IMPROVING METRO STATION NAVIGATION: FINDINGS FROM AN ONLINE VIRTUAL REALITY WAYFINDING EXPERIMENT

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Abstract. Metro stations in multi-modal transport hubs accommodating complex passenger flows with diverse travel purposes pose challenges for wayfinding. Passengers unfamiliar with the environment mostly rely on navigational clues provided by signage to find their way. This study aims to evaluate and improve wayfinding signage within metro stations at transport hubs. Considering the needs of both passengers and operational staff, this research proposed an evaluation method combining small-scale on-site tracking with large-scale online virtual experiments, along with three evaluation indicators. This study focused on the Shanghai Hongqiao Railway Station metro station to improve the signage systems by post-occupancy evaluation (POE) using this method. A thorough analysis of 4,368 wayfinding samples collected by the online virtual reality wayfinding experiment identified five shortcomings that required attention and improvement. Based on the POE results, this study proposed optimization suggestions for the signage systems in this metro station, providing valuable insights into the design and optimization of wayfinding systems in metro stations.

Keywords. Wayfinding, Web-based Virtual Reality, Post-occupancy Evaluation, On-site Tracking, Metro Station, Transportation Building.

1. Introduction

A primary concern in nearly all transportation building designs is efficiency. Due to the high efficiency, punctuality, and sustainability of the metro, over 50% of multi-modal passengers choose to metro travel. Efficiency-first has become the primary principle guiding the service at metro stations within multi-modal transport hubs, catering to the ever-growing travel demands of passengers. However, passengers who are unfamiliar with the environment face considerable challenges in navigating through the complex and enclosed system of metro stations. They primarily rely on navigational clues provided by signs to find their way within these buildings. Consequently, evaluating and optimizing the subway signage systems are of significant importance for improving transfer efficiency and the overall travel experience.

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Currently, many studies on wayfinding performance evaluation focus mainly on efficiency demands for passengers, which are undoubtedly crucial for the design and optimization of wayfinding systems. However, existing research overlooks the needs of metro operational staff in passenger flow organization. Metro stations in transport hubs are characterized by high volumes and frequencies of passenger flow. For such large crowds, the organization of passenger flow by operational staff plays a significant role in ensuring walking safety, transfer efficiency, and service levels. Therefore, the evaluation and optimization of wayfinding systems should consider not only passenger behaviors but also the organizational needs of operational staff. Moreover, researchers have recognized the challenges in collecting passenger behavior data within the context of large transport hubs. In recent years, virtual reality (VR) technology has been effectively employed to replicate real-life scenarios, offering convenience in collecting behavioral data throughout the building's lifecycle.

To evaluate and optimize metro station navigation, we proposed a method that combines small-scale on-site tracking with large-scale online virtual experiments to collect multi-dimensional wayfinding data from participants. Additionally, considering the diverse needs of passengers and operational staff, we introduced three indicators to evaluate wayfinding performance. Using the Shanghai Hongqiao Railway Station metro station as a study case, we applied this method to conduct a POE of its wayfinding system and provided suggestions for improvement. The results of this study offer valuable insights for the evaluation and optimization of metro wayfinding systems within multi-modal transport hubs.

2. Literature Review

2.1. WAYFINDING BEHAVIOR AND WAYFINDING SIGNAGE

Peponis et al. (1990) defined wayfinding as the ability to reach a destination in a short time without experiencing fear and stress. Typical wayfinding behaviors of passengers in metro stations under normal circumstances include entering, exiting, and transferring. At metro stations located in multi-modal transport hubs, passengers need to reach their destinations quickly. Correct platforms for entry and transfer lines and correct exits for departure lines are essential. Metro stations are generally built underground in enclosed environments, and lack reference landmarks for indoor wayfinding, making it easy for unfamiliar passengers to experience negative impacts during navigation. The most common measure to minimize these negative impacts is the installation of wayfinding signage. Properly placed guiding signs can assist first-time passengers or those unfamiliar with the environment in quickly obtaining correct wayfinding information and reaching their destinations (Hu and Xu, 2022).

