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Quantitative Analysis of User Navigation in Virtual Reality Environments: A Trajectory-Based Approach to Motion Smoothness

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Abstract: This study presents a trajectory-based analytical framework for evaluating spatial accessibility and wayfinding performance in immersive virtual environments. The method was applied to the proposed Emergency Department (ED) of Nasr City Hospital, Cairo, involving six medical professionals. Participants performed scenario-based tasks in Virtual Reality (VR), during which motion data—comprising spatial coordinates, yaw rotation, and timestamps—were collected. A custom Python workflow processed the data to compute key mobility metrics: total distance, average speed, speed variability, and rotational variability. A composite metric, the Normalized Weighted Smoothness Index (NWSI), was introduced to reflect temporal consistency and directional coherence. Results revealed differences in navigation fluency across participants. High smoothness and low variability suggested efficient spatial understanding and minimal cognitive load. In contrast, abrupt changes in speed and direction indicated wayfinding difficulties, often linked to reduced visibility or unclear spatial cues. Mapping these behaviors identified zones with potential design inefficiencies. The proposed method offers a quantitative, evidence-based approach for assessing environmental legibility and supports iterative improvements in VR-based healthcare design.

Keywords: Virtual Reality, Trajectory Analysis, Emergency Department, Wayfinding, Healthcare Design.

1. Introduction

Brain tumor (BT) is a type of tumor that develops in the brain or central nervous system as a result of uncontrolled cell growth [1]. According to statistics from the American Society of Clinical Oncology (ASCO), the 10th most common cause of death for both men and women is cancer of the brain and nervous system. According to brain tumor statistics, tumors that metastasize to the brain affect about 25% of cancer patients, or an estimated 150,000 people annually [2]. There are many symptoms of brain cancer such as frequent headaches, difficulty in concentration, memory loss, changes in speech, loss of balance, mood swings and seizures. When a mutation occurs in DNA, this causes a malfunctioning of the genes and thus uncontrolled growth of cells which is the main cause of a tumor. The degree of mutation and the type of gene determine the grade and type of brain tumor.

Immersive Virtual Environments (IVEs) have emerged as pivotal tools in analyzing human spatial behavior within architectural, healthcare, and urban contexts. These environments provide controlled yet realistic settings to assess how users navigate complex spatial configurations, which is essential for evaluating accessibility, legibility, and operational efficiency—core determinants of functional spatial design. Traditional VR studies often rely on coarse metrics like task completion time or path length, which offer limited insights into users' cognitive engagement and spatial processing [1-5]. Recent advancements in motion telemetry and trajectory analysis enable more granular assessments of user behavior by capturing continuous positional and rotational data [4, 6]. This allows for the reconstruction of navigation patterns that reflect perceptual, motor, and cognitive dimensions of spatial engagement. However, many VR studies overlook kinematic indicators such as motion smoothness or rotational stability, which serve as proxies for spatial comprehension and cognitive effort. Notably, rotational metrics—particularly yaw dynamics—remain underutilized in diagnosing directional uncertainty and wayfinding difficulty [7-9].

This study integrates two intersecting frameworks to address these gaps: (1) Cognitive Navigation Theory, emphasizing embodied spatial learning through sensorimotor exploration; and (2) Trajectory-Based Kinematics, where movement smoothness and speed variability quantify task proficiency and control fluency . By combining temporal and rotational metrics, a more comprehensive picture of navigational stability emerges. Smoothness reflects the continuity and coherence of motion [10-12], influenced by environmental legibility, spatial memory, and cognitive workload. Variability in speed or abrupt changes in orientation can indicate spatial disorientation, visual obstructions, or poorly integrated layouts—key design concerns in VR-based architectural evaluation [13-17].

Despite the growing use of behavior-based VR evaluations, several research gaps persist motion smoothness is rarely quantified using integrated temporal-rotational metrics; micro-fluctuations in trajectories, often indicative of spatial confusion, are underreported; and open-source, reproducible pipelines for analyzing raw VR telemetry remain scarce. To address these issues, this study poses two research questions: (1) Can a composite smoothness index derived from temporal and yaw variance serve as an indicator of spatial legibility in immersive environments? (2) How do trajectory-based metrics reflect wayfinding challenges and spatial inefficiencies within architectural VR simulations?

This study aims to develop a motion-based analytical framework to evaluate spatial accessibility and wayfinding in immersive virtual environments. By analyzing telemetry data such as trajectories and rotational dynamics, the method identifies spatial bottlenecks and legibility issues. Applied in an ED context, it supports evidence-based design by offering a replicable, data-driven approach to improve navigational efficiency in high-demand clinical settings.

Methodologically, the proposed method was applied on renovated design of ED at Nasr City Hospital to analyze this study's aim , The ED was selected as the focus of analysis due to the critical importance of wayfinding and spatial accessibility in high-stakes clinical environments. Efficient navigation in EDs directly impacts time-to-treatment, patient safety, and operational workflow—particularly under conditions of cognitive stress, urgency, and crowding. In such contexts, spatial disorientation or poor layout legibility can lead to life-threatening delays and workflow breakdowns. Previous studies have highlighted the ED as a spatially and cognitively demanding environment, where users' ability to quickly and intuitively navigate has a direct bearing on care quality and resource efficiency [18-22]. Therefore, the ED presents an ideal setting to assess the proposed trajectory-based method, as it enables the assessment of motion fluency and spatial comprehension under realistic and functionally complex conditions.

