contribute to hazard recognition outcomes.

The slight upward trend in HRP scores with higher spatial reasoning levels suggests that spatial reasoning may still have a marginal influence, albeit not statistically significant. This could imply that spatial reasoning interacts with other cognitive or experiential factors, such as visual scanning patterns or decision-making under pressure, to influence hazard recognition. Such interactions warrant further exploration in future studies. Moreover, the role of training and experience in hazard recognition cannot be overlooked. Workers with safety training or prior construction experience may be better equipped to adapt to dynamic environments and recognize hazards effectively, even when their spatial reasoning abilities are moderate. This highlights the critical importance of comprehensive safety training programs that simulate dynamic and realistic work conditions.
The absence of a significant correlation between spatial reasoning and hazard recognition performance suggests that other factors may have a stronger influence on hazard detection. For example, attention distribution is crucial in visual search tasks, as workers must allocate focus across multiple elements in a dynamic environment. Training and prior experience may also enhance hazard recognition by equipping workers with pattern recognition skills and situational awareness. Additionally, external factors such as distractions, task complexity, and time pressures may interact with cognitive processes to impact performance.

Future studies should also consider exploring these findings within a more diverse population to uncover broader insights. Examining populations with varying cultural, educational, and professional backgrounds could help identify additional factors that influence hazard recognition. For instance, differences in training practices, work environments, and cultural attitudes toward safety may reveal critical nuances that could inform tailored interventions. Such research could provide more inclusive and actionable recommendations for improving hazard recognition performance across diverse construction settings.

Conclusion

Although the findings did not demonstrate a significant relationship between hazard recognition performance (HRP) and spatial reasoning ability, they contribute to a deeper understanding of these constructs. The results suggest that spatial reasoning ability may not play a substantial role in HRP within the context of this study design. Nevertheless, the observed upward trend in mean hazard

recognition scores across groups highlights the need for further exploration of spatial reasoning or other contributing factors that may influence HRP. Additionally, the use of VR technology in this study provided a valuable, immersive platform for evaluating hazard recognition, underscoring its potential for advancing VR-based training programs. These findings suggest that focusing solely on spatial reasoning may be insufficient for enhancing hazard recognition skills, emphasizing the importance of investigating alternative or complementary factors.
Although VR provides an immersive and controlled environment for assessing hazard recognition, it is important to acknowledge its limitations as a proxy for real-world construction sites. The lack of physical interaction with real-world elements, the controlled nature of VR scenarios, and the potential for reduced participant engagement in virtual settings may affect the generalizability of the findings. Second, participants in VR simulations are aware that they are in a virtual setting, which may reduce the perceived consequences of errors and alter their decision-making processes. Another key limitation of this study is its narrow focus on spatial reasoning as a predictor of hazard recognition performance. Although spatial reasoning is important for visual-spatial tasks, hazard recognition is likely influenced by a combination of cognitive, experiential, and situational factors. These limitations highlight the need to interpret the findings with caution and suggest the value of complementing VR-based studies with field-based assessments to validate their applicability to real-world conditions. Future research should explore hybrid approaches that combine VR with field studies to address these limitations and enhance ecological validity.

The utilization of VR technology in this study provided an immersive platform for assessing hazard recognition, offering valuable insights into the potential of VR-based training programs. However, the findings indicate that focusing solely on spatial reasoning may not suffice to improve hazard recognition skills. While spatial reasoning alone may not have emerged as a significant determinant in this study, it remains a variable worth exploring within different populations or specific trades, where its relevance might vary. Future research should investigate the potential impact of spatial reasoning across diverse trades and varying levels of experience to determine whether its significance shifts in different contexts.
This study underscores the importance of incorporating various cognitive and experiential factors to develop more effective training interventions aimed at reducing workplace incidents in the construction industry. Factors such as attention distribution, training methodologies, and prior experience may play more significant roles in hazard recognition performance. Future research should adopt a multifaceted approach to better understand the interplay of these factors, thereby informing the development of more effective hazard recognition training programs. Expanding the scope to include variables such as attention, training, environmental context, and trade-specific factors would provide a more comprehensive framework for understanding hazard detection and enhancing safety outcomes across different construction settings.

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