Wayfinding Signage Spatial Cognition and Wayfinding Decision-Making Research Review on Pedestrian Wayfinding Behavior in Large-Scale Transportation Hubs

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Abstract: The spatial layout of large transportation hubs is becoming increasingly complex, and passengers' difficulties in wayfinding have emerged as a prominent issue impairing operational efficiency and service quality. This article looks back at the relationship between wayfinding signs, spatial understanding, and navigation decisions, and analyzes the factors that affect navigation behavior from three aspects: the physical environment, characteristics of the signage system, and interference caused by commercial information. The evolution logic of research methodologies is traced, and evaluation frameworks and optimization strategies are summarized. The review reveals that existing literature has yielded abundant findings on optimizing visual parameters of signage, yet lacks systematic theoretical explanations regarding multi-source visual competition in mixed transport-commercial spaces. Conventional evaluations mostly rely on single indicators, which fail to unpack the full-chain process of "visual attention – cognitive processing – behavioral output". Although the integration of virtual reality (VR) and eye-tracking offers novel research avenues, its application in signage research for transportation hubs remains in the initial stage. Future research should focus on constructing dynamic perceptual wayfinding models, developing high-fidelity simulation platforms, and exploring new paradigms for guidance system design within a multi-objective optimization framework.

Keywords: Transportation Hub; Guidance Sign; Wayfinding Behavior; Spatial Cognition; Virtual Reality; Eye-Tracking; Review

1. Introduction

Urban rail transit has become the backbone of public transport networks in large Chinese cities. By the end of 2025, 325 rail transit lines were in operation across 54 cities nationwide, with total operational mileage exceeding 10,000 km, and annual passenger ridership continued to maintain high growth [1]. As the internet expands, large transportation hubs, acting as key nodes where multiple lines intersect and various transportation modes connect, are increasingly showing characteristics of three-dimensional layouts and multifunctional integration: underground halls, transfer floors, and platforms stacked vertically, with signage, retail stores, and transportation facilities closely intertwined. This surge in spatial complexity has made it increasingly difficult for passengers to navigate. Stopping, wandering, backtracking, and getting lost are quite common, with about half of passengers experiencing navigation anxiety in unfamiliar hubs. Ineffective wayfinding not only prolongs transfer times and increases stress but also causes local congestion and safety hazards during peak hours.

Spatial cognition theory suggests that humans rely on continuously gathering information about the physical environment and dynamically building internal cognitive maps for navigation. When the complexity of a space exceeds what a person can process cognitively, external directional cues become a key way to make up for that gap. Signage is exactly this type of 'artificial aid.'

Existing studies focused on optimizing the visual aspects of signs themselves, such as color, size, brightness, and font. Although there are discussion about how these factors affect recognition efficiency, the academic community has not systematically studied the space or information environment where the signs are located.

Nowadays, modern transport hubs are no longer simple carriers of transportation functions. Commercial development and transportation

services are deeply integrated: self-illuminating LED ad screens, high-brightness commercial facades, and various retail and wayfinding signs all compete for the same visual space. Existing research has shown that too many commercial ads can reduce travelers' efficiency in perceiving space [2], and the brightness of self-illuminating ads can significantly interfere with visual task performance [3]. However, most current studies treat commercial information merely as background variables that need controlling, rather than studying them as independent variables. As a result, the actual ways in which visual competition mechanisms, attention-capturing effects, and commercial information influence decision-making paths still lack systematic theoretical explanations and empirical support.

At the same time, the evolution of research methods is reshaping the study landscape in this field. Traditional field surveys can capture real-world behavioral data, but they have many fundamental limitations, such as uncontrollable variables, difficulty in accessing extreme situations, and one-dimensional data collection. Over the past decade, virtual reality (VR) technology, with its high controllability, repeatability, and immersive realism, has been widely used in studies of navigation behavior [4,5]. The introduction of eye-tracking technology has further provided a real-time window into the 'visual–cognitive' black box [6,7]. The deep integration of these two methods has brought unprecedented technological possibilities for systematically analyzing navigation behavior under the influence of commercial signage in controlled conditions.

This article systematically reviews the relationships between wayfinding signage, spatial cognition, and navigation decisions in large rail transit hubs. Clear the theoretical connection between the guidance identification system and spatial cognition. Analyse the impact of physical environment, identification characteristics and information interference on navigation behaviour. Organise the development process of research methods. Summarise the existing evaluation framework and point out the key shortcomings of the current research.