Most evaluations primarily consider the behavioral needs of passengers (Lei et al., 2019). However, given the high transient passenger flow in metro stations within multi-modal transport hubs, it is crucial to reduce the pressure of transient passenger flow and avoid safety risks. From the perspective of a more efficient passenger flow organization, the shortest path desired by passengers may not always align with the ideal path preferred by the operational staff. Therefore, it is vital to evaluate the wayfinding system of metro stations in multi-modal transport hubs from both the perspectives of passengers and operational staff.

2.2. APPLICATION OF VR TECHNOLOGY

Various methods were employed in existing studies to collect wayfinding data for wayfinding performance evaluation, including field observations, manual tracking, on-site wayfinding experiments, and signage audits. However, these methods are limited by their high time costs and susceptibility to disruption by external factors. Furthermore, non-operational wayfinding activities within metro stations are often interrupted due to security management and control. The rapid development of VR technology, along with the availability of diverse virtual environments ranging from desktops to fully immersive settings, offers novel possibilities for studying wayfinding behaviors. Existing studies have confirmed that participants' wayfinding cognition and spatial knowledge acquisition in virtual environments are not significantly different from those in the real world (Dong et al., 2022). Therefore, an increasing number of researchers have employed VR in wayfinding research and validated its effectiveness in diverse settings such as head-mounted displays (HMDs), desktops, and Cave Automatic Virtual Environments (CAVEs).

3. Methodology

A novel method was proposed for evaluating wayfinding performance in metro stations. The workflow for this evaluation method is illustrated in Figure 1.

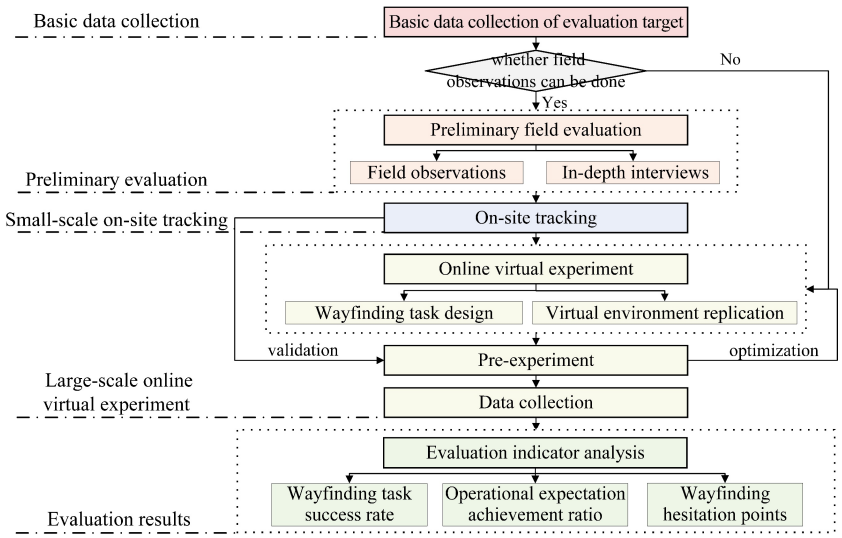

Figure 1. A workflow of the evaluation method

3.1. STUDY CASE

This study focused on the Hongqiao Railway Station metro station (hereinafter called Hongqiao metro station), located within the Shanghai Hongqiao Integrated Transport Hub (hereinafter called Hongqiao hub). The Hongqiao hub consists of two terminals: Hongqiao International Airport and Hongqiao Railway Station, which offer various transport modes. Based on statistical data, it was observed that among passengers using

public transport within the Hongqiao hub, 70% prefer metro transit. As a key part of intercity and urban transit systems, the Hongqiao metro station includes Lines 2, 10, and 17. The station layout comprises a B1 hall level at -9.0m and a B2 platform level at -16.0m. The hall features a symmetric layout with four exits (i.e., A-D) and four entrances (i.e., south 1-2, north 1-2), where the flows of passengers entering and exiting are mixed. The -9.0m level, serving as one of the key transfer zones within this hub, plays a crucial role in accommodating complex passenger flow and diverse travel purposes (as shown in Figure 2). Improving passenger navigation efficiency in this metro station is crucial to achieving 'zero transfers' throughout the Hongqiao hub, making this case highly relevant to the study's objectives.

