

Mapping Indoor Travel Patterns with Virtual Reality and Vision Transformer

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Abstract. *Aesthetically appealing buildings may incur substantial costs for underused spaces. Yet existing research either focuses on post-construction data when meaningful changes are impractical or relies on Space Syntax and agent-based predictions that often simplify the human experiences. We present a pre-construction assessment that combines Virtual Reality (VR) and Vision Transformer (ViT) to examine human navigation and perception of interior layouts. We collected egocentric views from participants traversing different virtual interiors and processed those into spatial and behavioral information. In a pilot study of 102 participants in a virtual office, we trained the base VR-ViT model, and achieved 93% accuracy. Results indicated that adjacency didn't guarantee usability: participants often entered one nearby room while missing another, spent most time at reception and staff break areas, and rarely engaged with collaboration and support spaces. We also discussed a follow-up study with 65 participants in a larger virtual art studio. While usability improved, particularly in key spaces like therapeutic and communal zones, adjacent restrooms and service zones were still skipped. Together, these findings validate that our approach can identify circulation problems and underused spaces pre-construction.*

Keywords. *Virtual Reality, Vision Transformer, Pre-Construction Evaluation, Navigation, Interior Design.*

INTRODUCTION

Aesthetically appealing yet functionally deficient buildings result in underused spaces and substantial maintenance costs (Ahmady et al., 2023). This problem is evident across public and private buildings, where low spatial usability continue to generate major financial losses (GAO, 2023). However, understanding how people actually move through and engage with interior space remains a critical research gap (Jamshidi & Pati, 2023).

Travel patterns reflect more than movement alone; they further indicate familiarity, engagement, and more importantly, navigational strategy (Sarihati et al., 2021). Prior studies show that users traverse spaces differently with age, interest, memory, and environmental cues (Mandel, 2018; Shapiro et al., 2017). Yet existing research on human-spatial interaction mainly depends on post-construction data, when opportunities for meaningful design changes are already limited (Li et al., 2018).

To address this critical gap, we propose a pre-construction assessment that combines Virtual Reality (VR) and Vision Transformer (ViT). First, VR enables immersive interior simulations, supporting early evaluation of user experience and spatial usability (Tseng & Do, 2022). Second, ViT enables the classification of egocentric visual data into precise spatial locations by learning relationships across image patches (Jelassi et al., 2022).

In this paper, we evaluate the accuracy and interpretability of a base VR-ViT model through two consecutive studies: a pilot study of 102 participants in a 3,000 ft² ($\approx$ 279 m²) virtual office and a follow-up study of 65 participants in a 5,000 ft² ($\approx$ 465 m²) virtual art studio. We discuss the implications of these results for pre-construction spatial analysis and argue that this approach offers both methodological innovation and practical value for assessing spatial usability before construction begins.

SPACE SYNTAX AND AGENT-BASED MODELING IN ASSESSING TRAVEL PATTERNS

Space Syntax, which links spatial configuration to human movement and usability of interiors and cities, remains a foundational framework for evaluating travel patterns in built environments (Karimi, 2018). As Space Syntax is fundamentally space-configuration-driven, this framework is not accountable for social and individual differences that shape behavior beyond spatial structure. This limitation led to complementary approaches like agent-based modeling (ABM) in Computer-Aided Design (CAD) simulations (Sousa et al., 2017).

Further efficient-space-planning computational approaches are graph-theoretic layout generation, multi-objective optimization, Building Information Modeling (BIM) simulations, and data-driven tools which match user preferences to design criteria (Gurcan Bahadır & Tong, 2026). Agent-based approaches are particularly useful because each agent can represent a user with specific goals, perceptual capacities, and decision rules within

game engines such as Unity3D and Unreal Engine (UE). Unlike Space Syntax configurative nature, these agents can even make dynamic, context-dependent decisions in response to built environments.

