Merging Graph Theory and VR

Human-Centred Assessment of Fire Evacuation Cognition

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Abstract. Conventional fire safety analysis focuses on distances and capacities but offers little insight into how occupants perceive and understand complex layouts under stress. This paper proposes a human-centred computational framework that links building spatial configuration with evacuation cognition. We introduce the Evacuation Cognitive Index (ECI), a composite metric that integrates Spatial Complexity (SC) from Graph Theory with Visual Load (VL) captured through eye tracking in immersive Virtual Reality (VR) evacuation scenarios. A BIM-based model provides the geometric and topological basis for GT analysis, while VR simulations record participants' gaze behaviour, route choice, and evacuation time in a school building under simulated fire conditions. Higher ECI values are associated with denser fixation patterns, increased decision uncertainty, and longer evacuation times, whereas low ECI routes support clearer spatial legibility. ECI thus functions as a cognition-informed design indicator that advances evacuation planning toward humanistic, perception-aware and performance-based building safety.

Keywords. Virtual Reality, Graph Theory, Eye-tracking, Fire Evacuation, Humanistic computation

1. Introduction

The spatial configuration of a building plays a decisive role in determining evacuation safety and efficiency during fire emergencies, as it governs accessibility, route selection, and overall movement performance. Although fire protection regulations such as GB50016-2014 (Ministry of Public Security of the People's Republic of China, 2014) specify quantitative requirements for evacuation distance and exit capacity, they provide limited guidance on qualitative aspects of spatial legibility and circulation clarity. Consequently, designers often rely on subjective judgment to address cognitive factors of wayfinding, such as intuitive navigation, spatial hierarchy, and environmental comprehension.

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To quantitatively assess how building layouts influence evacuation performance, numerous studies have employed Graph Theory (GT) to represent architectural spaces as topological networks that represent connectivity, accessibility, and circulation efficiency (Zhao et al., 2023). While GT has effectively identified critical nodes and optimal egress routes, most conventional models evaluate evacuation performance mainly in terms of evacuation time. Edge attributes such as visibility, signage, and environmental hazards are typically excluded, limiting their capacity to capture dynamic interactions between human cognition and spatial configuration during emergencies (Donato, 2017).

Recent developments in VR have enabled the study of evacuation behaviour in immersive and controllable environments, providing empirical insights into visual attention, decision-making, and navigation (Bernardini et al., 2023). However, most existing VR studies have primarily focused on external guidance systems, such as exit signage or lighting cues, while the cognitive effects of spatial configuration remain insufficiently explored (Fu et al., 2024a).

This paper proposes a human-centred computational framework that integrates BIM, GT, immersive VR, and eye-tracking to link building spatial configuration with evacuation cognition. It introduces the ECI, combining Spatial Complexity (SC) and Visual Load (VL) into a unified indicator of cognitive difficulty. VR and eye-tracking experiments were employed to empirically validate that higher ECI values are associated with increased gaze effort, decision uncertainty, and longer evacuation times, thereby informing cognition-aware design. By integrating spatial, perceptual, and behavioural dimensions, the framework establishes a cognition-informed and performance-based approach to building safety design, advancing understanding of the interplay between spatial topology and human cognition.

2. Methodology

The methodology integrates BIM, GT, VR and eye-tracking to investigate the cognitive mechanisms of fire evacuation (Figure 1).

BIM provides geometric and semantic information to develop a GT-based spatial network for quantifying SC and connectivity. The derived topological parameters guide the identification of potential evacuation routes and the evaluation of their structural efficiency. These routes are further examined within an immersive VR platform that simulates dynamic fire conditions and environmental cues to reproduce realistic evacuation scenarios. Eye-tracking data collected during VR experiments capture participants' visual attention, enabling real-time measurement of participants' visual attention allocation and route-selection behaviour. A case study conducted on the fourth floor of an engineering building demonstrates the implementation of this framework, from BIM-based graph generation to VR-based behavioural analysis, enabling a comprehensive understanding of how spatial configuration and visual cognition jointly influence evacuation performance. The integrated results are synthesised through the ECI, which quantitatively represents cognitive load under different spatial conditions.