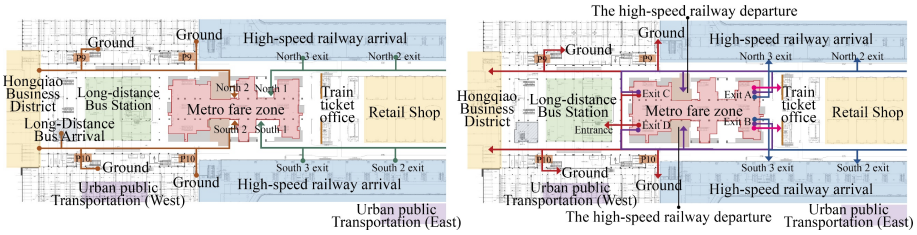

Figure 2. Passenger flow organization for entering and exiting at -9.0m level of this metro station

3.2. PRELIMINARY EVALUATION

The preliminary evaluation consists of two parts: field observations and in-depth Interviews. The field observations revealed a total of 150 guiding signs within the metro station (as shown in Figure 3). These signs can be broadly classified into four types: ground-standing, floor-attached, suspended, and wall-attached. Among these, wall-attached guiding signs are the most prevalent, comprising 42% of the total signs. In-depth interviews with operational staff obtained this station's management objectives and the optimal routes for passengers' different travel needs.

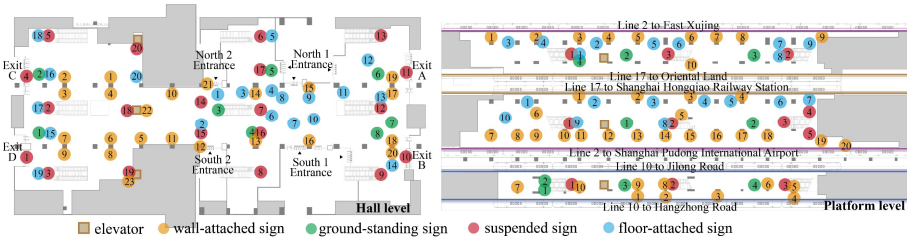

Figure 3. The layout of guiding signs in the Hongqiao metro station

3.3. SMALL-SCALE ON-SITE TRACKING

To validate the credibility of wayfinding data collected by VR technology, our team conducted on-site passenger tracking at the Hongqiao metro station. Two experimenters trailed behind a passenger, with one recording the passenger's trajectory and wayfinding behavior, while the other wielded a camera to capture the entire wayfinding process. A total of 256 passengers' wayfinding samples were collected, including 29 individuals identified as passengers with barrier-free needs. All valid wayfinding trajectories were overlaid on a 2D plan, see Figure 4.

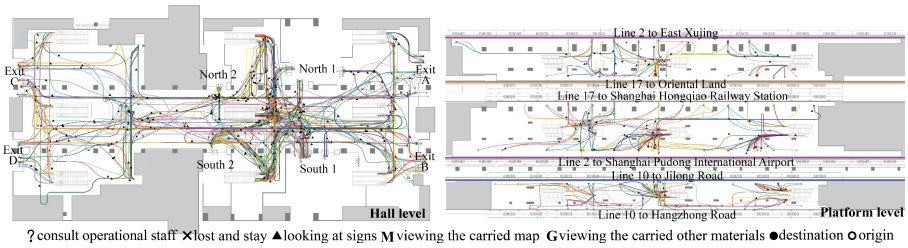

Figure 4. An overlay of all valid wayfinding trajectories from on-site tracking on a 2D plan

3.4. LARGE-SCALE ONLINE VIRTUAL EXPERIMENT

3.4.1. Wayfinding Task Design

Based on the characteristics of this metro station, participants were divided into two categories: general passengers, who were not instructed on specific vertical transfer modes (i.e., stairs, escalators, or elevators), and barrier-free passengers, who were required to utilize elevators for vertical transfers. Considering experimental resources and costs, wayfinding origins were strategically selected based on spatial features. For example, in the context of metro line arrivals, four metro carriage doors were chosen as the wayfinding origins. Overall, wayfinding tasks included three categories: exiting, entering, and transferring, amounting to a total of 43 types.

3.4.2. Virtual Environment Replication

Based on the architectural blueprints and on-site survey data of this metro station, a true-to-scale architectural model was constructed using Rhino software. The navigable area for participants and a total of 366 decision points along potential routes were determined based on wayfinding theories and findings from on-site tracking. High-resolution panoramic images were captured at each decision point using an Insta360 TITAN 8K panoramic camera. The 3D model and panoramic images were then imported into the Unity 3D game engine to replicate the architectural environments of the Hongqiao metro station. Avatars in virtual environments were driven by the real wayfinding trajectories of passengers. The highly realistic architectural environment and avatars driven by real wayfinding trajectories offer participants a more authentic virtual wayfinding experience (see Figure 5).