The study employs a structured analytical pipeline to process JSON-formatted motion data recorded during VR-based navigation. Data fields include 3D spatial coordinates (X, Y, Z), head orientation (pitch, yaw, roll), and temporal stamps. Using Python, key metrics are computed: total distance via cumulative Euclidean path length; mean speed and speed variability (standard deviation); and a smoothness index, defined as a weighted combination of temporal interval variation and yaw rotational variance. Trajectory maps and cumulative heatmaps are generated to localize spatial bottlenecks and assess interparticipant variation. Visualization and analysis are performed using Pandas, NumPy, and Matplotlib, with all outputs exported in standardized CSV and vector formats to enable reproducibility and further statistical modeling.

This study contributes a novel trajectory-based framework that integrates motion telemetry within immersive virtual environments to advance the understanding of spatial behavior in architectural contexts. By filling methodological gaps in VR-based design evaluation, it offers a quantitative approach to assess spatial legibility and navigational efficiency—supporting the development of more accessible, cognitively ergonomic, and operationally effective built environments.

2. RESEARCH BACKGROUND.

2.1 The Role of Mock-Ups in Healthcare Design

Mock-ups, whether physical or virtual, serve a pivotal function in design refinement and support data-driven decision-making. According to Durham and Kenyon [23] , rapid prototyping alongside physical and virtual mock-ups proves beneficial across various design phases, allowing for the early alignment of operational objectives. Peavey, Zoss and Watkins [24] reinforced this by emphasizing the role of Experiential Simulation Models (ESMs) and Virtual Prototypes in enabling detailed assessments of healthcare environments, streamlining workflows, and reducing pre-construction expenses. In a comparative study, Wingler, Machry [25] evaluated tools such as 2D drawings, 3D visualizations, and VR mock-ups, concluding that VR environments provide notable advantages in representing spatial relationships.

2.2 VR in Healthcare Design

VR mock-ups enable stakeholders to engage with and navigate virtual environments in ways that exceed the capabilities of traditional evaluation methods. Dunston, Arns [26] illustrated how VR simulations of hospital spaces—such as bariatric patient rooms—facilitated early identification of design flaws by allowing users to visualize and interact with elements like furniture and lighting configurations. Kuliga, Thrash [4] observed negligible differences between real and virtual spaces, reinforcing VR's strength in depicting spatial relationships and user-environment interactions. Nonetheless, certain experiential elements—particularly lighting accuracy and color rendering—remain in need of refinement. Joseph, Browning and Jiang [27] emphasized the significance of Immersive Virtual Environments (IVEs) in healthcare design research, noting their utility in replicating real-world settings for spatial evaluation. Utilizing head-mounted displays (HMDs) and high-fidelity software, IVEs support the simulation of real conditions and generate actionable insights for optimizing healthcare layouts. Clearly defined objectives remain critical to ensure systematic and effective design assessments within [28].

2.3 Wayfinding, Spatial Structure and Environmental Features

VR has been employed to assess wayfinding in healthcare settings, with particular attention to stress mitigation and overall user experience. Qi, Lu and Chen [29] demonstrated that design attributes such as window views and distinctive landmarks enhanced navigation and alleviated stress, underscoring the importance of integrating multiple environmental cues. Similarly, Brunec, Nantais [30] revealed that navigating through spatially integrated areas significantly improved cognitive map accuracy, whereas overall spatial coverage, or roaming entropy, showed no effect—emphasizing the influence of environmental configuration and exploratory behavior on spatial cognition.

3. MATERIALS AND METHODS.

3.1 Participants

Six medical doctors from the same hospital participated in the evaluation, representing diverse specialties: two intensivists, two general surgeons, and two internists (Table 1). All participants had prior experience working in multiple EDs and demonstrated familiarity with operational bottlenecks. The cohort included four males and two females, aged between 33 and 35 years (Mean age = 33.7), with 8 to 10 years of clinical experience (Mean = 8.7 years). Doctors were purposefully selected due to their comprehensive involvement in department-wide patient management, ensuring informed and contextually relevant evaluations of spatial workflow.

Although the sample comprised only six participants, all were experienced physicians working in emergency care, with deep familiarity with ED spatial organization and workflows. Their expertise ensured contextually valid navigation behavior without requiring spatial orientation training. the VR simulation generated continuous, high-density motion telemetry data (e.g., position, rotation, speed) with thousands of time-stamped records per participant, Such granularity supports detailed within-subject comparisons, which is a defining characteristic of non-parametric – non-survey - research designs [31]. Previous research has suggested that non-parametric approaches can be appropriate with sample sizes as small as four participants [32]. While no formal inferential test was applied in this study, the analytical logic adheres to non-parametric principles—emphasizing individual trajectory profiles, descriptive metrics, and variability-based scoring without assumptions of data normality. This makes the methodology suitable for exploratory behavioral studies in immersive environments. Given the volume of telemetry and processing demands, expanding the sample size was not feasible within this study's time constraints.

3.2 Hardware and equipment

A high-performance computer was utilized to model and simulate the proposed ED in VR with graphics card NVIDIA RTX 4070, and Intel Processor Core i9-14900HX, with total RAM memory of 96GB Also, Oculus quest 2 headset was used to immerse participants in the proposed ED within the VR simulation. In addition to GoPro Hero 12 Camera for capturing participants during the experiment.

