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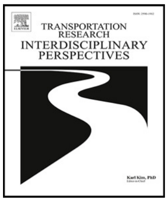
Citation (APA)
Richard, C., & Feng, Y. (2026). Effects of urban design elements on pedestrian wayfinding behavior and stress in a train station: A virtual reality study. *Transportation Research Interdisciplinary Perspectives*, *37*, Article 101999. https://doi.org/10.1016/j.trip.2026.101999

Transportation Research Interdisciplinary Perspectives 37 (2026) 101999

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.elsevier.com/locate/trip



Effects of urban design elements on pedestrian wayfinding behavior and stress in a train station: A virtual reality study

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ARTICLE INFO

Keywords:
Virtual Reality (VR)
Wayfinding
Pedestrian behavior
Wellbeing
Urban stress
Human-centered design & planning

ABSTRACT

This study employed Virtual Reality (VR) and physiological sensors to study the impact of different urban elements on pedestrian wayfinding behavior and physiological responses during outdoor-to-indoor transitions in a train station context. Three urban elements — greenery, water, and leading pavement — were placed either indoors, outdoors, both, or neither, creating four experimental scenarios. In total, 35 participants completed wayfinding tasks across all four scenarios. Behavioral, physiological, and eye-tracking data were collected and analyzed. The results revealed that outside-only placement of urban elements was associated with the worst wayfinding performance across all metrics, performing worse than even the control condition with no urban elements. Eye-tracking analysis demonstrated that outside-only placement of urban elements actively distracted participants from the indoor navigation path. Inside-only placement supported the most efficient navigation in terms of travel time, while the scenario with elements in both locations produced the most focused gaze behavior and the highest subjective comfort ratings. These findings highlight that the placement location of urban elements is more critical than their mere presence for supporting outdoor-to-indoor wayfinding, with important implications for human-centered design in transport hubs.

1. Introduction

What elements do designers take into account in the process of designing and planning urban environments and transportation infrastructure? While most people look for efficiency, connectivity, and smartness, less attention has been paid to people's wellbeing. People live in cities and experience urban environments and transportation infrastructure every day; their wellbeing should be considered a crucial element coming at an early stage in the design and planning process. As a matter of fact, mental health issues such as anxiety and stress have increased among people in recent years. The National Statistics Office (CBS) of The Netherlands has recorded 15% of residents aged 12 or older struggling with their mental health — the highest percentage recorded since the agency started monitoring mental health in 2001. Therefore, it becomes relevant to understand and measure people's well-being in the urban environment to develop a friendly and comfortable living environment.

Stress can come from a wide range of elements: from a person's personal life to urban stress factors that we are surrounded by every day, such as noise pollution or crowded environments in urban environments. Finding one's way in urban environments can be stressful (Bönsch et al., 2024). Urban transportation environments, particularly train stations during peak travel periods, can be highly stressful for pedestrians due to high passenger density, time pressure, and complex navigation demands (Schneider et al., 2021). In such contexts, pedestrians must reach the station, locate entrances, and find the correct platform within limited time, making wayfinding a critical and potentially stressful task.

This challenge becomes even more pronounced during the transition from outdoor urban spaces into indoor station environments. This transition is particularly critical because pedestrians must adapt to changing spatial cues, visual information, and navigation demands when moving from an open urban space into a complex indoor environment. This can create difficulties in locating entrances, interpreting signage, and navigating toward platforms, especially under time pressure. Such transitions may increase cognitive load and stress, potentially leading to inefficient navigation, missed connections, or reduced user experience in transport systems.

At the same time, urban and wayfinding elements can both contribute to or reduce stress. Urban stress can be defined as a mental

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https://doi.org/10.1016/j.trip.2026.101999
Received 19 December 2025; Received in revised form 31 March 2026; Accepted 12 April 2026

tension experienced by humans caused by their living environment coming from a wide range of factors arousing this tension. Attention Restoration Theory (ART) suggests that natural environments help restore directed attention and reduce cognitive fatigue (Kaplan, 1995), while Stress Reduction Theory (SRT) proposes that exposure to natural elements can promote physiological recovery from stress (Ulrich et al., 1991). For example, environmental stressors such as building density, crowdedness in public transport, and noise pollution can increase mental tension (Koene, 2018). In contrast, natural elements such as greenery and water haven been shown to have a positive impact on our mental state and can help reduce our stress levels (Vaeztavakoli et al., 2018). A study identified that nature outdoor areas such as urban parks or forests have positive effects on stress relief for wanderers compared to an urban built environment (Tyrväinen et al., 2014). However, most existing studies have examined these effects in outdoor or indoor environments separately (Ulrich, 1979; Tyrväinen et al., 2014; Smith et al., 2025; Zhang et al., 2024). Relatively little research has investigated how such elements influence pedestrian wayfinding performance and stress during outdoor-to-indoor transitions, particularly in transport environments.

Virtual Reality (VR) has increasingly been applied in transportation research to investigate safety and behavioral responses in different types of urban environments (van Beek et al., 2024; Feng et al., 2021a; Ayad et al., 2026; Angulo et al., 2023). By providing immersive and controlled experimental conditions, VR enables researchers to collect multi-dimensional data and study how individuals perceive and navigate complex transportation settings (Feng et al., 2021a). This makes it particularly suitable for investigating pedestrian wayfinding and experience in transport infrastructure environments such as train stations and multimodal hubs (Brengman et al., 2012; Dai et al., 2026). When combined with physiological sensors, VR offers a valuable approach to capturing both behavioral and stress-related responses during wayfinding tasks (Bönsch et al., 2024; Feng et al., 2021b; Kuliga et al., 2020).

This study addresses the identified gap by examining how selected urban elements influence pedestrian wayfinding performance and stress during outdoor-to-indoor navigation in a train station context by using VR and physiological sensors. Three urban elements — greenery, water, and leading pavement — are known to reduce urban stress and guide pedestrian wayfinding in urban environments (Sarhan et al., 2021; Tyrväinen et al., 2014). These elements are placed either inside or outside of the station to assess their effect on pedestrians' wayfinding performance and stress level. VR experiments were conducted to collect multi-dimensional data during wayfinding tasks to capture different aspects of the wayfinding experience. Trajectory data were used to quantify pedestrian wayfinding performance, including travel time, distance, and movement patterns. Heart rate data provided an objective indicator of physiological responses associated with stress during the task, while eye-tracking data complement these measures by revealing where participants direct their visual attention while navigating the environment, offering additional insight into how environmental features attract attention and potentially support the wayfinding process. Additionally, post-experiment surveys captured subjective perceptions of stress, comfort, and overall experience. By collecting these behavioral and physiological data during the VR experiments, this study aims to understand pedestrian wayfinding behavior and stress level in the outdoor–indoor wayfinding process and how urban elements can be used to reduce the experienced stress.