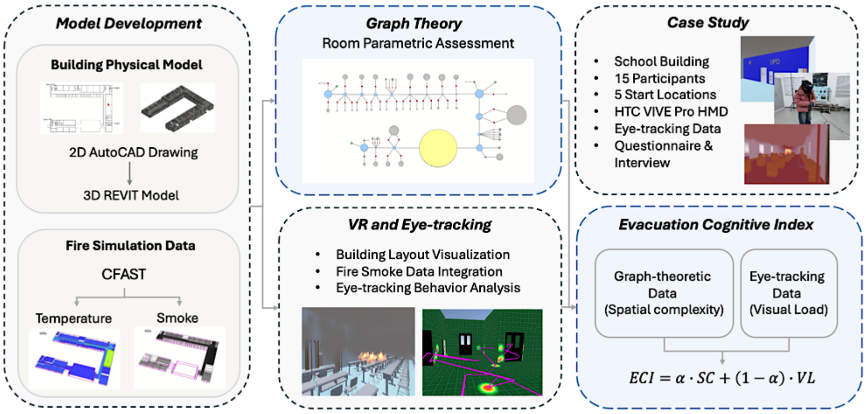

Figure 1. Methodology for cognition-informed fire evacuation analysis

2.1. MODEL DEVELOPMENT

The BIM model was generated from the floor plan to ensure the geometric accuracy of spatial components such as rooms, corridors, and vents, providing a reliable foundation for fire simulation. Fire dynamics were simulated in CFAST to compute the temporal evolution of temperature and smoke dispersion, generating realistic environmental data for behavioural experiments. The layer temperatures and smoke heights of each compartment were sampled at predefined intervals and compiled into structured datasets. These data were then integrated into the VR platform to enhance the visual and thermal realism of the evacuation simulations.

2.2. GRAPH-THEORETIC EVALUATION

The floor plan was abstracted into a graph to capture the building's spatial topology. Fire safety codes were formalised as graph-assembly rules to ensure that the GT network complied with evacuation design principles. To quantitatively assess the floor layout and evacuation performance, several GT parameters were derived from the network's structural and topological properties, including closeness centrality, circulation, connectivity, accessibility, and evacuation cost (Donato, 2017). Higher closeness centrality and connectivity indicate shorter path lengths and improved spatial integration, promoting efficient movement and reduced transition costs. Such configurations improve both routine circulation and emergency evacuation performance. However, excessive parameter distributions may cause congestion, overload critical nodes, and reduced route redundancy, thereby compromising system robustness. These parameters served as the basis for the SC component of the ECI. Table 1 summarises key GT parameters, their mathematical definitions, and their spatial implications. As illustrated in Figure 2, the building's schematic graph was constructed with vertices corresponding to spatial units, doors, transit points, and exits, positioned at their geometric centres and scaled by area. Edges represent the connectivity between nodes, weighted by walking distances. Nodes are colour-coded to clarify the topological and functional organisation for quantitative analysis.

Table 1. Key GT parameters and their spatial implications

GT Parameter	Spatial Interpretation	Cognitive Implication
Closeness Centrality	The average of the shortest path length from the node to every other node in the graph.	↑ → accessibility ↑
Circulation	The average distance between all pairs of its nodes.	↑ → graph complexity ↑
Connectivity	The ratio of edges to nodes in a graph.	↑ → graph complexity ↑
Accessibility	The total number of nodes in the graph.	↑ → space and route complexity ↑
Evacuation Cost	The total walking distance from the initial point to the exit.	↑ → efficient routes ↓