2. Conceptual Connotations and Theoretical Foundations

2.1 Systematic Classification and Functional Roles of Wayfinding Signage

The wayfinding sign is a visual carrier that transmits spatial information. Public guidance signs are mainly divided into six categories: direction signs, location signs, barrier-free signs, facility signs, safety signs, and commercial signs. According to the relevant theories of wayfindings, there are some differences in the roles played by various types of signs. Direction signs are responsible for guiding the route and directly determining the path selection of pedestrians. Location signs help pedestrians judge their spatial orientation; commercial signs serve publicity and promotion. They often using eye-catching colours and dynamic pictures to attract attention, which is easy to distract pedestrians.

Current research shows that when pedestrians are trying to find their way, dynamic signs are more likely to catch their visual attention, significantly improving the visibility of the signs and compliance rates. In recent years, domestic research on dynamic directional signage has further deepened. Bian et al. [8], using a BIM+VR platform in experiments at Sihui Hub, demonstrated that optimised dynamic signage schemes can significantly reduce wayfinding time and error counts, driving the transformation of guidance systems from "information display" to "information interaction." However, this trend has also raised new concerns—particularly in areas with dense commercial dynamic advertising, whether the competitiveness of directional dynamic signage may be overwhelmed by commercial dynamic information remains to be further substantiated by empirical evidence.

2.2 Theoretical Models of Spatial Cognition and Wayfinding Decision-Making

Wayfinding is a cognitive process of "determining and executing a route plan from an origin to a destination within a spatial environment". Classic theoretical frameworks generally decompose it into three progressive stages: information perception, decision-making, and action execution, and further emphasise the mediating role of spatial cognitive maps: pedestrians continuously encode environmental cues to form internal representations of spatial layout, which in turn support route planning and orientation judgments. This theoretical framework reveals the logical connection between wayfinding signs and spatial cognition

—signs are essentially designed "external cues," and their effectiveness depends on whether they can be efficiently translated into a pedestrian's internal understanding of space.

Scholars have also improved and expanded this theory from various angles. Studies on getting lost show that when external visual cues clash with our internal cognitive maps, or there's not enough environmental information, people feel a lot more uncertain about space, often stopping, turning back, or going around. The hierarchical pathfinding model breaks down route choices into three levels: strategic, tactical, and operational. This hierarchical thinking has provided a theoretical foundation for multi-agent simulation models. It is worth emphasising that all these classic models share a common cognitive premise—that pedestrians are bounded-rational decision-makers, whose wayfinding behaviour is constrained by attentional resources and cognitive load, rather than being a pure optimal-path solution. In recent years, Sargoni [9] further extended this hierarchical framework to multi-scale pedestrian navigation scenarios, validating the coupling mechanism between micro-level perceptual decisions and macro-level network decisions.

2.3 Coupling Mechanisms between Wayfinding Signage and Spatial Cognition

A bidirectional coupling relationship exists between wayfinding signage and spatial cognition: rational placement of signage can compensate for deficiencies in spatial cognition, whereas poor recognition efficiency may in turn exacerbate cognitive load and decision uncertainty. Existing empirical research has confirmed the specific manifestations of this coupling effect. In terms of signage facilitating spatial knowledge acquisition, the systematicity and consistency of signage are key predictors for passengers' establishment of spatial cognitive maps; the clearer the spatial relationships among signs, the more accurately passengers grasp the overall spatial layout.

However, the 'compensatory function' of signs isn't unconditional. When the information on signs is overloaded or contradictory, this compensatory effect can turn into interference. Yang [10], in a study on underground shopping complexes, pointed out that dense mixed information can significantly reduce pedestrians' spatial learning efficiency; similar studies have also reported that when non-wayfinding information in visual scenes increases, pedestrians spend noticeably less time looking at wayfinding cues. These findings indicate that optimizing wayfinding systems requires more than focusing on individual sign design. Researchers should adopt an information ecosystem view. They need to assess visual competition between wayfinding signs and commercial signs.