This paper is structured as follows. Section 2 presents the research methodology featuring the virtual environment, the experimental scenarios, experiment design, experimental apparatus, experimental procedure, and data collection. Accordingly, the results are presented and discussed in Section 3, looking into the behavioral and physiological data at both sequence and scenario analysis level. Section 4 discusses the results in relation to prior research, highlighting how environmental elements shape pedestrian comfort and performance. Finally, Section 5 concludes the paper by summarizing the key findings, outlining methodological limitations, and suggesting directions for future research.

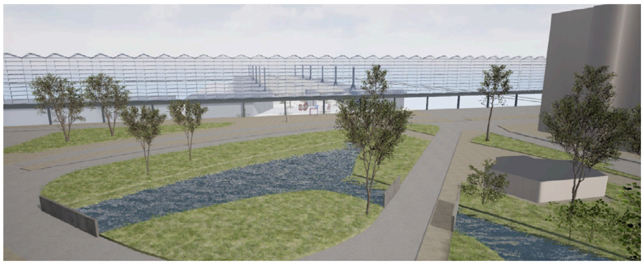


Fig. 1. Visualization of the north exit of the station.

2. Materials and methods

2.1. *The virtual environment*

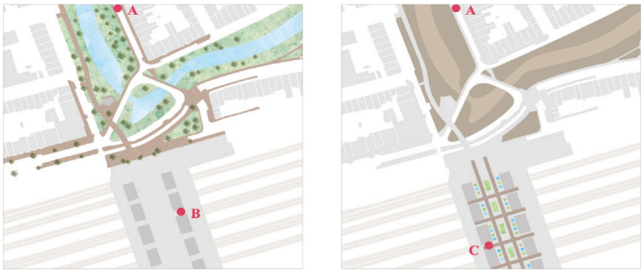
The virtual environment was modeled based on a current existing urban environment, which is based on the Rotterdam Central Station north exit area in the Netherlands (Fig. 1).

Several sets of data, including PDOK BGT (Publieke Dienstverlening Op de Kaart — Basisregistratie Grootschalige Topografie, i.e., the Dutch large-scale topography open dataset), 3D BAG (Basisregistratie Adressen en Gebouwen, i.e., the national register of addresses and buildings), and MVSA Architects' materials were used to build the 3D environment in Rhinoceros and later implemented in Unreal Engine. The station's glass–metal facade was modeled in more detail than other buildings in the virtual environment in order to draw participants' attention and help them find the station. Platform numbers in the station were designed and implemented on walls inside the station. Other urban elements in the virtual environment were downloaded and imported from Epic Games Marketplace, and materials were designed to make the VR environment more realistic such as animated grass and water, trees, and benches. In addition to visual elements helping to mimic realistic experiences, an urban soundtrack was added to the virtual environment, playing a looping city soundscape, consistent with findings that auditory–visual combinations can influence perceived restorative potential (Zhao et al., 2018).

2.2. *Experimental scenarios*

Three urban elements were included in the VR experiment to understand their impact on wayfinding behavior and people's wellbeing, which include greenery and water, as these are variables known to reduce stress, and leading pavement as it shows where to walk which can reduce stress due to the need to find one's way. In the virtual environment, greenery refers to vegetation elements such as trees and bushes placed along the walking paths. Outdoors, these elements appear as trees, grass, and bushes surrounding the station entrance area. Indoors, greenery is represented by smaller trees or bushes placed near the station columns and along the circulation corridors. Water elements are represented by a canal located outside near the station entrance and by small indoor water features positioned near the columns inside the station. The leading pavement corresponds to visually distinct paving patterns indicating the main circulation path, guiding pedestrians toward the station entrance and platform corridors, both indoors and outdoors. Depending on the scenario, these elements were either present or absent in the outdoor and/or indoor parts of the environment, resulting in four configurations: outside only (S0), inside only (S1), neither outside nor inside (S2), and both outside and inside (S3). Fig. 2 shows the visualization of the four experimental scenarios.

Fig. 2. Visualization of the experimental scenarios.



Scenario **0** - Find Platform **11a**
*Variables [**Outdoor** (1) ; **Indoor** (0)]*
Start A - End B

Scenario **1** - Find Platform **8b**
*Variables [**Outdoor** (0) ; **Indoor** (1)]*
Start A - End C

Scenario **2** - Find Platform **6a**
*Variables [**Outdoor** (0) ; **Indoor** (0)]*
Start A - End D

Scenario **3** - Find Platform **8a**
*Variables [**Outdoor** (1) ; **Indoor** (1)]*
Start A - End E

Fig. 3. Visualization of the wayfinding tasks in each scenario, starting and end points.

2.3. *Experiment design*

A within-subject design was employed for this experiment. Participants were asked to complete a wayfinding task in all four designed scenarios. They started at the outside of the station (see Fig. 3 point A) and were asked to reach a different platform inside the station each time.

2.4. *Experimental apparatus*

Once participants reached the correct corridor and found the correct platform, a green message popped up showing "Completed". Then participants were teleported back to a simple environment for 20 s. After this waiting time, participants were teleported back to the next scenario (either S1, S2, or S3) at the starting location A. The sequence repeats itself, once the new platform is found, the task is completed and participants are teleported back to the simple environment for 20 s. This sequence goes on until participants complete the four different scenarios with the wayfinding tasks. All participants started with Scenario 0 as the VR experiment design was scripted this way in the software blueprint. Then, the rest of the scenarios were randomized per participant. We acknowledge that starting all participants with Scenario 0 introduces a practice effect. Accordingly, in the analyses we consider this potential bias in mind; in future studies, full counterbalancing or Latin-square permutations should be implemented to eliminate ordering effects.

Participants used the HP Reverb G2 Omnicept head-mounted display during the VR experiment. The headset also equips a pair of headphones that can play the soundtrack while experiencing the virtual environment. Participants were given one controller to move in the virtual urban space based on a pre-defined navigation mesh. Participants could use the controller to teleport to a desired location by pressing the controller forward and releasing it. The teleportation mode was defined to mimic realistic step-by-step walking behavior. The movement direction was controlled by participant's head rotation. To run the VR experiments, the software Unreal UE4.27 and Windows Mixed Reality Portal were used. The headset integrates sensors enabling the automatic recording of movement trajectories, gaze direction, and physiological signals during the VR experiment. These signals were logged through the VR system and synchronized through timestamps in the dataset, allowing movement trajectories, gaze, and heart rate to be collected simultaneously.

2.5. *Experimental procedure*

Every participant followed the same procedure during the VR experiment, including an introduction, a pre-experiment survey (demographical data and familiarity with VR and train stations), a practice to get familiar with the VR navigation, the formal experiment, and post-experiment surveys. Each participant took approximately 30 min. The study was approved by the Human Research Ethics Committee of Delft University of Technology (Reference ID 2079).