For instance, Park et al. (2018) integrated BIM, Fire Dynamics Simulator (FDS), and UE to assess emergency behavior among 100 agents, revealing egress flaws not visible in two-dimensional (2D) plans. Schaumann et al. (2019) also used Multi-Agent Systems (MAS) with BIM in Unity3D to simulate healthcare behaviors among 150 agents, showing trade-offs between patient travel distance and nurse fatigue across layout options.

Neumayr (2021), despite not examining travel patterns, used NetLogo to model 24 agents with distinct social roles and behavioral rules across different office table configurations, finding that randomized layouts better supported collaboration and interaction. Cocho-Bermejo (2025) likewise used NetLogo to simulate 19 agents with exploratory behaviors, producing travel patterns closely aligned with real-world navigation in the Tate Britain Museum, suggesting that agent-based simulations can achieve accuracy comparable to Space Syntax.

VIRTUAL REALITY AND VISION TRANSFORMER IN ASSESSING TRAVEL PATTERNS

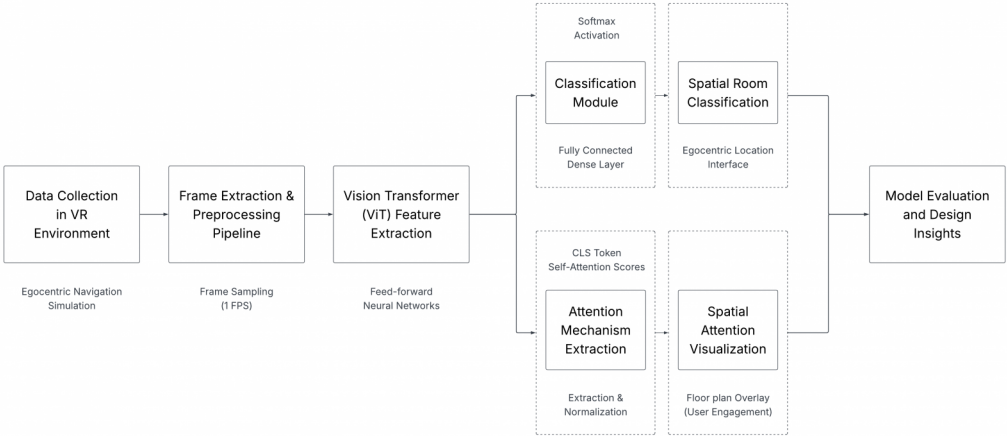
Agent-based approaches can extend analysis beyond 2D plans and help bridge the gap between static simulations and complex real-world travel patterns. Yet these agents still depend on behavioral rules, scenario assumptions, and calibration choices, constraints that become critical as social interactions and spatial configurations grow more complex (Neumayr, 2021). Our approach is more comprehensive by observing real human behavior in VR and analyzing it through ViT.

VR can capture navigational decisions and circulation paths through egocentric views, while ViT can interpret relationships across these visual fields (Tseng & Do, 2022; Jelassi et al., 2022). Together, the technologies support pre-construction

evaluation of indoor travel patterns by moving beyond simulated predictability toward empirically grounded observation within a controlled context.

Our pipeline (Figure 1) began by fine-tuning google/vit-base-patch16-224, a Vision Transformer with 12 transformer layers, 12 attention heads, 16×16 image patches, 224×224 input resolution, and approximately 85 million parameters. We then applied the model to egocentric frames recorded as participants moved through virtual interiors. The environments were developed in Twinmotion VR and experienced through a Meta Quest 3 headset tethered to a Dell XPS workstation with an NVIDIA RTX 4090 graphics processing unit (GPU). Participants navigated using controller-based six-degree-of-freedom (6DoF) teleportation.

Figure 1
Our workflow,
integrating ViT and
VR, for indoor travel
patterns



We segmented the egocentric recordings at 1 frame per second (FPS), resized, normalized them into approximately 109,044 frames, and evaluated frame-level error on held-out test frames using an 80/10/10 train-validation-test split with a fixed seed of 42. Occasional Meta Quest 3 tracking-loss events lasted about 1-3 seconds, corresponding to 1-3 sampled frames at 1 FPS, and could reduce class-specific precision and

recall. The tethered RTX 4090 setup reduced observable latency, but headset display limits and frame resizing mean that results are best interpreted at the aggregate travel-pattern level.