3. Multidimensional Influencing Mechanisms of Wayfinding Behaviour

3.1 Spatial Physical Environment: Configurational Complexity and Lighting Conditions

Research shows that the physical layout of the hub space will affect people's thinking and route choice. Lv et al. [4] use VR technology to study how people choose vertical traffic options in multi-storey buildings. They found that whether it was daily use or emergency, people usually choose the nearest elevator or escalator, which shows that they like to save brains. In addition, the study of spatial syntax supports the above research conclusions. For example, Wang et al. [11] studied problems such as integration and visual depth, and found that the layout of subway stations directly affects how people view the path and make direction decisions. The study of Beijing International Trade Station by Li et al. [12] also shows that when a space is easier to understand, people will make fewer navigation errors. Having multiple outlets will also change the way people find their way. Research by Wu et al. [13] shows that better signs provide guidance for people.

Lighting conditions are environmental factors that are easily ignored but may have an impact. Research shows that when the direction sign conflicts with the direction of natural light, more than 10% of the participants still choose the path towards natural light. When the two directions are completely opposite, the ratio will even rise to more than 30%. This further reveals that in emergency evacuation scenarios, people's instincts to move to the light sometimes surpass the guidance of the signage system. In addition, Zhao [2] found in the study of Xizhimen Transportation Hub that the brightness of commercial advertisements significantly affects the visual performance of pedestrians, which further confirms that brightness plays an important role in competing for visual attention.

3.2 Characteristics of Wayfinding Signage: Visual Parameters and Layout Effectiveness

The physical attributes of directional signage are also a core focus of academic research. In terms of color, Zhou et al. [14] conducted experiments on individuals with color vision deficiencies, confirming that the color contrast of signs and the use of graphic elements directly affect their ability to recognize and follow directions. This provides empirical support for inclusive wayfinding design. Research on subway fire evacuation also indicates that appropriately pairing sign colors can reduce pedestrian cognitive load and improve traffic efficiency,

Regarding size and brightness, existing research indicates that increasing the size of signs has a more significant effect on speeding up pedestrian movement compared to merely increasing brightness. However, when visibility decreases, the difference in their effectiveness narrows. This finding is particularly useful for underground hubs and other low-light locations, suggesting that designers should prioritize the spatial coverage of signs rather than just boosting brightness.

In terms of signage types and layout methods, research has shown that ground-mounted directional signs perform better in guidance. Compared to suspended directional signs, they can shorten walking paths and increase walking speed. In recent years, this research has led to the widespread application of ground guidance systems in subway stations. Based on a human factors analysis of Shanghai People's Square Station, Mei et al. [15] further pointed out that the distance between sign placement and decision points is a key factor affecting guidance efficiency. Positioning signs within the effective visual range ahead of decision points can shorten the time people spend looking around.

The serialisation of signage at decision points constitutes another critical issue. Weng et al. [1], based on wayfinding experiments at Beijing South Railway Station, pointed out that information-dense areas and key decision points are the bottlenecks of signage effectiveness, and that guidance signage should be prioritised in areas with high concentrations of stopping points such as corridors, stairwells, and ticket gates. Zhang [7], through VR eye-tracking experiments, further verified that after optimising signage layouts at decision hot spots, passengers' average movement speed increased significantly and regional congestion density decreased markedly. Together, these findings point to a design principle: the layout of guidance systems should precisely anchor pedestrians' decision hot spots rather than being uniformly distributed.

3.3 Social Influence and Commercial Information Interference

Wayfinding behaviour does not occur in isolation from social contexts. Existing studies have found that under conditions of uneven passenger flow distribution, individuals tend to follow the dominant direction, and this herding effect remains stable throughout the evacuation process, which can be further reinforced by flow direction cues and positive feedback from prior decisions. Under hazardous conditions such as thick smoke, the behavioural choices of nearby pedestrians exert a significantly greater influence on individual decision-making, although the number of pedestrians alone does not alter the intensity of social influence. Field evacuation experiments in retail scenarios have also confirmed this finding: after an alarm was triggered, a considerable proportion of dispersed customers actively sought out companions before evacuating. These findings suggest that the design of guidance systems should adequately account for the social dimension—namely, that “crowds are information”—and that additional redundancy in signage visibility should be provided in congested areas.