Figure 5. The virtual environment including the architectural environment and avatars

Different VR technologies have varying impacts on participants, particularly concerning their sense of immersion and VR sickness. For large-scale virtual environments, the benefits of enhanced immersion might not be universally beneficial as suggested in the literature, especially if passenger wayfinding requires less spatial understanding (Feng et al., 2022). Additionally, other factors such as the number of data samples required for evaluation have been considered. For the evaluation of each task, it was hypothesized that a minimum of eight wayfinding samples was necessary. Accounting for the two identified categories of participants, the predetermined wayfinding origins, and task types, the minimum number of effective trajectory samples required for evaluation was at least 1,978. The localized nature and VR sickness of the HMD VR experiments necessitated an extended duration to obtain the aforementioned quantity of wayfinding samples. Conversely, online virtual experiments could collect wayfinding data at this magnitude more efficiently and reach a wider participant base (i.e., Internet users). Additionally, online experiments relied on using a mouse and keyboard for navigation, offering more participant-friendly interaction. Therefore, the virtual environments were published on a web browser, enabling participants to engage in the online VR wayfinding experiment through a simple URL click.

3.5. PRE-EXPERIMENT

To collect more realistic wayfinding data that reflects the real world, pre-experiments recruiting fifteen individuals were conducted. The wayfinding data collected in the pre-experiment were compared with those obtained through on-site tracking. Employing the iterative steps outlined in Figure 1, optimizations were made in the wayfinding task design and virtual environment replication, which aimed to collect accurate and realistic wayfinding data especially trajectories from the online virtual experiment.

3.6. DATA COLLECTION

Participants were recruited through advertisements posted on popular social media platforms, such as WeChat. A total of 395 participants were recruited, including 202 females and 193 males. Their ages ranged from 18 to 23 years, with an average age of 21 years. Among the participants, 296 were categorized as general passengers, while 99 were categorized as barrier-free passengers. Before the experiment commenced, researchers provided online training for participants, offering instructions and highlighting important considerations. The wayfinding experiment was conducted within a preset time window, during which participants could freely choose their experimental time according to their availability. Each participant was required to conduct 10 different wayfinding tasks, which took approximately 40-50 minutes.

In this online virtual experiment, 4,368 wayfinding samples were collected, of which 4,243 were deemed valid with an effective rate of 97.14% (see Figure 6). Among these, 3,097 samples were of general passengers' wayfinding data, and 1,146 samples were of wayfinding data from barrier-free passengers. In addition to the pre-experiment, this study compared the wayfinding trajectories of general passengers collected through two methods: small-scale on-site tracking and the online VR experiment (see Figures 4 and 6). Through this comparison, the credibility of wayfinding data collected by this online VR experiment was validated.

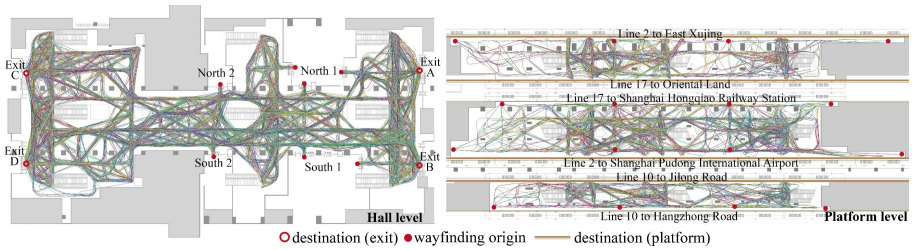

Figure 6. An overlay of valid wayfinding trajectories from the online VR experiment on a 2D plan

3.7. EVALUATION INDICATORS

Considering the efficiency-first principle in such metro stations, three indicators focusing on the accuracy and efficiency of wayfinding were introduced to evaluate the wayfinding performance. These indicators include wayfinding task success rate (Ws), wayfinding hesitation points (Hp), and operational expectation achievement ratio (Er).