METHODOLOGY

We conducted two IRB-approved studies (#22352, #28096) in two virtual interiors: an office with 102 participants and an art studio with 65 participants. Across 30.29 hours of recordings, we reconstructed 165 travel patterns by classifying frames into spatial zones and aggregating the predictions into frequency logs and heat maps. Travel patterns were defined as zone-level visitation and dwell distributions rather than continuous walking trajectories. Path

efficacy was approximated by whether participants reached high-importance zones or missed adjacent rooms; hesitation by repeated or lingering frames at doorways and transition areas; and engagement by time spent in each location.

Participants were recruited via convenience sampling from college students at Indiana University Bloomington (IUB) in the United States. Consenting participants completed a 10-minute training session

on using the Meta Quest 3 headset and controllers, then explored the virtual interiors for about 30 minutes while self-recording their egocentric views using the headset's built-in function. Each session was about 1 hour with a compensation of \$15 in the pilot or a \$25 in the follow-up as it involved additional measures.

Pilot Study

Participants (n = 102) were mostly 18 to 34 years old at 94%, with 50% male, 49% female, and 1% non-binary. All were fluent in English with bilingual participants also spoken Asian and Pacific Island languages (39%) or Spanish (5.8%). About half of the sample had no prior exposure to VR (50%), about one fourth had minimal experience (26%), and several had some experiences (17.6%).

The 3,000 ft² (≈ 279 m²) office space (Figure 2) was designed by an interior design student at IUB for a hypothetical client (i.e., Gaudium), featuring an open layout to foster a collaborative workplace culture. The design has 16 zones: (1) vestibule, (2) enclosed office space, (3) open office space, (4) short-term workspace, (5) closed conference room, (6) private break away, (7) open

collaboration, (8) reception, (9) self-care space, (10) toilet, (11) staff break, (12) communication closet, (13) media area, (14) mechanical equipment, (15) file storage, and (16) janitor closet.

Decision on adjacency and openness centered around the three clusters: quiet, varied, and loud spaces, with collaborative areas positioned near semi-private spaces to support fluid movement and balance interaction with privacy. To create a calm and flexible environment, the design employed: (i) natural materials to promote warmth and conversation (i.e., maple wood); (ii) glazed partitions to enhance daylight and visual openness; (iii) varied seatings to support comfort and choice; and (iv) ceiling accents for focal points and wayfinding cues.

Follow-up Study

Participants (n = 65) were mostly 18 to 34 years old at 92%, with 51% male and 49% female. All were fluent in English with bilingual participants also spoken Asian and Pacific Island languages (38%) or a mix of different languages (20%). About half of the sample had no prior exposure to VR (49%) and about one fourth had some (24%) or minimal experience (22%).