3.3 Case study: ED of Nasr City Hospital

The renovation of the Nasr City Health Insurance Hospital is underway, focusing on both new expansions and a comprehensive refurbishment of its departments, with a particular emphasis on the ED. Previously limited in services, the department has now been expanded to include emergency surgeries, specialized radiology, and independent laboratories, all aimed at improving operational efficiency and reducing response times (Figure 1). The renovation design is following Egyptian Design Standards for Hospitals and Health facilities, Part 3.

3.4 VR Environment Development.

The proposed ED layout was developed within Unreal Engine to construct an immersive and interactive virtual environment replicating real-world clinical conditions. The VR environment integrated three primary components: (1) Sensory Immersion—realism was enhanced through dynamic lighting scenarios (natural and artificial) and ambient audio captured from an operational ED, incorporating medical equipment sounds, staff dialogue, and general activity noise; (2) Avatar Behavior and User Movement—non-player avatars were scripted to reflect typical movement patterns of ED personnel and visitors based on empirical observations, while participants engaged with virtual nursing teams to simulate authentic clinical collaboration; and (3) Interactive Elements—key assets such as doors, trolleys, beds, and curtains were fully operable, and medical equipment was rendered interactive, enabling participants to manipulate tools as they would in a physical environment, thus fostering a realistic and functionally immersive user experience.

VR Simulation Procedure: The VR experiment followed a structured pathway comprising two distinct modules to ensure the collection of credible data (Figure 2). These modules are the Training Module, and the Exploration Module, each designed to address specific objectives in the evaluation process.

3.4.1 Training Module:

In the initial phase, participants were introduced to a generic VR layout to familiarize themselves with VR headsets, controllers, and navigation. They practiced interacting with key assets, such as opening doors, moving objects, and engaging with VR avatars, skills later incorporated into task simulations in the Exploration Module.

TABLE 1, Participant Demographic Profile. (Source: Authors)

Participant	Age (years)	Gender	Specialty	Experience (years)
P1	35	Male	Internist	10
P2	34	Male	General Surgeon	9
P3	33	Female	Intensivist	8
P4	34	Male	Internist	9
P5	33	Female	Intensivist	8
P6	33	Male	General Surgeon	8

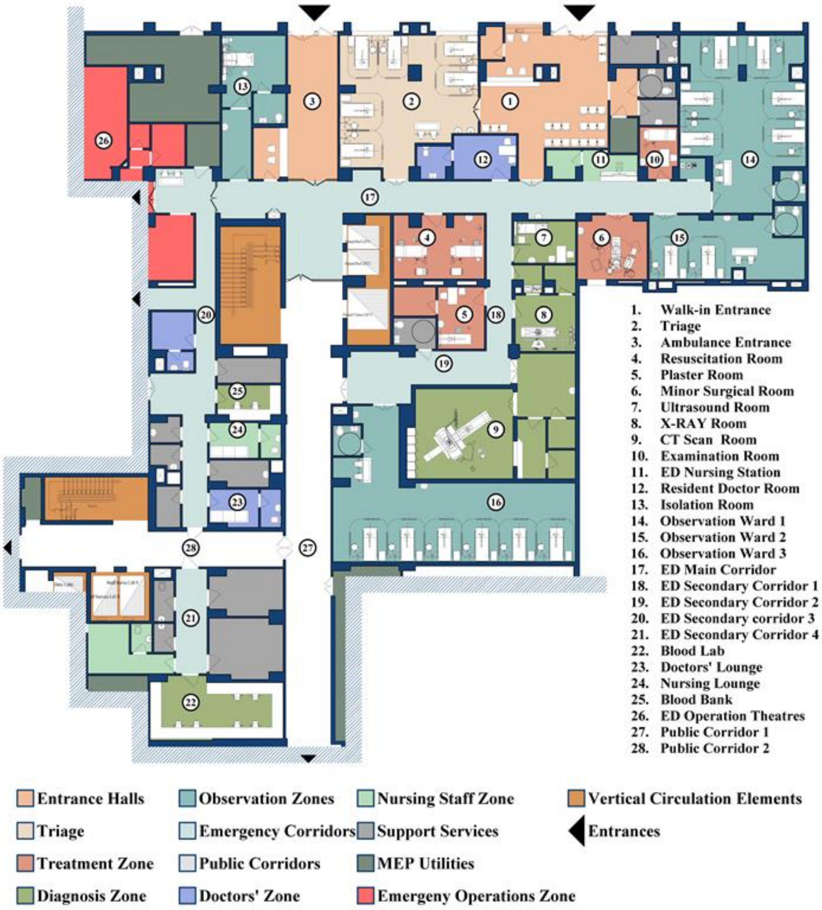

FIGURE 1, Emergency Department (ED) proposed design and its functional zones. (Source: Authors)

FIGURE 2, Participants engagement in the VR simulation. (Source: Authors)

FIGURE 3, snapshots of UI pop-up Instructions that guide participants exploring the emergency department (ED) in VR. (Source: Authors)

The Training Module's primary aim was to ensure participants were comfortable and proficient in manipulating the VR environment, reducing learning curves and improving the reliability of their navigations.

3.4.2 Exploration Module

Participants were first introduced to the ED layout via 2D blueprints to familiarize them with spatial zones and functions. They then navigated the layout in VR, following exploration patterns derived from diverse types of spaces along the whole layout (Figure 4).

FIGURE 4, Doctors' Guided Exploration map, representing probable navigational pathways. (Source: Authors)

Pop-up instructions guided systematic exploration across zones of ED as shown at Figure 3. Participant-specific exploration patterns (Figure 4) specific goal; locating efficient routes to different critical spaces (e.g., resuscitation room - blood lab).