In total, 35 participants took part in the VR experiment (Table 1). Participants were recruited from the university community and completed a short pre-experiment questionnaire regarding familiarity with VR technology and train station environments. The participants ranged in age from 19 to 30 years (M = 25.00, SD = 2.68). The sample consisted of 23 males (65.71%), 11 females (31.43%), and 1 non-binary participant (2.86%). The majority were Master's students (n = 29, 82.86%), followed by Bachelor's students (n = 4, 11.43%), and one PhD student and one graduated/working participant (each 2.86%). Regarding previous experience with VR, 11 participants (31.43%) had never used VR before, 23 (65.71%) had used it sometimes, and 1 (2.86%) used it often. No participants reported using VR quite often. In terms of familiarity with computer gaming, responses were more evenly distributed: 1 participants (2.86%) were not at all familiar, 11 (31.43%) were a little familiar, 9 (25.71%) were moderately familiar, 5 (14.29%) were quite a bit familiar, and 9 (25.71%) were very familiar.

The sequences that participants followed and tasks assigned in each sequence can be found in the table below (Table 2).

2.6. *Data collection*

During this VR study, three types of data were collected, namely (1) behavioral data informing the participant's movement in the VR environment, (2) physiological data informing the participant's stress level during the VR experiments, and (3) user experience data informing the participant's personal perception on the VR study and scenarios. The behavioral data consists of timestamps, X and Y coordinates as the participant walks through the VR environment, and eye-tracking data defined by visual points with 3D coordinates (Look X, Look Y, Look Z). Data from the headset (movement, gaze, and heart rate) were logged at 9 Hz. The logging pipeline integrated these different streams into a synchronized timeline, providing a consistent temporal basis to analyze task duration, spatial trajectories, gaze patterns, and

Table 1
Descriptive information of participants.

Descriptive information	Category	Number (percentage)
Gender	Male	23 (65.71%)
	Female	11 (31.43%)
	Non-binary	1 (2.86%)
Education	Bachelor	4 (11.43%)
	Master	29 (82.86%)
	PhD	1 (2.86%)
	Graduated/Working	1 (2.86%)
Previous experience with VR	Never	11 (31.43%)
	Sometimes	23 (65.71%)
	Often	1 (2.86%)
	Quite often	0 (0.0%)
Familiarity with computer gaming	Not at all familiar	1 (4.86%)
	A little familiar	11 (31.43%)
	Moderately familiar	9 (25.71%)
	Quite a bit familiar	5 (14.29%)
	Very familiar	9 (25.71%)

Table 2
Scenarios sequence followed by all participants.

Sequence followed	Platforms	Participants (n)	Percentage
0-1-3-2	11a-8b-8a-6a	6	17.14%
0-1-2-3	11a-8b-6a-8a	6	17.14%
0-2-3-1	11a-6a-8a-8b	7	20.00%
0-2-1-3	11a-6a-8b-8a	2	5.71%
0-3-2-1	11a-8a-6a-8b	10	28.57%
0-3-1-2	11a-8a-8b-6a	4	11.43%

physiological responses per participant. This behavioral dataset allows us to look into the time spent on each scenario per participant, as well as the trajectories chosen per participant and finally where participants mostly looked at while walking through the VR environment. The heart rate value was recorded via the headset sensor and synchronized on the same timeline. The heart rate value is measured in Beats Per Minute (BPM) and is directly linked to the behavioral dataset via the timestamp and X, Y coordinates. This simultaneous data recording allows us to look at the heart rate value in time and space per scenario. After completing the set of four VR experiments, participants filled in a post-experiment survey evaluating their perceptions of the different scenarios, including their overall comfort levels, preferred environments, and locations where they felt less comfortable during the navigation task. They also completed the Misery Scale (MISC; Bos et al., 2005) to evaluate their exposure to sickness because of virtual reality and the Presence Questionnaire (Witmer and Singer, 1998) to assess their sense of presence in the virtual environment. These subjective evaluations complement the behavioral observations (movement trajectories), physiological responses (heart rate), and visual attention patterns (eye-tracking) recorded during the VR experiments, providing a multimodal perspective on participants' wayfinding experience.

3. Results

3.1. Sequence analysis

As scenarios were randomized per participant for the VR study, two different sets of analyses were conducted regarding the behavioral and physiological data. Section 3.1 aims to look at the data in the sequence of the VR experiments that people followed, which investigates the learning behavior, familiarity, and comfort through the course of the VR experiments. Participants' datasets were reorganized based on their timestamp, to classify datasets per the first VR experiment, second, third, and fourth (i.e., VR0, VR1, VR2, VR3). VR0 corresponds to scenario S0, while VR1, VR2, and VR3 correspond to all other scenarios in a randomized order (S1, S2, S3). Given that all participants started with Scenario 0, VR0 is interpreted as a practice condition in the discussion to account for learning effects.

Table 3
Mean and standard deviation of travel time and distance per scenario.

Scenario	Travel time mean (s)	Travel time STD (s)	Travel distance mean (cm)	Travel distance STD (cm)
VR0	44.35	17.13	271.04	9.38
VR1	42.65	13.85	265.87	6.31
VR2	44.71	19.36	271.40	5.32
VR3	37.73	11.95	249.37	2.16

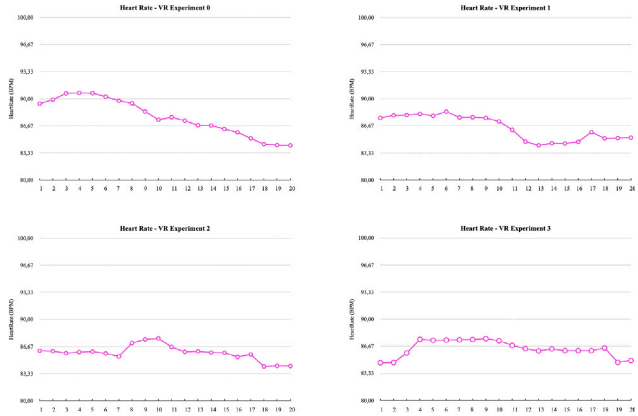


Fig. 4. Heart rate through time, for each VR experiment.

3.1.1. Behavioral data

The average time taken to complete tasks and the average distance were calculated per VR experiment. Travel time was computed as the difference between the first and last recorded timestamp for each participant per scenario. The average distance traveled by participants for each VR experiment was calculated using the X and Y coordinates, by accumulating the Euclidean distance between consecutive timestamps throughout the navigation task. Results can be found in Table 3.

For VR0, the average travel time to complete the wayfinding task is 44.35 s (SD = 17.13 s), while for VR1, and VR3 the average travel time is lower, respectively 42.65 s (SD = 13.85 s) and 37.73 s (SD = 11.95 s). VR2 shows a similar travel time to VR0 with 44.71 s (SD = 19.36 s) The average travel distance in VR0 is 271.10 cm (SD = 9.38 cm), then decreases for VR1 (M = 265.87 cm, SD = 6.31 cm) and VR3 (M = 249.37 cm, SD = 2.16 cm), but increases a little for VR2 (M = 271.40 cm, SD = 5.32 cm). The behavioral results suggest an overall learning trend across VR experiments: although VR2 does not follow a strictly decreasing pattern in travel time, VR3 achieves the lowest travel time and distance of all four experiments. This indicates that participants generally improved their wayfinding performance with experience, spending less time and covering less distance by the final experiment. In terms of travel distance, variation across experiments remains limited, suggesting that while efficiency in time improved, participants tended to follow similar path lengths throughout the study.