The 5,000 ft² (≈ 465 m²) art studio (Figure

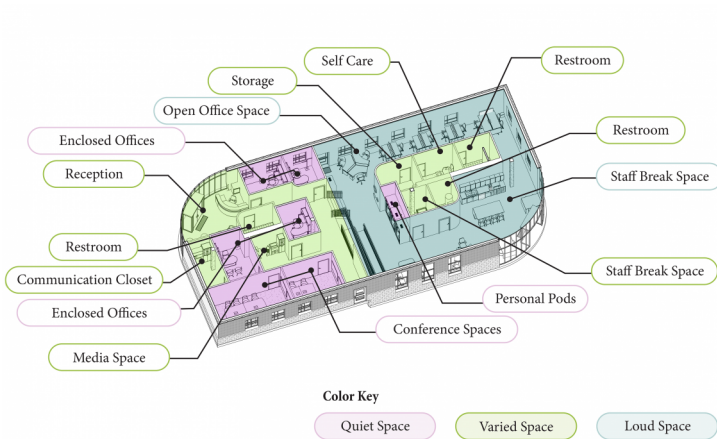
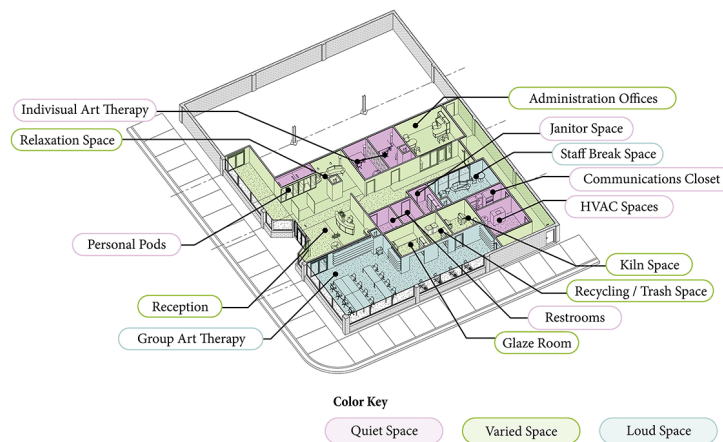


Figure 2
Gaudium office simulation, designed by Liliana Gonzalez Chavez, enhanced in VR by Caroline Alleva, axonometric by Carolyn Calbeck

3) was designed by another interior design student for a hypothetical client (i.e., Warriors, a philanthropy dedicated to mental well-being for veterans), featuring a calming and inclusive therapeutic art environment. The design has 14 zones: (1) reception, (2) restrooms, (3) individual art therapy, (4) group art therapy, (5) klin room, (6) recycling/Trash room, (7) glaze room, (8) relaxation space, (9) personal pods, (10) communication closet, (11) administration office, (12) staff break area, (13) janitor closet, and (14) heating, ventilation, and air conditioning (HVAC).

Figure 3
Warriors art studio simulation, designed by Kayla Perdue, enhanced in VR by Ceolrine Alleva, axonometric by Carolyn Calbeck



Decision on adjacency and openness centered around the three clusters: quiet, varied, and loud spaces, with a deliberate buffer that separates open, high-traffic areas from more private spaces via circulation paths and transitional zones to better support users with post-traumatic stress disorder (PTSD). To create an inclusive art environment, the design employed: (i) biophilic materials, such as maple wood and woven fabric; (ii) sustainable elements, including upcycled painted wood; and (iii) trauma-informed design features, such as soft lighting and low visual complexity supported by

wall color and flooring transitions for wayfinding.

RESULTS

Pilot: Indoor Travel Patterns in Gaudium

Across 21.8 hours of egocentric recordings, our base VR-ViT model revealed distinct travel patterns in the virtual office. The model also performed binary classification to distinguish doorway views from room interiors, indicating whether participants merely approached a space or entered it. In the Gaudium office, participants who paused at a



doorway typically entered and explored the room, whereas those who bypassed the doorway missed the space entirely. Even among adjacent enclosed offices near the reception (Figure 2), only 8% missed the first room, while 40% missed the second. A similar pattern appeared in the side-by-side conference rooms near the media space (Figure 2), where 17% skipped one and only 4% skipped the other. In both cases, the absence of doorway pauses signaled lower usability and engagement.

Frequency logs derived from participants' egocentric views showed the likelihood of visitation

across fine-grained spaces rather than broad zone categories (Table 1). Most of the sapces (68%) were visited by at least 90% of participants, including three spaces visited by all participants, while six spaces fell below 90% visitation and were missed by a larger share of participants. In addition to the three spatial clusters, quiet, varied, and loud, we classified zones by functional importance. Low-importance zones (25%) served mainly structural or service functions, such as storage and HVAC, whereas high-importance zones (75%) were intended to support workplace culture by connecting communal and private spaces.