3.5 Data Analysis

This study developed a Python-based analytical pipeline for processing JSON-formatted motion data collected from VR simulations. This data included spatial coordinates, orientation (pitch, yaw, roll), and timestamps. Key metrics were computed, including total distance, average speed, standard deviation of speed, and a composite smoothness index based on yaw and time variability. Trajectories were visualized to detect spatial clusters of navigational difficulty, and comparative analyses were performed across participants to interpret individual differences in movement behavior as indicators of environmental legibility.

The extracted JSON data captures participants' motion trajectories within a 3D virtual environment, including spatial coordinates (X, Y, Z), rotational orientation, pitch, yaw, and roll are rotational movements around the x-axis (up/down tilt), z-axis (left/right turn), and y-axis (side-to-side tilt) that define an object's orientation in 3D space, and timestamps. The analysis process involved data cleaning to remove irrelevant entries, followed by calculating key navigation metrics such as total distance traveled (via Euclidean distance), average speed, and speed variability (standard deviation). Smoothness was evaluated through time variability (consistency in time intervals) and rotational variability (Yaw variance), which were combined into an overall normalized weighted smoothness index (NWSI), reflecting the abruptness of motion. Trajectories were visualized with equal axis scaling for comparative analysis. Python was utilized for analysis, employing Pandas for data structuring, NumPy for numerical calculations, and Matplotlib for trajectory visualization. Custom functions calculated navigation metrics and smoothness scores, with results exported in CSV and vector formats for further interpretation. This workflow provided a detailed assessment of navigation behaviors in the virtual environment.

3.6 Experiment Constants and Variables.

While the aim of this study is to evaluate perceived wayfinding and accessibility within the proposed ED design and ensuring uniformity in evaluating navigational behavior, several environmental constants were applied across all simulations: (1) No signage or directional cues were present in the VR environment; (2) Participants received identical pre-navigation briefings and 2D layouts; (3) Lighting and ambient conditions were held constant throughout the experiment. These controls were implemented to isolate spatial configuration as the primary influence on wayfinding behavior.

In this study, several motion-based variables were extracted from VR trajectory data to quantify participants' spatial behavior and cognitive engagement.

(1) Total distance (m), computed as the cumulative Euclidean displacement, reflects the extent of spatial exploration and coverage within the environment [33]. (2) Total time (s), measured from the first to the last time-stamped sample, captures the duration of user engagement, with longer times often indicating elevated decision load or environmental complexity [34, 35]. (3) Average speed (m/s), defined as total distance divided by total time, serves as a proxy for navigational fluency, where lower values may reveal cautious or hesitant movement [36]. (4) To account for pacing irregularity, speed variability was measured via standard deviation of instantaneous speeds, which is known to reflect stop-start behavior or spatial uncertainty [37]. Additionally, maximum and minimum speeds provide

bounds on the range of user mobility, identifying bursts of confident motion or near-static moments, respectively [38]. (5) Head orientation dynamics were captured through yaw delta and its variability, which reflect rotational shifts in visual attention and are strongly linked to search and scanning behavior in virtual environments [39]. (6) Finally, a normalized weighted smoothness index was introduced to quantify overall navigational consistency by integrating both speed and yaw variability; higher values of this composite score denote erratic or fragmented movement trajectories, often indicative of environmental legibility issues or design-induced disorientation [40], the weighting coefficients W1 and W2 were treated equally (i.e., W1 = W2 = 0.5) due to the criticality of both temporal pacing and rotational fluency in ED operations. For high-stakes clinical environments like EDs, delays (temporal disfluency) and misdirection (rotational disorientation) carry comparable operational risks—justifying their equal contribution to overall smoothness scoring. In other settings, this weighting can be recalibrated according to the relative importance of speed vs. directional accuracy.

These variables collectively serve as behavioral indicators of spatial efficiency, cognitive load, and design performance in immersive architectural simulations. Table 2 demonstrates mathematical formulas to calculate study variables.

TABLE 2, Navigation metrics mathematical formulas.

Navigation Metrics Mathematics	
Total Distance: The cumulative Euclidean distance traveled by a participant during navigation in a 3D space [33].	
$D = \sum_{i=1}^{n-1} \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2 + (z_{i+1}-z_i)^2}$	*i*: Index of a position in the sequence, ranging from 1 to *n*-1. *n*: Total number of recorded positions.
Average Speed: The mean rate of movement over the total navigation time [34-36].	
$Average\ Speed = \frac{Total\ Distance}{Total\ Time}$ $Total\ Time = \sum_{i=1}^{n-1} (Timestamp_{i+1} - Timestamp_i)$	*i*: Index of a timestamp in the sequence, ranging from 1 to *n*-1. *n*: Total number of recorded timestamps.
Speed Variability (Standard Deviation): A measure of variability in speed, indicating consistency in movement [37, 38].	
$\sigma_{speed} = \sqrt{\frac{1}{n}\sum_{i=1} \left(Speed_i - \overline{Speed}\right)^2}$ $Speed_i = \frac{Distance_i}{Time\ Interval_i} = \frac{\Delta d_i}{\Delta t_i}$ $\Delta d_i = \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2 + (z_{i+1}-z_i)^2}$ $\Delta t_i = Timestamp_{i+1} - Timestamp_i$	$\overline{\text{Speed}}$: Average Speed *i*: Index of speed values, ranging from 1 to *n*-1. *n*: Total number of positions.
Normalized Weighted Smoothness Index (NWSI) for Path Smoothness: A metric assessing abruptness in navigation, derived from integrating the **variability in time intervals between positions** and **the variance of rotational changes** (angular jerk proxy) [39]. This hybrid approach provides a more comprehensive assessment of smoothness [40].	
The combined smoothness *NWSI* can be defined as: $NWSI = w1 \cdot S_{t.norm} + w2 \cdot S_{r.norm}$ $S_{t.norm} = \frac{1}{n-2}\sum_{i=1}^{n-2} \lvert \Delta t_{i+1} - \Delta t_i \rvert$ $S_{r.norm} = \frac{1}{n-1}\sum_{i=1}^{n-1} (R_{i+1} - R_i)^2$	w_1, w_2: Weights to balance the contribution of S_t and S_r (e.g., equal weights for EDs). *i*: Index of time intervals, ranging from 1 to n-2. *n*: Total number of recorded timestamps. R_i: represents the angular rotation (e.g., yaw) at step *i*.