3.1.2. Physiological data

To account for variations in the time participants took to complete tasks, we normalized the data to graph heart rates throughout the experiments. From each participant's dataset, 20 heart rate values were collected at regular intervals (step = int(n/20)), ensuring consistency in time normalization. We then averaged the heart rates of all participants over these intervals. The resulting average heart rate over normalized time for each VR experiment is displayed in (Fig. 4).

In VR0, the heart rate value is quite high at the start of the experiment (M = 89.37 BPM) and slowly decreases during the experiment, ending at an average of 84.26 BPM. We can observe the same trend for VR1. While the initial heart rate value is slightly lower than VR0 (M = 87.63 BPM) and continues to decrease, the ending heart rate is slightly higher than VR1 (M = 85.20 BPM). For VR2, the heart rate curve is

Table 4
Mean and standard deviation of travel speed, normalized travel time and distance.

Metric	S0	S1	S2	S3
Normalized travel time	2.49 ± 0.85	1.76 ± 0.58	2.06 ± 0.58	2.26 ± 0.90
Normalized travel distance	1.27 ± 0.39	1.08 ± 0.10	1.08 ± 0.16	1.18 ± 0.38
Speed (m/s)	5.20 ± 1.39	7.31 ± 1.81	7.63 ± 2.26	7.24 ± 2.18

more stable, starting at an average of 86.14 BPM and ending at 84.26 BPM. However, for VR3, although the heart rate curve is stable, the ending heart rate (M = 84.91 BPM) is slightly higher than the initial heart rate (M = 84.63 BPM). Regarding the average heart rate across VR experiments, there is a noticeable trend of improvement in the average heart rate over time in the last two VR experiments. In VR0, the initial average heart rate starts relatively high and decreases unevenly over time. VR1 follows a similar trend, with participants beginning the task at a lower average heart rate compared to VR0. However, in VR2, the heart rate curve begins to flatten out over time, indicating a stabilization in heart rate responses. This trend continues in VR3, where the heart rate curve shows further stabilization throughout the experiment. These results suggest that participants became more comfortable and less stressed as they progressed through the experiments, particularly noticeable from VR2 to VR3.

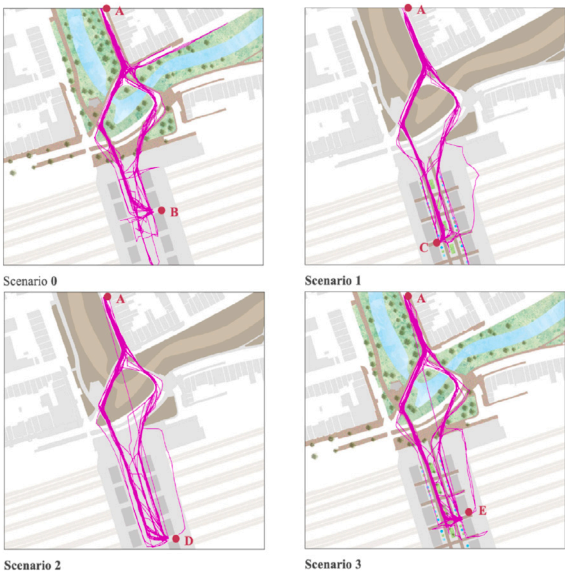


Fig. 5. Trajectories of participants in each scenario.

3.2. Scenario analysis

The scenario analysis is conducted based on each experimental scenario experienced by participants, namely S0, S1, S2, and S3.

3.2.1. Behavioral data

1. Wayfinding performance and movement trajectories. Using the same method as for the sequence analysis, the average travel time and distance were calculated for all scenarios S0, S1, S2, and S3. Due to variations in platform locations across the four scenarios, travel time and travel distance were normalized by dividing each by the minimum observed value. Travel speed is calculated as the distance traveled divided by the total travel time. Results can be found in Table 4.

Amongst all scenarios, S1 records the lowest normalized travel time of all scenarios (M = 1.76, SD = 0.58) and together with S2 the lowest normalized travel distance (M = 1.08, SD = 0.10 and M = 1.08, SD = 0.16 respectively). S0 records the highest travel time (M = 2.49, SD = 0.85) and the highest travel distance (M = 1.27, SD = 0.39), while S3 shows intermediate values for both time (M = 2.26, SD = 0.90) and distance (M = 1.18, SD = 0.38). In terms of speed, S0 recorded the lowest average speed (M = 5.20 m/s, SD = 1.39), while S2 recorded the highest (M = 7.63 m/s, SD = 2.26), followed by S1 (M = 7.31 m/s, SD = 1.81) and S3 (M = 7.24 m/s, SD = 2.18).

To examine differences in wayfinding performance across the four scenarios, normality of the data was first assessed using the Shapiro–Wilk test. The test revealed significant differences in normalized travel time ($\chi^2 = 27.72$, $p < 0.001$), normalized travel distance ($\chi^2 = 27.86$, $p < 0.001$), and speed ($\chi^2 = 52.41$, $p < 0.001$) across the four scenarios. Therefore the non-parametric Friedman test and post-hoc pairwise comparisons were conducted using the Wilcoxon signed-rank test with Bonferroni correction. The Friedman test revealed significant differences in both normalized travel time ($\chi^2 = 27.72$, $p < 0.001$) and normalized travel distance ($\chi^2 = 27.86$, $p < 0.001$) across the four scenarios. Post-hoc Wilcoxon tests with Bonferroni correction showed that S1 was significantly different than all other scenarios in terms of travel time (S1 vs S0: $p < 0.001$, S1 vs S2: $p < 0.01$, S1 vs S3: $p < 0.01$), while S0 was significantly different than S1 and S2 ($p < 0.05$). S2 and S3 did not differ significantly from each other. For travel distance, S0 covered significantly more distance than both S1 ($p < 0.01$) and S2 ($p < 0.001$), while S2 and S3 differed significantly ($p < 0.001$). No significant difference was found between S1 and S2, S1 and S3, or S0 and S3 in terms of travel distance. For speed, S0 was significantly slower than all other scenarios (S0 vs S1: $p < 0.001$, S0 vs S2: $p < 0.001$, S0 vs S3: $p < 0.001$), while S1, S2, and S3 did not differ significantly from each other.

These results indicate that outside-only placement of urban elements (S0) was associated with the worst wayfinding performance across all three metrics. Participants had the longest travel time, the greatest travel distance, and the lowest navigation speed in S0, performing worse than even the control condition (S2) in which no urban elements were present. However, it should be noted that all participants completed S0 first, which may have contributed to its poor performance due to reduced familiarity with the VR navigation controls at this stage. Inside-only placement (S1) supported the most efficient wayfinding in terms of travel time, while all non-S0 scenarios achieved comparable navigation speed and distance. This suggests that the location of urban elements, specifically their placement inside the station, is more critical for supporting outdoor–indoor wayfinding transition than their mere presence, and that outside-only placement may actively hinder navigation by drawing visual attention away from the indoor path. Trajectories of participants were then plotted in space using the movement coordinates recorded at every sampling interval for each scenario (Fig. 5).