Our base VR-ViT model yielded 102 heat maps (Figure 4) showing how participants spent time in the virtual office. Room-level frame counts, captured every 7 seconds, were plotted directly onto the floor plan. The color scale represents aggregated dwell-time frequency, with warmer values indicating longer durations and/or repeated visits and cooler values indicating shorter or more transient visits. Overall, participants spent

Zone	Function	Cluster	Importance	Visited (%)
1	Vestibule	Varied	Low	100%
2 _a	Enclosed office I	Quiet	High	92%
2 _b	Enclosed office II	Quiet	High	60%
3 _a	Open office I	Loud	High	89%
3 _b	Open office II	Loud	High	98%
4	Short-term workspace	Loud	High	96%
5 _a	Closed conference I	Quiet	High	83%
5 _b	Closed conference II	Quiet	High	96%
6	Private breakaway	Quiet	High	100%
7	Open collaboration	Loud	High	98%
8	Reception	Loud	High	100%
9	Self-care space	Varied	High	74%
10	Toilet I	Varied	High	98%
10	Toilet II	Varied	High	82%
11	Staff break	Varied	High	99%
12	Communication closet	Varied	Low	78%
13	Media area	Varied	High	98%
14	Mechanical equipment	Varied	Low	99%
15	File storage	Varied	Low	99%
16	Janitor closet	Varied	Low	95%

Table 1
VR-ViT analysis of
16 zones in
Gaudium office
(one zone might
have more than
one room)

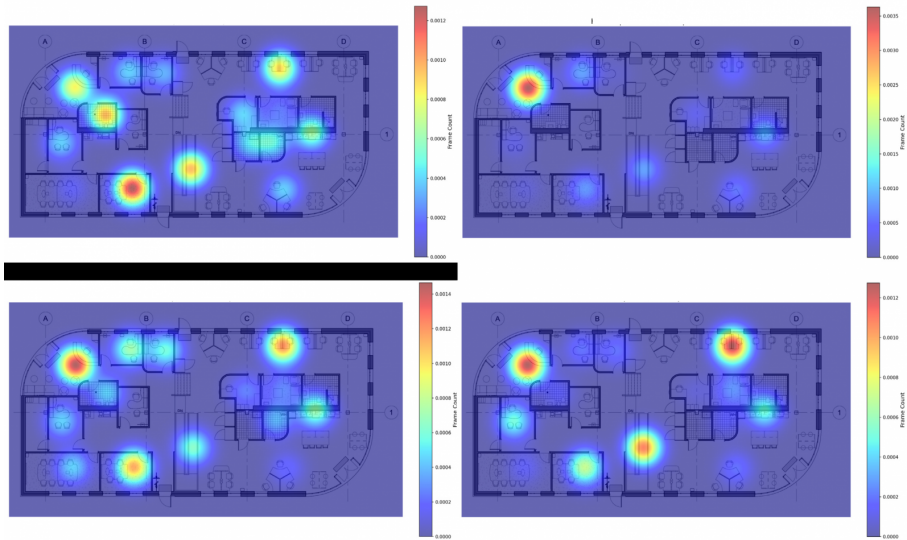


Figure 4
Heat maps for
Gaudium office,
showcasing dwell
time variances
across 102
participants with
four enlarged
samples

Table 2
VR-ViT analysis of
14 zones in
Warriors art studio
(one zone might
have more than
one room)

the most time in reception (14,504 seconds) and private break away (7,784 seconds), and the least time in the second enclosed office (735 seconds) and selfcare space (1,155 seconds). These visualizations capture time-stamped navigation across rooms and pathways, revealing which spaces drew attention and sustained engagement.

Follow-up: Indoor Travel Patterns in Warriors

Across 8.49 hours of egocentric recordings, our VR-ViT model detected distinct travel patterns in the virtual Warriors art studio. The issue of missing one of two adjacent rooms persisted, although overall usability improved across the floor plan. For the adjacent individual art therapy rooms near the relaxation space (Figure 3), 99% of participants entered the first room, and only 21% missed the second. By contrast, for the adjacent restrooms near reception (Figure 3), only 59% entered the first restroom, while 66% missed the second.

