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How Individual Differences Influence Indoor Emergency Escape Training under 2D Mini-maps and X-ray Visualizations: A Webcam User Study

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Abstract:

In emergency scenarios, first-time visitors often struggle to interpret building layouts under high-stress conditions. Research suggests that unfamiliar occupants frequently overlook exit signs due to fragmented spatial knowledge induced by stress (Fu et al., 2024). Therefore, providing effective indoor emergency escape training for individuals unfamiliar with complex buildings is necessary. However, such training programs incur high deployment costs and are limited in accessibility, which significantly hinders their large-scale implementation. Consequently, developing an easily deployable navigation aid system that can efficiently facilitate indoor escape training for first-time visitors represents a significant advancement toward scalable and accessible emergency preparedness (Wang et al., 2023).

While 2D mini-maps (allocentric, top-down views) and X-ray navigation aids (egocentric, see-through visualizations) have shown potential for indoor spatial learning as navigation aids, their effectiveness and efficiency in preparing users for unassisted emergency escapes remain underexplored (Wang et al., 2025b, a). To address this gap, the primary objective of this study is twofold: first, to evaluate and compare the efficacy of these two distinct visualization approaches in facilitating indoor spatial learning and unassisted emergency evacuation; and second, to investigate how individual differences influence users' learning performance and subsequent evacuation outcomes under each condition.

To address the scalability limitations, we developed a lightweight, web-based desktop virtual reality platform (Figure 1). As a case study, the user study was conducted in a controlled laboratory environment using a standardized hardware configuration to ensure a rigorous evaluation. A total of 28 Participants completed the study using a uniform setup consisting of a 27-inch desktop monitor and a Logitech HD 1080P webcam.

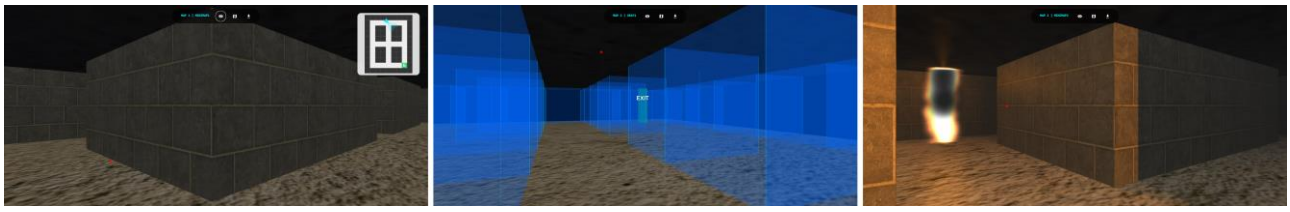

Figure 1. 2D mini-map (left); X-ray vision (middle); Unassisted escape test featuring virtual fire (right).

The methodology employs a counterbalanced within-subjects experimental design to evaluate the acquisition and transfer of spatial knowledge. Participants interact with two distinct virtual mazes of comparable complexity, controlled for variables such as the number of turns, total floor area, and corridor lengths to minimize learning and sequence effects. To establish a baseline for individual differences, participants first complete the Santa Barbara Sense of Direction Scale (SBSOD) as a standardized self-report measure of environmental spatial ability (Hegarty et al., 2002), alongside personal and professional factors such as gaming frequency and map familiarity. A key technical component of this study is the integration of WebGazer, a web-based eye-tracking tool, which records participants' visual attention and gaze patterns during the learning phase (Papoutsaki et al., 2016). This allows for a granular analysis of how different visualization aids influence overall gaze behavior and how users process spatial information at decision points.

The experimental procedure is structured into four distinct phases per condition to assess both learning efficiency and knowledge retention. During the Assisted Navigation Phase, participants are tasked with finding the exit while the assigned navigation aid (either the Mini-map or X-ray vision) remains active. We record completion time, movement–pause ratios, and look-around behavior to measure navigational efficiency. This is followed by the Unassisted Escape

Test, the core of the evaluation, where participants must evacuate the same maze without any digital assistance. To simulate the pressure of a real-world emergency, the environment is modified with virtual fire, forcing participants to replan their routes. Performance indicators in this phase include total escape time, replanning latency after encountering obstructions, and the frequency of incorrect path traversals. The session concludes with subjective assessments using the NASA Task Load Index (TLX) to measure cognitive workload, supplemented by qualitative interviews regarding the ease of use, perceived helpfulness, and the participant's overall confidence in their spatial understanding of the building (Anon, 1988).

Our finalized results reveal a clear performance gap between the two navigation aids, with the 2D mini-map consistently leading to shorter learning durations and marginally shorter unassisted evacuation times and distances compared to the X-ray visualization ($p < 0.07$).

Interestingly, when exploring individual differences, we found that participants' gaming frequency had a much more pronounced impact on learning and evacuation efficiency than spatial literacy variables derived from the SBSOD scale. Under the Minimap condition, a higher gaming frequency was significantly correlated with reduced learning time ($\rho = -0.51$, $p < 0.05$) and shorter evacuation time ($\rho = -0.48$, $p < 0.05$). This mitigating effect on time metrics was particularly robust under the X-ray condition, where higher gaming frequency strongly correlated with a highly significant reduction in learning time ($\rho = -0.67$, $p < 0.001$), evacuation time ($\rho = -0.50$, $p < 0.05$), and evacuation distance ($\rho = -0.56$, $p < 0.01$).

This performance matrix is further elucidated by the eye-tracking data. Gaze analysis indicated that mini-map users exhibited significantly more dispersed saccadic patterns compared to those in the X-ray condition. This dispersion is driven by the spatial layout of the interface, as participants using the mini-map had to repeatedly shift their foveal attention upward from the central game view to consult the map before returning downward, whereas the X-ray overlay remained centered on the primary forward view.

Subjective feedback mirrors the findings of quantitative analysis. A majority of participants noted that the mini-map was superior for building a coherent cognitive map of the maze. As one user highlighted: "The mini map allows me to have a better overall mental image of the space as a whole… I could remember the overall area and calculate the alternative route". This enhanced spatial understanding directly explains why participants exhibited higher confidence and superior routing flexibility during the unassisted fire evacuation phase after training with the 2D mini-map.

Ultimately, while the training system is architected as a web-based platform to facilitate low-barrier deployment, this controlled laboratory evaluation provides a mathematically validated baseline for the visual aids themselves. By uncovering how interactive habits like gaming frequency and visual layout structures dictate spatial cognition, this research offers critical, empirically grounded insights for designing scalable and effective emergency preparedness tools.

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