Indicator Ws quantifies the proportion of participants successfully reaching their destination as required during a wayfinding task. The indicator Ws is categorized into six levels. Generally, a value of Ws below 50% is considered poor, 50-60% is deemed a pass, 60-70% falls within the average range, 70-80% is considered medium, 80-95% is classified as good, and anything above 95% is rated as excellent. Decision time refers to the duration a participant takes from reaching a decision point until leaving it. In virtual experiments, if a passenger's decision time at a certain decision point exceeds 10 seconds, this point is considered a wayfinding hesitation point. Moreover, hesitation points should exclude wayfinding origins and locations where station maps and block maps are placed. Indicator Er represents the proportion of wayfinding trajectories where participants follow the operational staff's expected optimal route, which may not always be unique, or reach the destination through the staff's preferred exits, out of the total number of wayfinding trajectories. Similarly, this indicator is categorized into six levels, identical to indicator Ws.

4. Evaluation Results and Discussion

4.1. EVALUATION INDICATOR ANALYSIS

Based on the task types, this study quantified the indicator Ws among participants with varying characteristics. The results revealed that for participants as general passengers, the Ws for wayfinding tasks to Hongqiao Business District and the high-speed railway arrival exit for meeting arrivals were 66.84% and 56.78% respectively. Participants with barrier-free needs demonstrated a significantly lower Ws of 31% for exiting tasks to meeting individuals at the high-speed railway arrival exits. Therefore, participants faced challenges in finding the correct metro exit when heading to either the Hongqiao Business District or the high-speed railway arrival exit. Additionally, the exits to the Hongqiao Business District (i.e., exit C-D) were near the elevators, which could explain why participants with barrier-free needs showed higher Ws for this task than those as general passengers.

The existing wayfinding signage system does not include guidance for the high-

speed railway arrival exit, which is a reason for the lower Ws in such tasks. The guiding signs of the exits for the Hongqiao Business District rely on both ground-standing and wall-attached signs, but their visual expressions (e.g., content, font, and color) lack consistency, which leads to potential confusion and uncertainty among participants.

The analysis of participants' decision time at various decision points revealed four wayfinding hesitation points, located at points 26, 94, 84, and 76 within the hall level (see Figure 7). The average decision time of participants at these points was 20.4, 14.6, 16.5, and 15.8 seconds, respectively. Insufficient and improper placement of guiding signs were identified as the primary formation cause of these hesitation points.

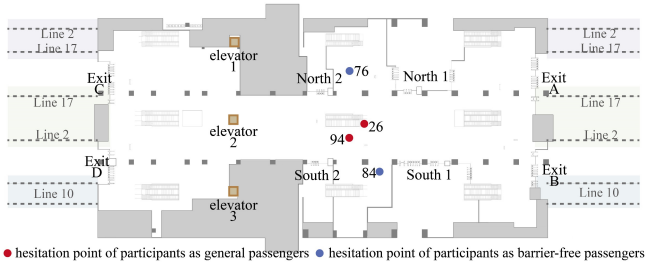

Figure 7. Wayfinding hesitation points

At decision point 26, participants with general passenger attributes made decisions after reaching the hall from the platform level via stairs. However, the guiding signs near this point failed to provide clear location and direction information for all exits A-D, leading to confusion and hesitation among the participants.

Regarding decision point 94, participants with general passenger attributes entering from the south 2 entrance towards Line 2 to Pudong International Airport would pass through this location. However, the guiding signs oriented toward participants near this point lacked guidance regarding Line 2 to Pudong International Airport, which was a significant reason for the participants' hesitation at this decision point. Additionally, the prolonged decision time for passengers with barrier-free needs at decision points 84 and 76 can be principally attributed to the absence of guidance information concerning elevators near these points.

Based on passenger flow organization and wayfinding data, the indicator Er for different wayfinding tasks was statistically analyzed. For participants as general passengers, the Er values were 76.48% for entering, 78.44% for exiting, and 79.98% for transferring. However, for participants as barrier-free passengers, the Er values were significantly lower, measuring 36.14% for entering, 56.41% for exiting, and 36.85% for transferring. The results indicated a poor operational expectation achievement for entering and transferring tasks. Moreover, the Er values for entering and transferring tasks were significantly lower than those for exiting tasks, suggesting difficulties in locating elevators in the hall for participants.