Of the 14 zones (open navigation areas were annotated separately for model training, resulting in 18 trained classes), eight were visited by nearly all participants, three received moderate visitation, and three were skipped by some (Table 2). Among those, zones that supported structural or procedural purposes and high hazard (e.g., trash room, HVAC) were classified as low importance for typical user access (43%). Zones that facilitated public-facing, community-building, and art-healing (e.g., individual and group art therapy)

Zone	Function	Cluster	Importance	Visited (%)
1	Reception	Varied	High	97%
2 _a	Restroom	Quiet	High	59%
2 _b	Restroom	Quiet	High	34%
3 _a	Individual art therapy	Quiet	High	99%
3 _b	Individual art therapy	Quiet	High	79%
4	Group art therapy	Loud	High	95%
5	Klin room	Varied	Low	80%
6	Recycling/Trash room	Varied	Low	40%
7	Glaze room	Varied	Low	34%
8	Relaxation space	Varied	High	85%
9	Personal pods	Quiet	High	85%
10	Communication closet	Quiet	Low	52%
11	Administration office	Varied	Low	83%
12	Staff break area	Loud	Low	60%
13	Janitor closet	Quiet	Low	63%
14	HVAC	Quiet	Low	35%

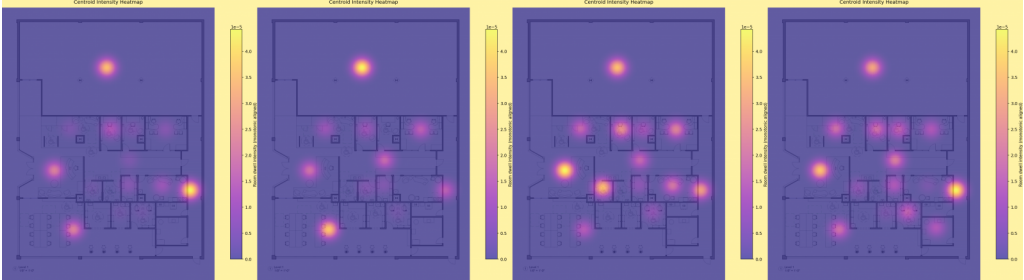
activities were classified as high importance (57%).

Our base VR-ViT model yielded 65 heat maps (Figure 5) of how participants spent time inside the virtual art studio. Overall, participants spent most of their time at the reception (12,020 seconds) and the first individual art therapy room (8,370 seconds). They spent the least of their time at HVAC (560 seconds) and the glaze room (460 seconds).

Model Accuracy

The training pipeline automatically detected the number of output classes, compensated for class imbalance through weighted cross-entropy loss,

Figure 5
Heat maps for
Warriors art studio,
showcasing dwell
time variances
across 65
participants with
four enlarged
samples



and optimized learning with AdamW and a CosineAnnealingLR scheduler (Zhu et al., 2025). We further included automatic device selection, like MPS, CUDA, or CPU (Szigeti et al., 2025), modular control of classifier and backbone parameters, real-time training feedback, and final test evaluation using the best saved checkpoint.

The pilot model initially achieved 93% accuracy (7% error rate) across 16 zones. However, after identifying confusion among open spaces without wall separations, we refined the zone labels and expanded to 19 trained zones, such as separating two toilets that had previously been coded as one. Accuracy dropped to 77% (macro $F_1=0.73$, weighted $F_1=0.74$), increasing the error rate to 23%. In contrast, the follow-up model achieved 96% accuracy (4% error rate) across 14 zones (macro $F_1=0.96$, weighted $F_1=0.95$). These results suggest that distinguishing a larger number of visually similar rooms creates a harder, more realistic classification problem rather than indicating a weaker model.

DISCUSSION

General indoor travel patterns

Our base VR-ViT model successfully mapped indoor travel patterns from participants' egocentric views into frequency logs and time-stamped heat maps. The findings suggest that human-spatial interaction cannot be explained by spatial configuration or agent-based calibration alone (Cocho-Bermejo, 2025; Neumayr, 2021; Schaumann et al., 2019; Sousa et al., 2017). The pilot study also pointed to the importance of doorways in addition to overall spatial configuration. Spatial adjacency did not ensure equivalent usability; rather, room entry appeared to depend on how clearly a doorway conveyed invitation, function, and continuity of movement.