Depending on the platform's attribute, participants had to reach the endpoint either on the left (platform with "a") or on the right (platform with "b") of the station. For scenario S0 — the first VR experiment for all participants; most participants walked on the right to reach the left side of the station (platform 11a). Similarly, for the rest of the VR experiments, regardless of the final platform locations, most participants tended to turn right first at the first intersection. This observation can be attributed to a prevalent right-hand tendency among participants when navigating and finding their way.

2. Gaze behavior. The eye-tracking data was processed using the visual points defined by (Look X, Look Y, Look Z) coordinates from the dataset. The visual points are then mapped in 2D (Fig. 6) as well as in 3D in Unreal software. All visual points for each scenario were aggregated, resulting in an overall dataset per scenario.

Regarding the eye-tracking data, there is a clear significance of the participant's interest in the urban elements known to reduce stress. Some examples of where participants looked during Scenario 3 are highlighted in Fig. 7. It shows that even if participants had the objective to reach inside the station, they took time to look at their surroundings

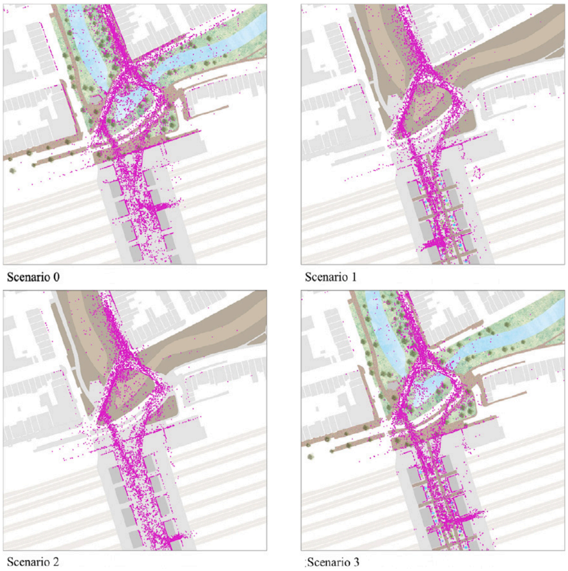

Scenario 0
Scenario 1
Scenario 2
Scenario 3

Fig. 6. Eye-tracking data mapped in each scenario.

Fig. 7. Example of points of attention in the virtual environment.

and laid their eyes on trees, grass, bushes, and river. While these maps are visually informative, a future extension should compute difference maps of gaze density across scenarios to quantitatively highlight areas with higher interest.

To examine differences in gaze behavior across the four scenarios, gaze variability was computed as the standard deviation of the visual point coordinates for each participant, capturing the spatial spread of gaze landing points in the virtual environment. Three components were analyzed: LookX standard deviation (left/right horizontal scanning), LookZ standard deviation (up/down vertical scanning), and total variability, calculated as the Euclidean magnitude of all three standard deviation components (Look X, Y, Z). Gaze samples with a certainty value below 0.8 were excluded to retain only measurements where the system was at least 80% confident in the gaze detection, removing samples potentially affected by blinks, headset movement, or tracking failures. The Shapiro–Wilk test showed non-normal distributions for all three metrics across scenarios, thus the non-parametric Friedman test was applied, with post-hoc pairwise comparisons conducted using the Wilcoxon signed-rank test with Bonferroni correction.

The Friedman test revealed significant differences across scenarios for all three gaze variability metrics: total variability ($\chi^2 = 13.90$, $p = 0.003$), left/right horizontal scanning ($\chi^2 = 39.93$, $p < 0.001$), and up/down vertical scanning ($\chi^2 = 26.69$, $p < 0.001$). For left/right horizontal scanning, S0 (outside only, M = 2737.13) showed significantly higher gaze variability than all other scenarios (S0 vs S1: $p < 0.001$, S0 vs S2: $p < 0.001$, S0 vs S3: $p < 0.001$), while S1 (inside only, M = 1857.80) was also significantly lower than S2 ($p < 0.01$). S1 and S3 did not differ significantly. For up/down vertical scanning, S0 (M = 150.24) was significantly higher than all other scenarios (S0 vs S1: $p < 0.001$, S0 vs S2: $p < 0.01$, S0 vs S3: $p < 0.001$), while S1, S2, and S3 showed no significant differences among themselves. For total variability, S0 recorded the highest overall gaze spread (M = 7680.59), while S3 recorded the lowest (M = 7089.01). Post-hoc tests confirmed significant differences only between S0 and S3 ($p < 0.05$) and S2 and S3 ($p < 0.001$).

The results indicated that S0 (outside only) consistently produced the most visually scattered gaze behavior across all three metrics, including the highest left/right horizontal scanning, up/down vertical scanning, and total variability. This suggests that outdoor-only placement of urban elements actively distracted participants from the navigation task. Since S0 was always completed first, this effect cannot be fully ruled out as a contributing factor. In contrast, S1 (inside only) showed the lowest horizontal scanning variability, indicating that indoor placement of urban elements guided visual attention along the navigation path rather than distracting from it. Meanwhile, S3 (both inside and outside) recorded the lowest total gaze variability, significantly lower than both S0 and S2, suggesting that the simultaneous presence of urban elements both inside and outside the environment may have contributed to a more focused visual attention during the outdoor-to-indoor wayfinding transition. This finding is particularly noteworthy given that S3 contains urban elements in both locations, which might be expected to increase visual distraction, yet produced the most spatially concentrated gaze overall. A possible explanation is that indoor elements in S3 provided sufficient visual guidance to anchor participants' attention along the navigation path, partially compensating for the distracting effect of outdoor elements and facilitating a smoother visual transition between the outdoor and indoor environments.

3.2.2. Physiological data

1. Heart rate through time. Average heart rate per participant per scenario was calculated and compared across the four scenarios. As all scenarios met the normality assumption (Shapiro–Wilk: $p > 0.05$), a repeated measures ANOVA was applied. The results shows that S0 (outside only) recorded the highest average heart rate (M = 87.51 BPM, SD = 9.74), followed by S3 (M = 86.96 BPM, SD = 11.06), S2 (M = 86.38 BPM, SD = 10.35), and S1 (M = 85.85 BPM, SD = 9.34). However, the repeated measures ANOVA revealed no significant difference in average heart rate across the four scenarios ($F = 1.578$, $p = 0.199$), indicating that the placement of urban elements did not have a significant impact on overall physiological arousal during the wayfinding task.