Considering the unique spatial layout of the Hongqiao metro station, the elevator configuration is relatively centralized in a linear formation. Specifically, elevators 1 and 3 are positioned at the two ends, resulting in a more obscured placement that might not be easily perceptible by passengers (see Figure 7). The entrance and signs of elevator 2 face towards exits C and D, lacking a strong visual appeal for incoming

passengers. It is recommended to install directional signs oriented toward the entrances for these passengers, facilitating better visibility and orientation. The relative positioning of the three elevators poses a challenge for first-time arrivals at this metro station to form clear spatial cognition. Moreover, the existing floor-attached directional signs near the elevators are currently arranged in a scattered pattern. When the hall is crowded, they are not easily noticed. Consequently, continuous floor-attached directional signs are proposed to improve navigational clarity and accessibility.

4.2. EVALUATION RESULTS

The passenger capacity of elevators is inherently limited. Overall, the operation of the current signage system demonstrated satisfactory performance: the average value of Ws for wayfinding tasks among general passengers was about 89.9%, which was considered good. Furthermore, the value of Er for wayfinding tasks among general passengers was about 78.3%, closely approaching a good level. The evaluation based on three indicators identified five shortcomings within the signage system at Hongqiao metro station: (1) variable visual expression in signage, (2) content of some signs not aligning with the objectives in passenger flow organization of operational staff, (3) inadequate contrast between the content and background in signs obscuring readability, (4) insufficient guidance provided by directional signs at key decision points, and (5) inadequate guidance for elevators.

This study proposed the following optimization suggestions. These also offer insights for the design and optimization of wayfinding signage in other metro stations. Firstly, regarding the overall design principles of signage: (1) The visual expression of the same elements in signs should be standardized, including font, color, icons, size, etc. Moreover, any damages should be promptly updated and replaced. (2) The design of the signs should reflect the passenger flow organization by the operational staff, ensuring no critical information is missing. (3) Signage design should consider the contrast between the content and the background of signs under actual lighting conditions to facilitate the recognizability and legibility of the content.

Secondly, recommendations for the placement and layout of signage: (1) In the case of mixed flow in the station hall, there should be at least one suspended directional sign placed along the path from the entrance to an escalator. It should cover guidance information for all lines at the platforms (except for terminal destinations) where this escalator is located. (2) Directional signs at key decision points (e.g., main paths, turning corners, intersections, and vertical traffic entrances and exits) should be both complete and continuous. (3) Elevators should be easily visible to passengers and their entrances should be oriented towards the station entrance. Each preset passenger route should be equipped with at least one directional sign guiding the elevators' direction.

5. Conclusions and future work

This study combined the demands of passenger behavior and passenger flow organization by operational staff to propose a virtual-real integration method for evaluating wayfinding performance. We developed an online virtual environment to replicate the Hongqiao metro station and collected 4,368 wayfinding samples through an online virtual experiment. Through the analysis of three evaluation indicators, this study identified wayfinding issues within the evaluation target and provided

optimization suggestions. The results demonstrate that the proposed evaluation method is effective in obtaining a significantly larger amount of valid wayfinding data for wayfinding performance evaluation. Moreover, the insights obtained from our study can provide theoretical and practical guidance for the design and optimization of wayfinding systems in metro stations serving high-traffic transport hubs.

However, there are still some limitations that need to be discussed. This study discusses the evaluation and optimization of the wayfinding system for metro stations under normal circumstances. The outcomes may not be applicable for special events, such as major festivals that necessitate specific passenger flow management. Moreover, although the study considered passengers' barrier-free needs, the majority of participants were young individuals familiar with computer operations, resulting in a limited representation of elderly individuals. Hence, our future work aims to diversify the participant samples, considering a broader age range.

Additionally, while online virtual experiments can control experimental variables and quickly collect a large amount of wayfinding data, the disparity between virtual environments and real physical environments, such as noise, congestion, and other environmental factors in metro stations, might lead to differences in participant decision-making compared to those in real physical environments. To address the discrepancy, this study ensured the validity of data obtained from virtual experiments through small-scale on-site tracking and pre-experiments, and proposed indicators for wayfinding signage evaluation based on the characteristics of this evaluation method. In the future, we plan to further develop the audio effects of the virtual environment to make it more closely real physical environments and optimize VR interface design, thus providing a more realistic and richer VR experience for participants.

Acknowledgements

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