Human navigation, therefore, seems to emerge from the interaction between macro-level spatial legibility and micro-level design elements such as sightlines, openness, visual anchors, and perceived accessibility. The follow-up study showed a

similar but less pronounced pattern of selective usability between adjacent spaces, along with stronger overall usability across the floor plan. Compared with the Gaudium office, the Warriors art studio supported more balanced exploration of high-importance zones, especially those tied to therapeutic and communal goals. This difference may reflect its use of transitional spaces, buffering strategies, and reduced visual complexity, which appeared to support clearer navigation judgments. Together, the two studies validate the base VR-ViT model as a data-driven approach for assessing human navigation and spatial usability in interior design before construction.

Potential biases and future work for the VR-ViT method

First, our analysis classifies egocentric views into predefined spatial zones, making the method effective for identifying room-level navigation patterns. However, the model is less sensitive to subtle behaviors, such as brief glances, hesitation, or confusion near room boundaries, when they do not result in explicit movement. Thus, the base VR-ViT model is well suited to revealing how individuals respond to environmental cues in immersive environments, but it does not provide definitive evidence of the psychological or social factors that may shape those behaviors.

Second, both studies relied on convenience samples drawn largely from young, English-fluent participants who were enrolled at a single university, most with limited prior VR experience. This may limit generalizability to other user groups, including children, older adults, and users navigating built environments with more explicit task-driven goals.

Third, the higher accuracy in the follow-up study compared with the pilot study may partly reflect the smaller number of spatial zones classified, 14 rather than 16, rather than design differences alone. Future work will extend the base VR-ViT model by incorporating finer-grained behavioral indicators, such as electroencephalography (EEG), recruiting

more diverse participant groups, and conducting controlled comparisons across environments with equivalent spatial complexity to better assess generalizability and model performance.

Lastly, the two VR environments and the Meta Quest 3 headset allowed full-scale assessments pre-construction, yet headset resolution, rendering quality, lighting/material fidelity, and tracking loss may have simplified environmental cues. Teleportation reduced discomfort, but also removed continuous walking speed and acceleration. Thus, these constraints limit direct generalization to real-world scenarios, but they also clarify our VR-ViT method's value as a critical diagnostic tool for identifying (and likely preventing) usability concerns that can later be materialized in physical buildings.

CONCLUSION

We demonstrated a pre-construction assessment method for space planning that integrates VR with a fine-tuned ViT model to map indoor travel patterns from participants' egocentric views onto architectural floor plans. The base VR-ViT model achieved sufficient-to-strong classification accuracy, 77% in the 16-zone office and 96% in the 14-zone art studio, while revealing differences in visitation, doorway crossing, and dwell time across spaces. These findings thus identify where intended circulation worked, where it broke down, and which underutilization risks pre-construction.

The broader contribution of this work is both methodological and practical. Methodologically, it extends rule-based and simulation-driven methods, like Space Syntax and ABM, by analyzing behavioral traces from real users in immersive environments. Practically, it offers architects and interior designers an evidence-based way to assess spatial usability before construction, when revisions remain feasible and less costly. By visualizing anticipated travel patterns early, the base VR-ViT model helps identify spatial problems before they are built.

DISCLOSURE OF AI USES

The authors conceptualized and developed the VR-ViT model, designed the studies, collected data, analyzed and interpreted the results. Chat GPT 5.4, 5.5, Codex, and Co-pilot Pro were used for language editing and refinement.

ACKNOWLEDGEMENT

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The two interior projects were designed by Liliana Gonzalez Chavez (Gaudium) and Kayla Perdue (Warriors). VR enhancements were performed by Duyen Nguyen and Caroline Alleva. Axonometric diagrams were created by Carolyn Calbeck.

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