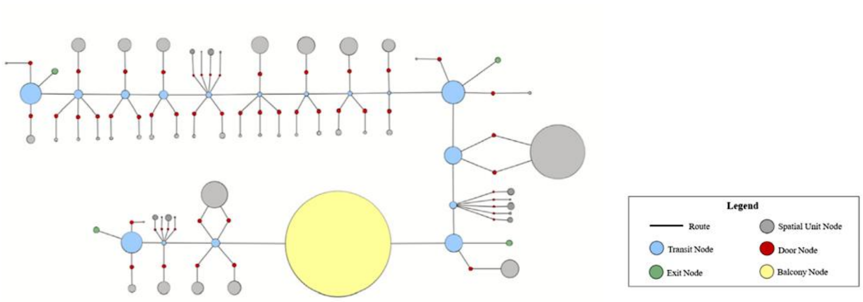

Figure 2. Schematic Graph

2.3. VR ENVIRONMENT AND EYE-TRACKING

The immersive virtual environment was developed in Unity3D using C# scripting, integrating the BIM model with fire simulation data from CFAST. The architectural geometry, fire safety facilities, and evacuation signage were modelled in Autodesk Revit and imported into Unity3D for real-time simulation. Temperature and smoke height outputs from CFAST were mapped to visual cues following established VR fire simulation practices (e.g., colour gradients, visibility reduction), consistent with prior evacuation cognition studies. Dynamic smoke and temperature fields were visualised to represent the temporal evolution of the fire, with colour transitions indicating heat intensity and a particle system rendering smoke dispersion. When local temperature exceeded 26 °C, the field of view shifted toward red hues, and darker tones represented higher thermal intensity.

Participants experienced the simulation through an HTC Vive Pro HMD equipped with Tobii eye-tracking. The system continuously recorded gaze coordinates, fixation counts, durations, and timestamps to capture visual attention and behavioural responses. Eye-tracking metrics, including fixation duration, fixation count, and Areas of Interest, were extracted for quantitative assessment. A customised 'UnityHeatmapShader' visualised gaze data as scan paths and heatmaps, with yellow spheres denoting gaze points, magenta lines representing scan paths, and colour gradients from green to red indicating increasing attention intensity.

2.4. CASE STUDY

The case study was conducted on the fourth floor of a school building (4,856 m²), comprising 32 offices, 10 washrooms, 5 low-voltage rooms, and 4 exits. The fire ignition point was positioned in the middle room of the right-side corridor. The U-shaped layout posed potential fire safety risks in long corridors and dead-end rooms due to limited escape routes (Fu et al., 2024b). Therefore, five starting locations within these critical areas were selected to evaluate evacuation efficiency. The fire scenario was simulated using CFAST, with ignition in the centre of the computer room (Figure 3). Three workstation panels were defined as combustibles under normal environmental conditions. Simulation results were imported into Unity 3D to visualise dynamic smoke and temperature fields for VR experiments.

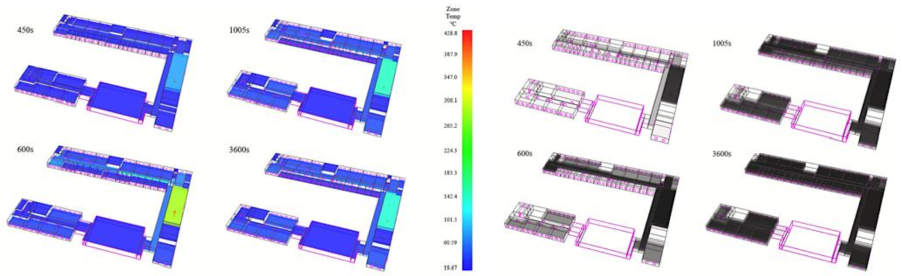

Figure 3. Left: Temperature change with timestamp. Right: Fire smoke distribution with timestamp.

Fifteen participants (10 female, 5 males; aged 20–31) with normal vision were randomly assigned to five groups, each starting from a designated room. After completing the pre-experiment questionnaire on demographics and prior VR experience and receiving brief navigation training, participants were instructed to evacuate the virtual environment via any available exit as efficiently as possible. Eye-tracking data, behavioural timing, and route selection were recorded. Complementary video recordings enabled classification of behaviour types and measurement of their frequency and duration. Following the task, participants completed a post-experiment questionnaire evaluating task difficulty, layout familiarity, exit visibility, and evacuation efficiency on a five-point Likert scale. Semi-structured interviews were subsequently conducted to investigate further participants' perceptions of the building layout and the reasons for their route selection during evacuation.