To examine whether heart rate changed significantly over the course of each scenario, time was normalized into 20 timestamps to calculate the average heart rate through time in BPM. This approach enables analysis of relative changes in physiological responses over the course of each task. To examine whether heart rate changed significantly over the course of each scenario, heart rate values at each of the 20 timestamps were normalized by subtracting the value at timestamp 1. Spearman rank correlation was applied to test whether the normalized heart rate showed a consistent trend across the 20 timestamps within each scenario. Results revealed a significant negative trend in S0 ($r = -0.809$, $p < 0.001$), S1 ($r = -0.965$, $p < 0.001$), and S2 ($r = -0.791$, $p < 0.001$), confirming that heart rate decreased consistently over time in these three scenarios (Fig. 8), likely reflecting a physiological habituation effect as participants became more accustomed to the navigation task. By the final timestamp, heart rate had dropped by 2.38 BPM in S0, 5.54 BPM in S1, and 2.51 BPM in S2 relative to their respective baselines.

The results indicated that S1 (inside only) had the strongest and most consistent decrease of heart rate, suggesting that indoor placement of urban elements was associated with the greatest degree of physiological relaxation over the course of the task. In contrast, S3 (both inside and outside) showed no significant trend ($r = 0.053$, $p = 0.823$), with heart rate remaining close to baseline throughout the task and recording the second highest average heart rate (M = 86.96 BPM) across all scenarios. This pattern may reflect sustained

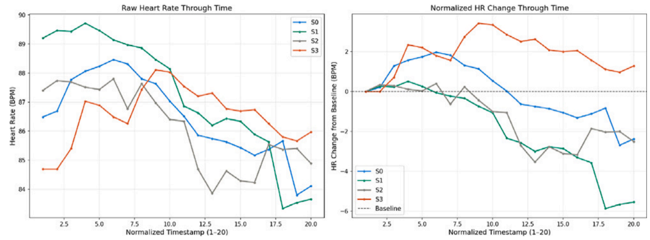
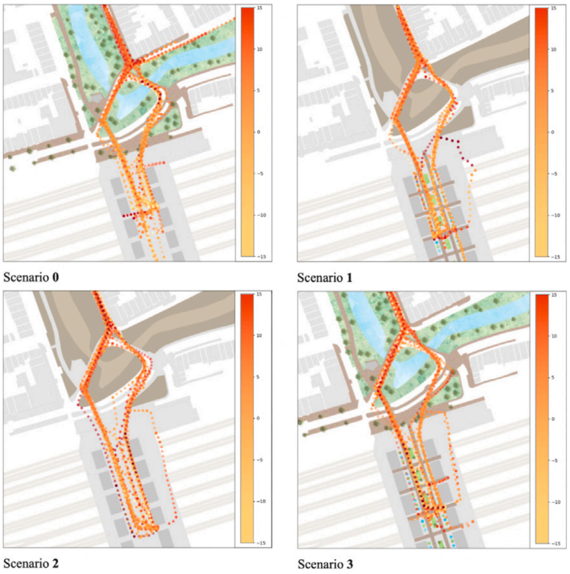


Fig. 8. Average heart rate through time for all scenarios.



Scenario **0**

Scenario **1**

Scenario **2**

Scenario **3**

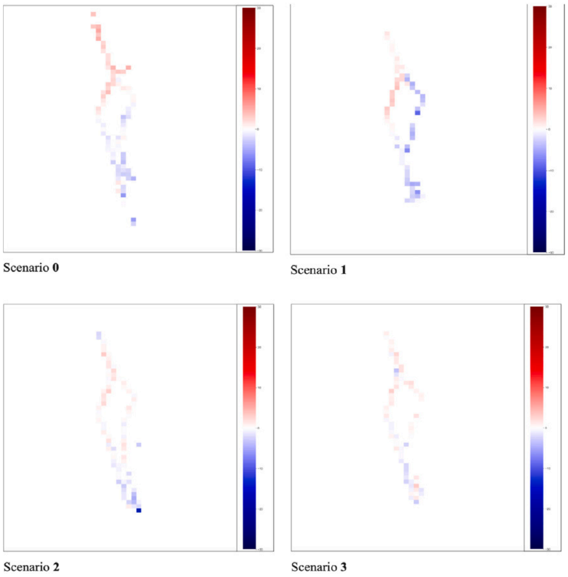
Fig. 9. Heart rate average through time for all scenarios.

physiological arousal maintained by the simultaneous presence of both indoor and outdoor urban elements, resulting from the continuous availability of visual guidance cues throughout the outdoor-to-indoor transition. The absence of the habituation effect observed in S0, S1, and S2 suggests that S3 produced a qualitatively different physiological response, though the direction of this difference cannot be conclusively determined from heart rate data alone.

2. Heart rate through space. To understand the relation between heart rate and physical space, each participant's average heart rates were plotted along their respective paths. For each scenario, the participant's average heart rate was calculated and mapped based on their movement trajectories (Fig. 9).

When mapping participants' average heart rates along their trajectories across all scenarios, a consistent trend emerges: participants' heart rate fluctuations tend to decrease noticeably once they enter the station compared to when they are outside. This shift can be attributed to several factors. Firstly, inside the station, participants are closer to their endpoint, which likely reduces stress about navigation and finding their destinations. Secondly, increased visibility inside the station, such as platform numbers and landmarks, provides visual feedback that aids navigation and decreases stress. In contrast, outside the station, participants lack such visual cues, leading to higher stress and higher heart rate variability.

The previous results show the average heart rate per participant per scenario. The results shown in Fig. 10 illustrate the average heart rate for all participants in relation to space. A grid was implemented to create a heat map displaying the average heart rate based on participants' location. Since no participant used the exact same path, a threshold was implemented to display a cell with a color related to heart rate fluctuation. The analysis of aggregated average heart rate fluctuation reveals distinct patterns. Overall, there are more red dots outside of the stations and more blue dots inside the stations. This suggests that participants' average heart rates are higher outside the station compared to inside, aligning with previous observations. In scenarios S0 and S1, there is a noticeable fluctuation in the average heart rate across space, indicated by high intensities of red (higher heart rate) and blue (lower heart rate) colors. In scenario S2, the fluctuation in average heart rate is less intense. Similarly, scenario S3 shows even less fluctuation, which indicates minimal variability in average heart rate. The finding indicates that participants maintained a more stable and consistent average heart rate in scenarios S2 and S3, reflecting a higher level of physiological stability and possibly reduced stress compared to scenarios S0 and S1.



Scenario **0**

Scenario **1**

Scenario **2**

Scenario **3**

Fig. 10. Average heart rate fluctuation for all participants, for each scenario.

3.3. *User experience analysis*

3.3.1. *Realism*

Regarding the perceived realism of the virtual environment, the majority of participants rated it positively. Specifically, 28 participants (80.00%) found the environment somewhat realistic, and 4 (11.43%) found it very realistic, resulting in a combined positive realism rating of 91.43%. Three participants (8.57%) rated the environment as neither realistic nor unrealistic, while no participant found it somewhat unrealistic and none found it very unrealistic. These results indicate that the virtual environment was perceived as sufficiently realistic by the large majority of participants, supporting the ecological validity of the VR experiment.