Beyond social influence, commercial information constitutes another critical source of interference in the visual information environment—a topic that has only recently attracted research attention and remains the least developed area in the existing literature. Zhao [2] conducted virtual reality simulation experiments at Beijing Xizhimen subway station. The study showed that a large number of commercial ads can reduce passengers' efficiency in getting spatial information, while pedestrians’ preference for decorative elements had no significant correlation with their spatial cognition ability. This suggests that the interference mechanism of commercial ads isn’t driven by aesthetic attraction, but mainly relies on high brightness and dynamic features to grab visual attention. Hu [3] combined virtual reality eye-tracking technology to study self-illuminating guide signs in the subway, confirming again that brightness and color contrast determine how visually prominent a

guide sign is, and that this effect is amplified in areas dense with commercial ads. Huang [16], using a virtual reality simulation platform for a controlled experiment, confirmed that both the relative position of commercial billboards and guide signs and the brightness difference can significantly change pedestrians' directional accuracy and gaze duration, providing direct evidence for quantitatively measuring information interference effects.

4. Research Methods: From Field Observation to Immersive Human Factors Experiments

4.1 Traditional Paradigms: Behavioural Observation and Questionnaire Surveys

Early research on wayfinding mostly relied on field tracking, behavior recording, and surveys. These methods can capture real-world behavior data, but they have obvious limitations: they require a lot of manpower, it's hard to expand the sample size, controlling variables is tough, and they can't track the constantly changing cognitive state during wayfinding. Studies have shown that people's recollection of their wayfinding experiences is easily influenced by hindsight bias, leading to systematic errors when looking back at real-time decisions. Recently, Wen et al. [1] found that relying on a single survey often systematically overestimates the actual effect of signs. This shows that traditional research methods are difficult to deeply explore the internal cognitive process.

4.2 Spatial Quantification Methods: Space Syntax and Computer Simulation

Space syntax theory provides a way to quantify spatial configurations. Studies have been conducted to analyse the way\finding behaviour of subway stations based on syntactic parameters such as integration, connectivity and selection [11]. There is also a study to integrate the field of view model and the axis model to establish a quantitative relationship between spatial structure characteristics and navigation efficiency [12]. These methods transform the understanding of space from qualitative description to measurable indicators, supporting the selection of key spatial anchor points for signage layout.

Computer simulation model is another important method. However, the accuracy of these simulation models depends on the built-in behaviour rules. Most existing models simplify the perception of signs. For example, they define signage as a passively effective source of information within a certain range, ignoring the active visual search behaviour of pedestrians. Although this simplification is conducive to calculation, they weaken the model's ability to explain the underlying cognitive mechanism. In recent years, Zhang [7] has incorporated the eye movement attention index into the simulation model and used the visual significant weight to calibrate the perception radius of the signage, which effectively improved the consistency between the model output and the observed behaviour data.

4.3 The Integrated Paradigm of VR and Eye-Tracking

Existing comparative studies of wayfinding performance in virtual and real environments have confirmed the external validity of VR data—participants' accuracy in distance estimation was even higher in the virtual environment than in real-world scenarios. Yu et al. [5], using a VR eye-tracking system, systematically examined passengers' behavioural response patterns to wayfinding under signage exposure conditions; Yang et al. [17], through VR eye-tracking experiments, analysed the influence of individual differences on wayfinding outcomes in subway station fire evacuations.

The incorporation of eye-tracking has further extended the observational dimensions of VR experiments. Metrics such as time to first fixation, total fixation duration, fixation count, and saccade path provide real-time physiological evidence for the "visual–cognitive" mapping relationship. Lan [6] employed multidimensional eye-tracking data to comprehensively analyse wayfinding behavioural characteristics within rail transit hubs; Zeng et al. [18] further coupled eye-tracking data with space syntax parameters to quantitatively analyse the influence mechanism of underground spatial attributes on route choice in high-speed railway stations. Wang et al. [19], in their most recent study published in 2026, further established a quantitative relationship model between eye-tracking metrics and signage navigation satisfaction, providing an operational human-factors evaluation criterion for signage optimisation.

The research paradigm that integrates VR with

eye-tracking effectively realises a leap from "behavioural observation" to "cognitive observation." It enables researchers to trace pedestrians' attentional trajectories during the wayfinding process, pinpoint bottlenecks in information processing, and thereby infer patterns of cognitive load variation in reverse. However, it should be noted that the application of this paradigm in transport hub wayfinding research remains in its infancy; in particular, systematic experimental evidence for the specific scenario of mixed interference between commercial signage and wayfinding signage is extremely scarce, which represents a critical direction that subsequent research urgently needs to address.