2.5. EVACUATION COGNITIVE INDEX (ECI)

The ECI integrates spatial and perceptual dimensions of evacuation cognition by combining SC and VL. SC represents the topological difficulty of evacuation routes, derived from normalised GT metrics (Lg, D, β, AC, Cost) and weighted via the entropy method to reflect each variable's information contribution. VL quantifies attentional effort in visual information processing. Both indices were normalised to [0–1] for comparability, with higher values indicating greater cognitive difficulty. The integrated

ECI was then computed as a weighted linear combination:

$$\mathrm{ECI} = \alpha \cdot \mathrm{SC} + (1 - \alpha) \cdot \mathrm{VL} \quad [1]$$

where α represents the relative contribution of spatial configuration to evacuation cognition, although the weighting parameter is partly heuristic, its selection was informed by both theoretical considerations in spatial cognition and empirical validation. Alternative weighting schemes (α = 0.3, 0.5, 0.7) and equal-weight baselines were tested, and correlation analyses revealed that α = 0.6 maximised the correlation between ECI and evacuation time. This indicates that integrating VL with SC significantly improves the index's explanatory power compared to using spatial metrics alone.

3. Results

3.1. SPATIAL ACCESSIBILITY AND ROUTE EVALUATION

This study evaluated 20 evacuation routes to assess spatial configuration and potential evacuation efficiency based on average path length, β-value, accessible space, and evacuation cost. Table 2 presents the average values calculated from 20 evacuation routes as a reference for 8 representative routes. Considerable variation among routes indicated that evacuation performance is highly dependent on the spatial configuration. Routes with lower evacuation costs generally exhibited shorter path lengths, lower topological complexity, and limited connectivity, suggesting that simplified spatial layouts with direct circulation and fewer decision points enhance evacuation efficiency.

Table 2. The characteristics of various evacuation routes

	Vertices	Edges	Density	Diameter	Lg	β	AC	Cost
422-Route1	77	78	0.027	15	6.77	1	31	174.38
436-Route1	111	112	0.018	19	8	1	46	208.85
441-Route1	44	45	0.048	10	4.77	1	17	137.25
441-Route3	11	10	0.182	5	2.56	0.91	2	54.38
461-Route2	4	3	0.25	3	1.67	0.75	1	11.37
461-Route4	93	93	0.022	16	6.65	1	38	147.22
482-Route1	6	5	0.333	4	2.07	0.83	1	9.57
482-Route4	118	119	0.017	20	8.24	1	48	221.77
Average	50	50	0.083	10	4.70	0.97	19.55	98.93

Four representative routes (436-Route4, 441-Route3, 461-Route2, and 482-Route1) exhibited optimal performance across all indicators. These routes featured fewer accessible subspaces along corridors, reducing SC and enhancing directional clarity. In VR experiments, 73.3% participants selected these routes, with an average evacuation time of 46.37s, SD = 5.12s, confirming their superior spatial legibility and navigational efficiency.

Conversely, high-ECI routes generally exhibited longer path lengths, higher accessibility, and increased decision points, leading to extended exploration and route verification (422-Route1, 436-Route1, 441-Route1, 461-Route4, and 482-Route4). Multiple accessible rooms along these paths increased topological complexity, leading to longer exploration behaviour and more frequent route changes during evacuation. Although high accessibility facilitates routine circulation, it becomes a cognitive distractor in emergencies by introducing additional decision points and visual uncertainty. Participants navigating these complex routes spent more time on exploration and route verification, ultimately reducing evacuation performance.