3.3.2. *Reported stress and comfort*

Overall, most participants (60.00%) did not report feeling more stressed in any specific areas during the VR experiments. In contrast, 14 participants (40.00%) reported that they felt less comfortable, with 13 (92.86%) of those indicating discomfort and more stress specifically outside of the station. This finding aligns with the objective measures, where the average heart rate tended to fluctuate more intensely outside the station compared to inside. This correlation underscores the link between subjective stress perception and objective physiological responses during the VR experiment, also highlighting the impact of environmental factors on participant comfort and stress levels in virtual environments.

Table 5
Attributes from explanation for the most comfortable scenario (S3).

Attributes from explanation	Mentions (n)	Quotes
Greenery	26	"Green space, trees, greenery, plants, vegetation, nature, flowers, landscape elements, more green, grass, green elements"
Water	6	"Canal, lake, running water, landscape elements, water"
Familiarity	5	"Used to environment, know where to go, already familiar with the environment"
Leading pavement	3	"Better visibility of pavements, sidewalks, followed designated path instead of jaywalking"
Pleasant/Comfortable sensation	23	"Pleasing to eye, quiet sensation, felt inviting, pleasant, soothing experience, felt very relaxing, put you at ease, much more comfortable, visually appealing, calming atmosphere, feel better, makes me feel more relaxed, gives sense of peace, improving ambient on inside public spaces"
Continuity	6	"Felt continuous, no big changes as you went inside, both outside and inside felt very relaxing, transition from outdoor to indoor felt more real, outside station more comfortable same goes for inside, seeing plants and green both inside and outside pleases me"

At the scenario level, subjective evaluations further highlight differences in perceived stress and comfort. A majority of participants (71.43%) reported higher comfort in scenario S3 compared to the other scenarios, while 60.00% reported lower comfort in S2. These subjective perceptions are consistent with the physiological measures, where heart rate fluctuations were more stable in scenario S3, suggesting lower stress levels. Moreover, 77.14% of participants indicated increasing comfort over successive VR experiment, with 74.07% reporting improvement from the second trial (VR1) onward, suggesting a potential reduction in perceived stress over time due to familiarity. The higher comfort level reported in scenario S3 can also be linked to better wayfinding performance, indicating a positive correlation between comfort and task performance. Participants' responses provide further insight into these patterns. Regarding the most comfortable scenario (i.e., S3), the participants' explanations were grouped into six categories, including greenery, water, familiarity, leading pavement, pleasant sensation, and continuity (see Table 5).. Participants highlighted several factors that contributed to their comfort in scenario 3; they often mentioned "greenery, water, and clear pathways", which corresponds to elements that attracted visual attention in the eye-tracking data. Additionally, participants mentioned feelings of "familiarity, continuity, and pleasant sensations", all of which positively influenced their comfort levels. The continuity aspect is noteworthy as it suggests that having similar urban elements both indoor and outdoor may support smoother transition and reduce stress.

Regarding the least comfortable scenario (i.e., S2), the participants' explanations were categorized into: lack of nature, no leading pavement, not pleasant, and about the transition from indoor to outdoor that was not pleasant (see Table 6). These findings indicate that both the presence of supportive environmental elements and the quality of the outdoor-to-indoor transition play an important role in shaping perceived stress and comfort during wayfinding .

3.3.3. Simulation sickness and presence questionnaire

In terms of simulation sickness (Bos et al., 2005), there were minimal reports of sickness symptoms after the experiments, with the majority of participants (88.57%) experiencing no issues during the VR experiments (Table 7).

The presence questionnaire results indicated a high level of presence among participants, with the immersion item scoring the highest (M = 5.54), indicating that participants were deeply engaged in the virtual environment (Table 8).

Table 6
Attributes from explanation for the less comfortable scenario (S2).

Attributes from explanation	Mentions (n)	Quotes
Lack of nature elements/emptiness	19	"No greenery, empty, no nature, absence of grass and plants, no green stuff, no plants nor garden, no natural elements, no vegetation, absence of green areas"
No leading pavement	6	"Roads not clearly visualised, harder to differentiate where to walk, didn't know where to go, undistinguishable pavements, empty of elements to guide the walk, visibility of streets and pavements not high"
Not pleasant/comfortable	13	"Not inviting, less liveable, cold dead feeling, no points where I felt relaxed, sad, depressing, cold environment, doesn't look attractive, not welcoming, less comfortable and desirable, no fun, makes me wanna commute less"
Transition	4	"Cold feeling inside like I already had outside, cold environment both outside and inside, no natural elements both outside and inside"

Table 7
Misery Scale scores after VR experiments.

Descriptive information	Category	Number (percentage)	Score
How do you feel?	No problems	31 (88.57%)	0
	Uneasiness	4 (11.43%)	4
If symptoms (dizziness, warmth, headache, stomach, sweating…)	Vague	4 (11.43%)	8
	Slight	1 (2.86%)	3
	Fairly	0 (0.0%)	0
	Severe	0 (0.0%)	0
If nausea	Slight	1 (2.86%)	6
	Fairly	0 (0.0%)	0
	Severe	0 (0.0%)	0
	Retching	0 (0.0%)	0
If vomiting			0

Table 8
Presence Questionnaire scores after VR experiments.

Item	Mean	SD
Involvement	5.42	1.39
Sensory Fidelity	5.32	1.35
Immersion	5.54	0.55
Interface quality	4.49	1.47

4. Discussion

This study demonstrates that urban elements such as greenery, water, and guiding pavements influence wayfinding performance and physiological responses differently depending on their placement location.

The behavioral results consistently identified S0 (outside only) as the worst-performing scenario across all three wayfinding metrics, including normalized travel time, normalized travel distance, and navigation speed. Participants in S0 took significantly longer, covered more distance, and moved more slowly than in all other scenarios, including S2 (neither), where no urban elements were present at all. This finding is particularly interesting because it suggests that the presence of urban elements in the wrong location can actively hinder navigation rather than support it. The eye-tracking results provide a explanation for this effect, where S0 produced significantly higher left/right horizontal gaze variability and up/down vertical gaze variability than all other scenarios, indicating that outdoor urban elements drew participants' visual attention sideways and upward, away from the wayfinding task. This visual distraction likely contributed directly to the longer travel times and lower speeds observed in S0, consistent with research showing that irrelevant visual stimuli can disrupt navigation performance (Geisen et al., 2021; Dogu and Erkip, 2000).

In contrast, S1 (inside only) supported the most efficient wayfinding in terms of travel time and showed the lowest horizontal gaze variability, suggesting that indoor placement of urban elements guided visual attention along the navigation path rather than distracting from it. This finding aligns with research on the role of environmental cues in supporting wayfinding (Hund and Gill, 2014; Iftikhar et al., 2021), and extends it by showing that natural elements can function as complementary wayfinding cues to support navigation alongside conventional guidance systems but only when placed in the appropriate location. In this case, placing natural elements inside of the train station is critical for their effectiveness during outdoor-to-indoor transitions.