4. RESULTS

4.1 Traced Trajectories for 6 participants.

Recorded trajectories for 6 participants were recorded and further analyzed for motion smoothness interpretation, Figure 5 illustrating these trajectories in exploration module session and according to pre-defined targets.

4.2 Motion Dynamics Results

Based on the results (Table 3), Participant 1 traveled the greatest distance (61.64 m) over 19.94 minutes with a moderate average speed (0.05 m/s) and a normalized speed variability of 0.87, coupled with a yaw delta standard deviation of 20.35°/s. Despite consistent linear movement, their normalized weighted smoothness index (0.86) suggests moderate rotational instability. Participant 2 demonstrated the slowest yet most deliberate movement, covering 35.02 m in 18.03 minutes with the lowest average speed (0.03 m/s) and lowest smoothness index (0.67), reflecting steady, controlled navigation. Participant 3, traveling 56.52 m over 19.98 minutes, showed moderate variability (speed SD = 0.06 m/s; yaw delta = 16.71°/s) and a smoothness index of 0.78, suggesting balanced but cautious movement. Participant 4, with the shortest duration (10.19 min), exhibited high normalized speed variability (0.93) and yaw instability (19.64°/s), though their smoothness index remained relatively high (0.88). Participant 5 recorded the highest average speed (0.07 m/s) and yaw delta (23.78°/s), aligning with the highest smoothness score (0.96), reflecting confident but dynamic navigation. Participant 6, covering 47.24 m in 13.04 minutes, exhibited the highest normalized speed variability (1.00) and maintained a high smoothness index (0.94), suggesting efficient yet fluctuating control.

FIGURE 5, Overlayed trajectories for 6 participants. (Source: Authors)

TABLE 3, Navigation metrics results for all participants. (Source: Authors)

Participant	Total Distance (m)	Total Time (min)	Average Speed (m/s)	Speed Std Dev (m/s)	Normalized Speed Std Dev	Yaw Std Dev (Â°)	Yaw Delta Std Dev (Â°/s)	Normalized Yaw Delta	Normalized Weighted Smoothness Index
P1	61.64	19.94	0.05	0.07	0.87	88.82	20.35	0.86	0.86
P2	35.02	18.03	0.03	0.06	0.73	99.15	14.77	0.62	0.67
P3	56.52	19.98	0.05	0.06	0.85	106.75	16.71	0.70	0.78
P4	39.16	10.19	0.06	0.07	0.93	102.72	19.64	0.83	0.88
P5	43.77	11.07	0.07	0.07	0.92	119.86	23.78	1.00	0.96
P6	47.24	13.04	0.06	0.08	1.00	108.14	20.78	0.87	0.94

Overall, Participants 2 and 3 demonstrated the most stable movement profiles, whereas Participants 5 and 6 combined higher speeds with increased rotational adjustments, indicating proactive spatial exploration.

5. DISCUSSION

5.1 Implications for Proposed ED Design

Motion smoothness, speed stability, and path visualization collectively offered a diagnostic lens to identify design flaws and inform layout revisions. These findings have several implications for both architectural design and virtual simulation methodologies. First, spatial environments that elicit low speed variability and consistent yaw movement—such as those navigated by Participants 2 and 3—suggest configurations with intuitive flow and clear spatial cues. Such spaces likely reduce cognitive load and support efficient wayfinding. Conversely, environments that correlate with abrupt movement shifts or yaw instability—such as those experienced by Participants 5 and 6—may benefit from clearer visual anchors, wider visibility fields, or simplified layout intersections. This trajectory-derived insight provides actionable data for improving legibility in early design stages. Furthermore, the ability to detect these issues pre-construction underscores the potential of VR-based diagnostics as an integral component of user-centered spatial planning.

By analyzing and mapping the passage frequency and duration of time spent at various locations using motion trajectory data from the six participants, a distinct spatial bottleneck was identified. As shown in Figure 6, the intersection points between the main ED corridor and the corridor leading to the support service areas consistently recorded the highest frequency of participant passages. In addition, this location exhibited the longest cumulative time spent among all participants, indicating not only repeated traversal but also moments of hesitation or delay. These findings strongly suggest that the transition zone at this corner imposes a cognitive and visual burden on users, likely due to suboptimal visibility or poor spatial cues.

The difficulty in clearly identifying the entrance to the supporting corridor may result in disorientation, decreased wayfinding efficiency, and potential workflow interruptions, especially critical in high-stress, time-sensitive environments such as EDs. Therefore, this zone merits design reconsideration to enhance visual connectivity and orientation support.