Behavioural data further confirmed this trend: 11.1% participants selected Route 3, characterised by the highest accessibility and complexity, even though it was not the shortest path. Their mean evacuation time (63.43s, SD=6.84s) was 36.8% longer than that of the optimal route. Overall, these findings reveal the duality of spatial accessibility: although it improves flexibility and usability under normal conditions, it can impede evacuation under stress by increasing cognitive demands, as evidenced by significant correlations between ECI and evacuation time ($r = 0.68$, $p = 0.01 < 0.05$), highlighting the necessity of balancing accessibility and legibility through optimised spatial hierarchy and clear circulation cues.

3.2. EVACUATION COGNITIVE INDEX ANALYSIS

Individuals' cognitive load during evacuation is influenced by both SC (e.g., path accessibility and topological configuration) and visual information-processing demands (e.g., signage, lighting, and obstacles). Evaluating these factors separately fails to capture overall cognitive stress and behavioural performance. To address this gap, ECI is used to integrate spatial and visual dimensions into a unified quantitative framework, enabling comparative analysis across building layouts and supporting evidence-based optimisation of evacuation design.

SC was calculated using normalised GT indicators, including average path length (Lg), network diameter (Diameter), complexity coefficient (β), path cost (Cost), number of edges (Edges), network density (Density), and angular connectivity (AC). Entropy-based weighting determined the relative contribution of each parameter (Table 3). Edges, Diameter, Cost, and AC increased SC, whereas Density had a negative effect, indicating that denser networks may reduce spatial differentiation and legibility.

Table 3. Entropy-Based Weighting for SC Calculation

	Lg	Diameter	β	Cost	Edges	Density	AC
Weight	0.159	0.269	0.056	0.202	0.122	0.064	0.129

VL was derived from eye-tracking data collected during VR evacuation experiments using three indicators: fixation count, total fixation duration, and mean fixation duration. According to cognitive resource allocation theory (Holmqvist et al., 2011), total fixation duration is a direct and reliable indicator of the overall cognitive resources allocated to a visual task. Therefore, the total fixation duration was assigned the highest weight (0.4), with the other two indicators each receiving a weight of 0.3, reflecting their comparatively lower contribution to overall visual load. Both SC and VL were normalised to 0–1, with higher values indicating greater cognitive difficulty. The final ECI was calculated as [1] with $\alpha = 0.6$, emphasising the dominant role of SC in evacuation cognition (Franz and Wiener, 2008). Sensitivity analysis confirmed that this weighting maximised the correlation between ECI and evacuation time. The results of SC, VL, and ECI are summarised in Table 4.

Table 4. Results of SC, VL, and ECI

	SC	VL	ECI
422-Route4	0.464	0.503	0.480
422-Route3	0.468	0.992	0.678
436-Route3	0.523	0.828	0.645
436-Route4	0.375	0.420	0.393
441-Route3	0.403	0.599	0.481
461-Route2	0.269	0.300	0.281
482-Route1	0.292	0.283	0.289

Conversely, 436-Route3 and 422-Route3 exhibited the highest ECI values, accompanied by longer fixation durations and more frequent gaze shifts during evacuation. Introducing VL alone significantly improves SC's explanatory power, confirming that ECI captures evacuation cognition more comprehensively than topological indicators in isolation. These results demonstrate that ECI effectively quantifies the interaction between spatial topology and visual cognition, linking building layout with cognitive load and decision-making efficiency.

3.3. VR BEHAVIOURAL OBSERVATIONS

Eye-tracking data empirically validate the ECI analysis. Heatmaps and scan paths revealed that participants navigating high-ECI routes exhibited denser fixation and longer dwell times at corridor junctions and doors, indicating increased visual attention and decision uncertainty. For instance, one participant on 436-Route4 misidentified a blue wall near Exit 3 as an exit cue, resulting in unnecessary deviation and a higher VL value. Interviews confirmed that this misjudgement was driven by perceptual ambiguity between the blue wall at Exit 3 and the opposite corridor end, which terminated in a reflective window. Conversely, low-ECI routes produced more linear scan paths, fewer fixations, and smoother navigation, reflecting reduced cognitive load and clearer spatial comprehension. These visual patterns align with the quantitative relationship between higher ECI and longer evacuation time.