S3 (both inside and outside) produced intermediate wayfinding performance in terms of travel time and distance, but recorded the lowest total gaze variability of all scenarios, significantly lower than both S0 and S2. This suggests that the simultaneous presence of urban elements in both locations may have produced a more focused visual attention pattern during the outdoor-to-indoor transition, with indoor elements partially compensating for the distracting effect of outdoor elements. This interpretation is further supported by the subjective survey results, where 71.43% of participants reported higher comfort in S3, and participants cited continuity of environmental elements across the outdoor-to-indoor boundary as a key factor in their comfort. The continuity aspect is noteworthy as it suggests that having similar urban elements both indoor and outdoor may support a smoother transition.

Physiological responses provided partial support for the role of environmental design in shaping user experience. While there was no significant difference in average heart rate across scenarios, a significant decreasing trend in heart rate over time was observed in S0, S1, and S2, likely reflecting a physiological habituation effect as participants became more accustomed to the navigation task. S3 showed no such trend, suggesting a qualitatively different physiological response. The absence of the habituation effect in S3 may reflect either sustained physiological arousal maintained by the simultaneous presence of both indoor and outdoor urban elements, or alternatively a stable level of physiological comfort resulting from the continuous availability of visual guidance cues. These findings are consistent with studies showing that supportive visual–spatial configurations can influence physiological arousal (Lin et al., 2019; Torku et al., 2021).

These results are consistent with prior research on the restorative effects of natural environments on pedestrian wellbeing. Ulrich (1979) and Tyrväinen et al. (2014) showed that exposure to greenery and water alleviates stress in outdoor contexts, while Brengman et al. (2012) and documented similar benefits in built environments such as retail spaces. In particular, our findings are also aligned with those of Smith et al. (2025) and Zhang et al. (2024), who reported that green spaces and the presence of greenery have a positive impact on pedestrians' walking experiences. While previous studies have largely examined restorative effects in outdoor urban environments or individual indoor settings, the current study extends this body of work by demonstrating that the continuity of biophilic elements across outdoor–indoor transitions can provide comparable stress-reducing benefits to pedestrian wayfinding experience, even in complex and time-pressured environments such as transit hubs.

Taken together, these findings suggest that integrating natural and guiding elements in transport environments support wayfinding efficiency and perceived comfort, but that the effectiveness of such elements is critically dependent on their placement location. Human-centered environmental design in transport hubs should therefore prioritize the placement of natural and guiding elements inside the building, where they can guide visual attention along the navigation path, rather than exclusively in outdoor spaces where they may create visual distraction. By combining behavioral, physiological, eye-tracking, and self-report data, this study contributes to the multimodal research agenda in pedestrian studies, as recommended by Feng et al. (2021a,b). Such integration demonstrates the value of VR as a platform for capturing both objective and subjective dimensions of wayfinding. Finally, certain methodological aspects shape the interpretation of findings. Locomotion was implemented via teleportation, which minimizes simulation sickness but may affect immersion compared to continuous navigation modes (Boletsis, 2017; Schneider and Bengler, 2020; Segarra Martinez et al., 2022). Similarly, data logged at 9 Hz was sufficient for analyzing travel patterns and heart-rate trends but lacks the resolution for fine-grained analyses such as saccades or beat-to-beat variability. These design decisions highlight the balance between experimental control, participant comfort, and data resolution, and they suggest directions for refinement in future VR-based studies.

5. Conclusion and future work

This study employed immersive VR experiments to examine the effects of urban design elements on pedestrian wayfinding behavior and associated physiological responses during the outdoor–indoor transition in a train station. The results reveal that the placement location of urban elements, namely greenery, water, and leading pavement, specifically whether they are positioned inside or outside the station, is more critical for supporting wayfinding performance than their mere presence. Across all three behavioral metrics, S0 (outside only) was consistently associated with the worst wayfinding performance, performing worse than even the control condition S2 (neither). S1 (inside only) supported the most efficient wayfinding in terms of travel time, while S3 (both inside and outside) produced the most focused gaze behavior despite containing elements in both locations. Eye-tracking analysis revealed that S0 produced significantly higher horizontal and vertical gaze variability than all other scenarios, suggesting that outdoor urban elements drew visual attention away from the indoor navigation path, directly explaining its poor wayfinding outcomes. Physiological data showed no significant difference in average heart rate across scenarios, though a consistent decreasing trend over time was observed in S0, S1, and S2, while S3 showed a stable physiological response throughout. Subjective reports further confirmed that participants perceived S3 as the most comfortable scenario, citing the continuity of environmental elements across the outdoor-to-indoor boundary as a key factor, consistent with the stable physiological response observed in this scenario.

These findings contribute to interdisciplinary transportation research by demonstrating how environmental design influences pedestrian navigation and experience in transport infrastructure. In particular, the results highlight that outdoor-to-indoor transitions are critical spaces in transport hubs where the placement of natural and guiding elements must be carefully considered: inside placement supports focused visual attention and efficient navigation, while outside-only placement may actively hinder wayfinding by creating visual distraction. Furthermore, this study demonstrates the effectiveness of VR methods combined with multimodal data collection — behavioral, physiological, eye-tracking, and subjective — to provide an in-depth understanding of pedestrian wayfinding performance and comfort.

This study has several limitations. The modest sample size and demographic composition constrain generalizability. Locomotion was limited to teleportation, which may not fully capture step-by-step walking behavior. All participants began with Scenario 0, which might confounds the environmental influence of outside-only urban element placement. In addition, because participants experienced multiple scenarios within the same virtual environment, repeated exposure to the same architectural layout may have allowed participants to gradually develop spatial familiarity with the environment. Such cognitive carry-over effects could influence wayfinding strategies or task performance in later trials. While scenario randomization helps mitigate ordering effects, this potential learning effect should be considered when interpreting the results. Eye-tracking was analyzed using aggregate gaze variability metrics, and data were logged at 9 Hz, which is sufficient for overall trends but limits the capture of fine-grained dynamics such as saccadic eye movements or beat-to-beat variability.

Future studies could strengthen this work by incorporating larger and more diverse participant samples, applying full counterbalanced scenario orders, and extending the range of physiological measures to include more sensitive indicators of stress such as galvanic skin response or cortisol levels. It would also be valuable to explore different locomotion methods, and more advanced eye-tracking analyses. Finally, integrating intelligent agents into similar experimental frameworks could open new possibilities for adaptive, stress-aware wayfinding support in XR environments.

CRediT authorship contribution statement

Céleste Richard: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization, Writing – review & editing. **Yan Feng:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization, Formal analysis, Visualization, Writing – original draft.

Use of Generative AI

During the preparation of this work, the authors used ChatGPT (OpenAI) for language editing purposes. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Céleste would like to thank Maurice Harteveld and Stefan van der Spek for their continuous supervision and support for the VR devices. A warm thank you to the whole VR & Script Team that helped during the VR development: Hugo Richard, Alena Shcheglova, Jair Lemmens, the VR Zone & BK VR lab at TU Delft, Yosua AP Andoko, Jeroen Boots and Chris Benning. As a last note, thank you to all the VR participants for turning this research idea into a tangible project.

Data availability

Data will be made available on request.

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