5.2 Telemetric data, motion and headtracking.

During participants’ exploration of the proposed design in VR, the "Game Telemetry and Heatmap Recorder" plugin was employed to capture events such as movement paths and head-tracking orientations for every participant, which were visualized through heat maps (Figure 7 shows recorded traced movements as an example). These heat maps provide insights into the spatial proximity achieved between spaces of high-cruciality levels while highlighting the crowdedness of corridors connecting them, highlighted in magenta on Figure 7, suggesting the need for wider corridors to accommodate traffic effectively.

The heatmaps also reveal the segregation of the blood lab and doctors’ restroom. The left corridor, highlighted in red on Figure 6, which connects these spaces internally within the ED, was rarely utilized or not easily located by participants. Instead, the majority preferred using the public corridor outside the ED to access these segregated areas. This observation indicates that wider corridors not only enhance visibility but also improve wayfinding behavior, underscoring their importance in optimizing spatial navigation and operational efficiency.

FIGURE 6, Map showing cumulative motion frequency of all participants, (a) resembles passage frequency, (b) Time spent, where higher values resemble hesitation and losing navigation clues, while lower values resemble intuitive and confident navigation. (Source: Authors)

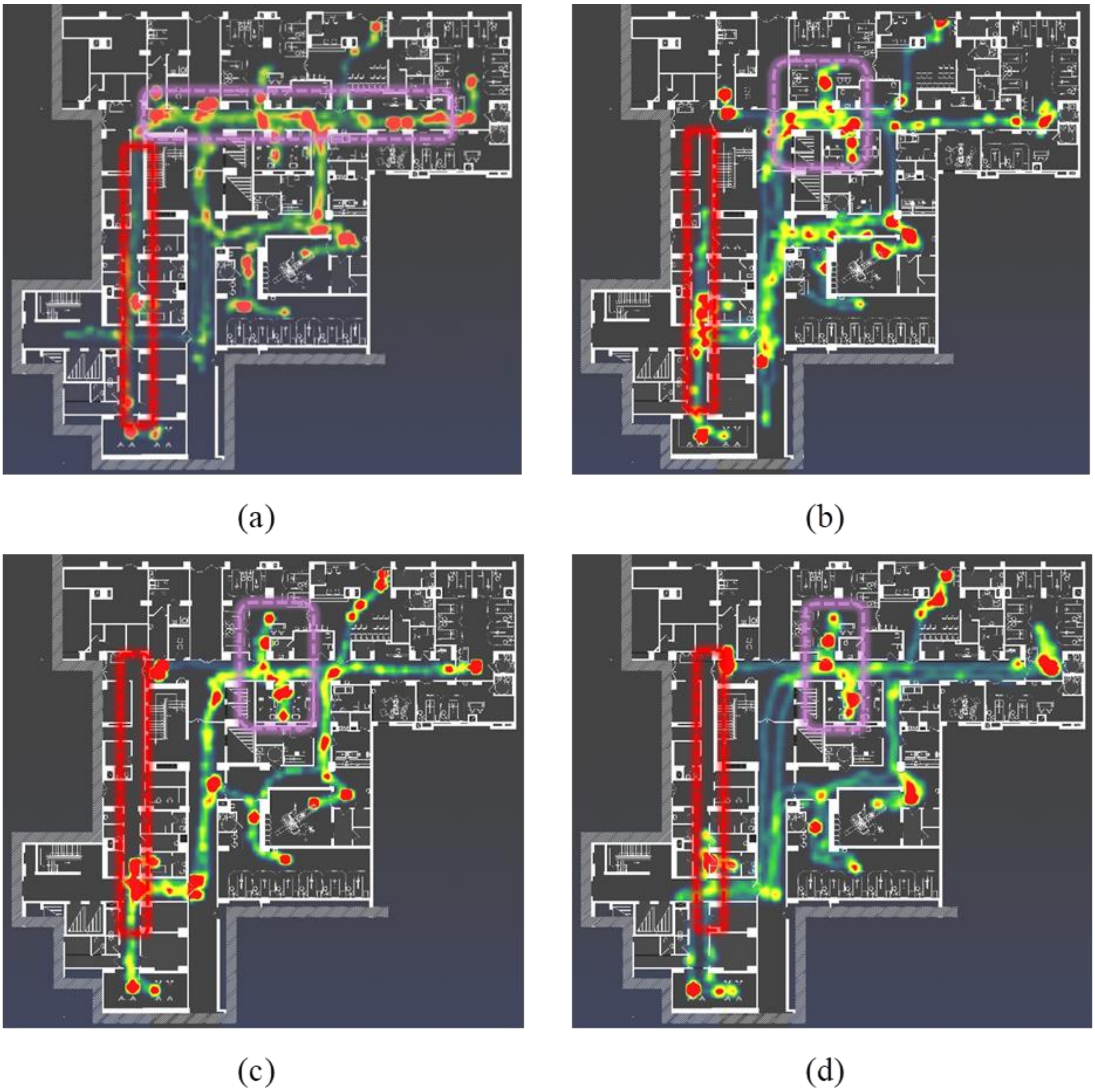

FIGURE 7, Participants traced movements in VR by employing "Game Telemetry and Heatmap Recorder" plugin, which were visualized through heatmaps. (Source: Authors)

5.3 Research Limitations

Despite its contributions, this study presents several limitations that guide future research. First, while kinematic metrics revealed behavioral symptoms of spatial confusion, the analysis did not incorporate configurational variables such as spatial integration or connectivity. Including such syntactic parameters would support a more comprehensive understanding of legibility. Second, the absence of structured user feedback limited interpretation of perceived navigational cues, making the analysis purely behavior-based. Additionally, the large volume of motion telemetry per participant required substantial processing time, constraining the feasible sample size. Similarly, VR modeling and programming demands limited the number of design alternatives evaluated. This study therefore focused on identifying behavioral navigation patterns and spatial bottlenecks using NWSI, to be addressed in future re-design iterations. Comparable constraints were noted in similar VR studies, such as Okuyucu and Yazici [41], which analyzed only one design scenario with three participants due to similar data and modeling complexities.