4. Discussion

This study demonstrates how computational tools can approximate the cognitive effort required for fire evacuation in complex buildings. By combining GT, VR, and eye-tracking within a BIM-based workflow, the ECI links spatial configuration with evacuation cognition. ECI captures how SC and VL jointly influence behaviour. In the VR experiment, higher ECI values were associated with greater cognitive demand and longer evacuation times, whereas lower ECI values were associated with better spatial legibility and wayfinding efficiency.

The integration of GT, VR, and eye-tracking confirms that ECI provides a sensitive diagnostic measure for identifying cognitively demanding areas within architectural layouts. High-ECI zones are often located along corridors with numerous accessible subspaces or ambiguous junctions, exhibiting increased spatial and perceptual complexity. In contrast, simplified configurations with clear visual hierarchies promote efficient and confident navigation. These findings highlight the dual role of spatial accessibility: while beneficial for circulation flexibility in normal conditions, excessive accessibility may increase decision uncertainty and cognitive effort during emergencies.

From a design perspective, ECI enables evidence-based optimisation by quantitatively identifying high cognitive-load regions and informing design strategies to mitigate them. Designers can refine spatial hierarchy to reduce redundant connections, clarify circulation paths, and enhance visual differentiation through lighting, material colour, or contrast. Directional cues and strategically positioned signage further strengthen spatial legibility and reduce visual load. Through these interventions, ECI evolves from a diagnostic indicator into a predictive design tool that supports cognition-informed and performance-based building design.

Beyond practical implications, the ECI framework offers an initial integrated approach for combining spatial syntax, visual cognition, and behavioural modelling within a single cognitive evaluation scheme. When incorporated into simulation-based workflows, ECI allows architects to anticipate user behaviour, assess perceptual clarity, and optimise spatial configuration during early design phases. The framework thus bridges quantitative topology analysis with perceptual and behavioural evidence, offering a more holistic understanding of how humans interact with architectural space under stress.

However, this study has several limitations. The findings are based on a single school building with limited evacuation routes and a relatively small participant sample, constraining generalisability. The VR environment cannot fully reproduce the emotional and social conditions of real emergencies, such as higher stress, crowding and collective behaviour. Moreover, the weighting of spatial and visual components in ECI is informed by theory and sensitivity analysis. Still, it remains partly heuristic, and individual differences in visual exploration may influence VL measures. Future research should therefore involve larger and more diverse samples, additional building types, refinement of the weighting scheme and comparative studies between VR-based experiments and real or drill-based evacuations.

In the future, the ECI framework could be integrated into a Digital Twin platform to support cognition-aware and adaptive evacuation management. In this system, building layout and GT representations would form the spatial and topological layer, while VR and eye-tracking studies would provide parameters for a human-interaction layer. ECI could operate as a cognitive evaluation engine that quantifies SC and VL and is updated with sensor and localisation data. This would allow the Digital Twin to identify cognitively demanding regions, suggest adjustments to lighting, signage or guidance strategies, and, in the future, provide more tailored evacuation support. Such an integration would extend building safety beyond static structural optimisation toward more dynamic, human-centred and cognition-aware evacuation systems.

5. Discussion

This study presented a human-centred computational framework that combines BIM, GT, VR, and eye-tracking to investigate the cognitive aspects of fire evacuation. The ECI was developed to couple SC and VL, providing a quantitative indication of the mental demands imposed by different spatial configurations and evacuation routes. In the VR evacuation study, higher ECI values were associated with increased gaze effort, greater decision uncertainty, and longer evacuation times, while lower ECI routes supported clearer spatial legibility and more efficient wayfinding.

The ECI framework offers an initial integrated approach for linking spatial syntax, visual cognition, and behavioural performance, supporting cognition-informed architectural decisions. In practice, ECI can function as a diagnostic indicator to highlight cognitively demanding zones and to guide adjustments to circulation structure, signage, and lighting. In the future, integrating ECI within Digital Twin environments could enable cognition-aware, adaptive evacuation planning and management. Overall, this research contributes to advancing building safety toward more human-centred, perception-aware and performance-based design.

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