5. Evaluation of Guidance System Effectiveness and Layout Optimisation

5.1 Evolution of Evaluation Indicator Systems

The use of eye tracking indicators expands the dimension of the evaluation system. Early studies mainly relied on behavioural indicators such as travel time and the number of navigation errors. With the popularisation of eye tracking technology, parameters such as gaze duration, gaze space distribution, and first-time gaze incubation period have been widely adopted, which helps to accurately locate the cognitive bottleneck in the logo layout. Related research [7] combines eye movement tracking observation data with spatial syntactic indicators to build a comprehensive evaluation framework covering the neurophysiology and behavioural levels. Another study [1] developed a quantifiable two-dimensional system to measure the effectiveness and operational efficiency of the wayfinding sign.

At the level of comprehensive evaluation methods, approaches such as the grey near-optimal method, Analytic Hierarchy Process (AHP), and fuzzy comprehensive evaluation have been applied in various cases. However, a common limitation of these methods is the strong subjectivity inherent in weight assignment, and the mechanism for integrating objective behavioural data with subjective weights still requires further refinement. In recent years, objective weighting methods such as entropy weight-TOPSIS have been introduced into signage effectiveness evaluation, which to some extent mitigates the issue of subjective bias in weight determination [19].

5.2 Optimisation Practices Based on Simulation and Experimentation

Research on guidance system optimisation has accumulated a number of case studies with practical guiding value. Weng et al. [1], based on VR wayfinding experiments at Beijing South Railway Station, found that the optimal wayfinding ratio exceeded 85% for simple wayfinding tasks, whereas for complex tasks it fell below 50%, indicating that the same signage system exhibits substantially different effectiveness across different task scenarios—a finding that poses a strong challenge to the conventional practice of "uniform standard deployment." Bian et al. [8], in their optimisation study of dynamic directional signage at Sihui Hub, similarly confirmed that guidance system effectiveness varies significantly across different route types, and that local optimisation needs are often masked by overall evaluations.

From the perspective of technological development, the integration of BIM and VR is a key trend. Bian et al. [8] will develop integrated signage system visualisation and decision-making tools. Qi et al. [20] created a "line-level" and "station-level" dynamic guidance system for stations with large passenger flow, which has achieved good results in the trial operation of the Beijing Metro Daxing Airport Line. Although the relevant technology exploration has not yet formed a mature general standard, they clearly point out the feasible path from experience-driven design to data-driven design.

Based on the practical experience of existing guidance system optimisation, three design points can be summarised. The sign should not be placed evenly, and priority should be placed in the key position where people need to make route selection. The program optimisation should be combined with the real data of the scene. The general standards should not be directly applicable; when evaluating the effect. It is necessary to take into account the characteristics of traffic efficiency and visual cognition at the same time, and do not use a single general judgement method.

6. Conclusion

This article sorts out the relevant research literature and summarises the research progress and existing shortcomings of pedestrian finding the way at transportation hubs. Identification

guidance, spatial cognition and path decision-making together constitute a complete pedestrian path-finding behaviour process. Nowadays, relevant research is no longer only qualitative description, but more quantitative analysis and empirical verification. Virtual reality, eye tracking and other technologies can also analyse the complete behavioural logic of pedestrians from visual observation and brain cognitive processing to the final walking choice.

At present, there are still shortcomings in the relevant research. Most of the existing studies on the analysis of various variables only focus on the identification arrangement or the single spatial level. These studies lack multi-level interaction research combining the site environment, visual characteristics and pedestrian cognition. At the same time, most of them are carried out in the ideal experimental scenarios with low passenger flow. It does not cover real extreme scenarios such as passenger flow peaks, cognitive fatigue, and tight decision-making time, which is inconsistent with the actual operation of transportation hubs.

Therefore, future research can have three directions: first, optimise the simplified perception hypothesis of the traditional model, and realise the probability prediction of pedestrian navigation efficiency under different business information layout and density. Second, a composite centre experimental platform that combines VR and eye tracking can be built to collect and analyse behaviour and eye movement data synchronously, and improve the controllability of the experiment and the effectiveness of the research. Third, establish a multi-objective optimisation framework that takes into account guidance efficiency and business benefits. Future research should take improving the experience of passengers' wayfinding as the core, and helps urban public transportation to upgrade to a humanised and intelligent direction. At the same time, it provides theoretical basis and practical reference for the spatial design, information layout and operation optimisation of transportation hubs.

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