6. CONCLUSION

This study presents a trajectory-based method for evaluating spatial accessibility and wayfinding efficiency within virtual environments, offering a novel, motion-centric diagnostic lens for architectural simulation. By extracting and analyzing temporal and rotational telemetry from VR navigation sessions, the study quantifies navigational fluency through metrics such as speed variability and composite smoothness scores. These metrics effectively distinguished between intuitive and hindered navigation patterns and enabled the localization of spatial bottlenecks within the virtual layout.

The findings validate motion smoothness and speed stability as proxies for spatial legibility and cognitive load, reinforcing their utility in evaluating design performance beyond traditional spatial metrics. The observed behavioral divergences—such as the avoidance of internal corridors or detours to peripheral zones—underscore the importance of aligning spatial configuration with visual connectivity and perceptual cues.

This work contributes a replicable analytical pipeline for trajectory analysis using accessible computational tools and offers a scalable framework applicable across diverse design typologies, including hospitals, urban districts, and transportation hubs. By embedding quantitative motion analytics into the design evaluation process, the proposed method enhances evidence-based decision-making in VR-supported architectural workflows.

7. RECOMMENDATIONS

To strengthen the findings of this study, future research should integrate configurational spatial metrics—such as integration and connectivity—to enable a more holistic evaluation of environmental legibility through the triangulation of spatial properties and navigational behavior. Additionally, incorporating structured user feedback regarding navigational cues and perceived affordances would complement motion-based metrics with subjective insights. Expanding the sample size is also recommended, made feasible through automation of data processing pipelines to accommodate larger datasets. Furthermore, future studies should explore multiple design alternatives and iterative simulations by optimizing VR modeling workflows, enabling broader testing of spatial layouts and their effects on user behavior. These steps will enhance the scalability, generalizability, and applicability of the proposed framework in diverse architectural settings.

REFERENCES

[1] Azarby, S. and A. Rice, Understanding the Effects of Virtual Reality System Usage on Spatial Perception: The Potential Impacts of Immersive Virtual Reality on Spatial Design Decisions. Sustainability, 2022. null: p. null.

[2] Azarby, S. and A. Rice, User Performance in Virtual Reality Environments: The Capability of Immersive Virtual Reality Systems in Enhancing User Spatial Awareness an d Producing Consistent Design Results. Sustainability, 2022. 14(21): p. 14129.

[3] Kuliga, S., et al., Developing a Replication of a Wayfinding Study. From a Large-Scale Real Building to a Virtual Reality Simulation. 2020.

[4] Kuliga, S., et al., Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model. Comput. Environ. Urban Syst., 2015. 54: p. 363-375.

[5] Li, J., et al., Building environment information and human perceptual feedback collected through a combined virtual reality (VR) and electroencephalogram (EEG) method. Energy and Buildings, 2020. 224: p. 110259.

[6] Feng, Y., D.C. Duives, and S.P. Hoogendoorn, Wayfinding behaviour in a multi-level building: A comparative study of HMD VR and Desktop VR. Advanced Engineering Informatics, 2022. 51: p. 101475.

[7] Kondyli, V. and M. Bhatt, Rotational locomotion in large-scale environments: A survey and implications for evidence-based design practice. Built Environment, 2018. 44(2): p. 241-258.

[8] Paes, D. and J. Irizarry. The relevance of visual cues in immersive environments: Does pictorial realism matter? in ASCE International Conference on Computing in Civil Engineering 2019. 2019. American Society of Civil Engineers Reston, VA.

[9] Teipel, S.J., et al., Prediction of disorientation by accelerometric and gait features in young and older adults navigating in a virtually enriched environment. Frontiers in Psychology, 2022. 13: p. 882446.

[10] Liu, H., X. Lai, and W. Wu, Time-optimal and jerk-continuous trajectory planning for robot manipulators with kinematic constraints. Robotics and Computer-Integrated Manufacturing, 2013. 29(2): p. 309-317.

[11] Singh, S., et al., Motion smoothness metrics for cannulation skill assessment: What factors matter? Frontiers in Robotics and AI, 2021. 8: p. 625003.

[12] Hogan, N. and D. Sternad, Sensitivity of smoothness measures to movement duration, amplitude, and arrests. Journal of motor behavior, 2009. 41(6): p. 529-534.

[13] Joseph, A., M.H. Browning, and S. Jiang, Using immersive virtual environments (IVEs) to conduct environmental design research: A primer and decision framework. HERD: Health Environments Research & Design Journal, 2020. 13(3): p. 11-25.

[14] Kalantari, S., et al., Evaluating the impacts of color, graphics, and architectural features on wayfinding in healthcare settings using EEG data and virtual response testing. Journal of Environmental Psychology, 2022. 79: p. 101744.

[15] Kalantari, S., et al., Comparing Spatial Navigation and Human Environment Interaction in Virtual Reality vs. Identical Real Environments across the Adult Lifespan. arXiv preprint arXiv:2308.15774, 2023.

[16] Memikoğlu, İ. and H. Demirkan, Exploring staircases as architectural cues in virtual vertical navigation. International Journal of Human-Computer Studies, 2020. 138: p. 102397.

[17] Chrastil, E.R. and W.H. Warren, Active and passive spatial learning in human navigation: acquisition of survey knowledge. Journal of experimental psychology: learning, memory, and cognition, 2013. 39(5): p. 1520.

[18] Abdelsamad, Y., M.A. Rushdi, and B. Tawfik, Functional and Spatial Design of Emergency Departments Using Quality Function Deployment. Hindawi Publishing Corporation, 2018. 2018: p. 1-7.

[19] El-Hadedy, N. and M. El-Husseiny, Evidence-Based Design for Workplace Violence Prevention in Emergency Departments Utilizing CPTED and Space Syntax Analyses. Herd, 2022. 15(1): p. 333-352.

[20] Haj-Saleh, O. and Ç. Çağnan, A Comparative Analysis of the Spatial Design Perspective of Wayfinding: The Emergency Room as a Case Study. Buildings, 2025. 15(4): p. 516.

[21] Yuan, H. and Y. Zhou, The impact of crowds on visibility in emergency department: Integrating agent-based simulation and space syntax analysis. Frontiers of Architectural Research, 2025.

[22] Zamani, Z., Effects of Emergency Department Physical Design Elements on Security, Wayfinding, Visibility, Privacy, and Efficiency and Its Implications on Staff Satisfaction and Performance. HERD, 2019. 12(3): p. 72-88.

[23] Durham, J. and A. Kenyon, Mock-Ups: Using Experiential Simulation Models in the Healthcare Design Process. HERD, 2019. 12(2): p. 11-20.

[24] Peavey, E.K., J. Zoss, and N. Watkins, Simulation and Mock-Up Research Methods to Enhance Design Decision Making. HERD: Health Environments Research & Design Journal, 2012. 5(3): p. 133-144.

[25] Wingler, D., et al., Comparing the Effectiveness of Four Different Design Media in Communicating Desired Performance Outcomes With Clinical End Users. SAGE Publishing, 2018. 12(2): p. 87-99.

[26] Dunston, P.S., et al. An Immersive Virtual Reality Mock-Up for Design Review of Hospital Patient Rooms. in Collaborative Design in Virtual Environments. 2011.

[27] Joseph, A., M. Browning, and S. Jiang, Using Immersive Virtual Environments (IVEs) to Conduct Environmental Design Research: A Primer and Decision Framework. HERD, 2020. 13(3): p. 11-25.

[28] Xin, Y., et al., Enhancing healthcare environment design evaluations through an interactive virtual reality-based approach: A design science research. Developments in the Built Environment, 2024. 18.

[29] Qi, F., Z. Lu, and Y. Chen, Investigating the Influences of Healthcare Facility Features on Wayfinding Performance and Associated Stress Using Virtual Reality. HERD: Health Environments Research & Design Journal, 2022. 15(4): p. 131-151.

[30] Brunec, I.K., et al., Exploration patterns shape cognitive map learning. Cognition, 2023. 233: p. 105360.

[31] Elsayed, M., et al., Exploring the restorative environments in Bratislava using EEG and VR: a neuro-urbanism approach. Archnet-IJAR: International Journal of Architectural Research, 2024.

[32] Hu, M. and J. Roberts, Built environment evaluation in virtual reality environments—a cognitive neuroscience approach. Urban Science, 2020. 4(4): p. 48.

[33] Slater, M. and M. Usoh, Representations systems, perceptual position, and presence in immersive virtual environments. Presence: Teleoperators & Virtual Environments, 1993. 2(3): p. 221-233.

[34] Anton, D., G. Kurillo, and R. Bajcsy, User experience and interaction performance in 2D/3D telecollaboration. Future Generation Computer Systems, 2018. 82: p. 77-88.

[35] Bowman, D.A., et al., An introduction to 3-D user interface design. Presence, 2001. 10(1): p. 96-108.

[36] Wiener, J.M., S.J. Büchner, and C. Hölscher, Taxonomy of human wayfinding tasks: A knowledge-based approach. Spatial Cognition & Computation, 2009. 9(2): p. 152-165.

[37] Darken, R.P. and J.L. Sibert. Wayfinding strategies and behaviors in large virtual worlds. in Proceedings of the SIGCHI conference on Human factors in computing systems. 1996.

[38] Renner, R.S., B.M. Velichkovsky, and J.R. Helmert, The perception of egocentric distances in virtual environments-a review. ACM Computing Surveys (CSUR), 2013. 46(2): p. 1-40.

[39] Yang, U. and G.J. Kim, Implementation and evaluation of "just follow me": An immersive, VR-based, motion-training system. Presence, 2002. 11(3): p. 304-323.

[40] Kuliga, S.F., R. Dalton, and C. Hölscher, Aesthetic and Emotional Appraisal of the Seattle Public Library and its relation to spatial configuration. 2013.

[41] Okuyucu, B. and S. Yazici, A Comparative Study driven by Spatial Performance and VR toward Wayfinding in Architectural Space: Healthcare Buildings as a Case Study. ESTOA, 2024. 13(26): p. 79-94.