The POMS Effect: Reducing Cybersickness in VR with Overlapping Architectures

Puru Ojha
International Institute of Information Technology
Hyderabad, India
puru.ojha@research.iiit.ac.in

Aaditya Vardhan Narain
International Institute of Information Technology
Hyderabad, India
aaditya.narain@research.iiit.ac.in

Y. Raghu Reddy
International Institute of Information Technology
Hyderabad, India
raghu.reddy@iiit.ac.in

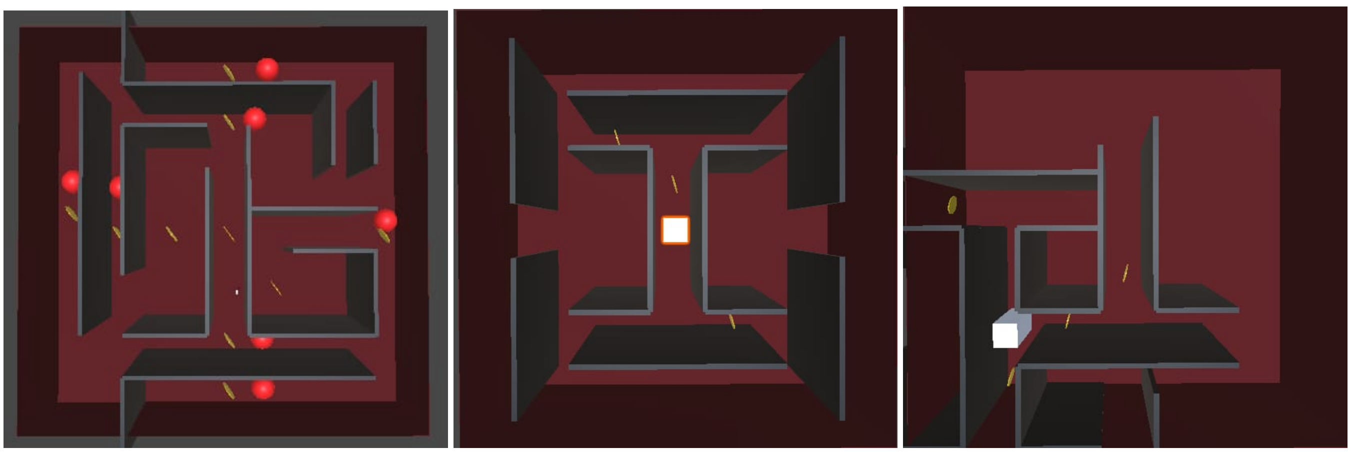


Figure 1: Representative visuals from the Static (left) and POMS (middle and right) conditions used in the study.

ABSTRACT

Natural walking offers high immersion in Virtual Reality (VR) but is constrained by physical space. Overlapping architectures, which reuse physical space, are a potential solution. Building on foundational principles of Architecturally Consistent Maze Generation in VR [16], we developed,implemented, and evaluated the **Procedural Overlapping Maze System (POMS)**. POMS procedurally generates and prunes right-angled, overlapping maze corridors in real-time, enabling continuous natural walking in footprints ≥ 4x4m. This paper presents a controlled, between-group empirical evaluation (N=17 matched pairs) comparing POMS against a spatially equivalent static maze in an 8x8m tracked area using an Oculus Quest 3. Participants performed a time-constrained navigation task. We investigated effects on user engagement (time-on-task), usability (User Experience Questionnaire - UEQ), presence (igroup Presence Questionnaire - iPQ), and cybersickness (Simulator Sickness Questionnaire - SSQ). We hypothesized POMS would lead to increased time-on-task (H1), and that its dynamic nature would not negatively impact user experience, aiming for UEQ, iPQ, and SSQ outcomes comparable to a static environment (H2-H4).

Results indicated **no statistically significant differences** in UEQ (H2) or iPQ (H3) between conditions, supporting our hypotheses that POMS could maintain these experiential qualities. Surprisingly, regarding cybersickness (H4), the increase in Oculomotor, Disorientation, and **Total SSQ symptoms was significantly smaller** in the POMS condition compared to the Static condition, while there was no significant difference for Nausea. This finding demonstrates an unexpected and substantial comfort benefit with POMS, exceeding our initial hypothesis of mere comparability. While POMS **did not show a statistically significant increase** in time-on-task (H1) in this study, a numerical trend suggesting longer engagement was observed. The markedly improved comfort achieved with POMS strongly suggests that such architectures have the potential to facilitate longer interaction periods, warranting further investigation into task design to fully leverage this benefit. These findings highlight that procedurally overlapping architectures like POMS can enable extended natural walking, not only without degrading core experiential qualities, but also by significantly enhancing user comfort.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Empirical studies in HCI**; *Interaction techniques.*

Conference acronym 'XX, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/18/06
https://doi.org/XXXXXXX.XXXXXXX

KEYWORDS

Virtual Reality (VR), Procedural Content Generation (PCG), Locomotion, Cybersicknes, User Experience (UX), Overlapping Architectures, Maze Generation, User Study

ACM Reference Format:

Puru Ojha, Aaditya Vardhan Narain, and Y. Raghu Reddy. 2018. The POMS Effect: Reducing Cybersickness in VR with Overlapping Architectures. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation emai (Conference acronym 'XX).* ACM, New York, NY, USA, 15 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Virtual Reality (VR) offers the profound potential to transport users into expansive digital realms, fostering unprecedented levels of immersion and engagement. Central to realizing this potential is the challenge of locomotion – how users navigate these virtual environments (VEs). While numerous techniques exist, natural walking, leveraging the user's own physical movement, remains the gold standard, offering unparalleled intuition and significantly enhancing the sense of presence [12, 18]. However, this ideal is often fundamentally constrained by the limited physical space available to most users, creating a stark mismatch between the desire for boundless exploration and the reality of room-scale boundaries.

To bridge this gap, various locomotion techniques have been developed. Supernatural methods, such as teleportation (cf. [9]) or controller-based movement, bypass physical limitations but often come at the cost of reduced immersion and can induce cybersickness due to sensory conflicts [11]. Redirected Walking (RDW) techniques aim to preserve natural walking by subtly manipulating the mapping between real and virtual movements [18, 32]. While powerful, RDW often requires substantial physical tracking areas [1, 2], sophisticated steering algorithms [14, 29], and its manipulations can sometimes become perceptible, potentially disrupting user experience.

An alternative strategy involves manipulating the VE's architecture itself, creating "overlapping" or "impossible spaces" that reuse the physical area by ensuring local consistency while allowing global geometric impossibilities [28]. Prior work has explored this through methods such as tile-based mazes relying on portals for transitions between overlapping sections [8], or by leveraging discrete environmental changes during moments like passing through doorways [26]. While these approaches demonstrate the feasibility of space reuse, they often involve distinct transitions or are suited to specific types of environmental structures.

Building upon the conceptual framework for architecturally consistent dynamic maze generation presented in [16] — which highlighted the potential but remained untested—this work introduces the concrete implementation and rigorous evaluation of the Procedural Overlapping Maze System (POMS). POMS represents a distinct approach by procedurally generating right-angled maze corridors in real-time, dynamically extending paths ahead of the user and pruning those behind. This is designed to achieve a seamless experience of infinite exploration within constrained physical footprints (e.g., ≥4x4m), navigated solely through natural walking.

Despite the promise of such continuous, procedurally reconfigured environments for natural walking, rigorous empirical evaluation of their impact on user experience and comfort is lacking. This study, therefore, conducts a controlled empirical comparison of POMS against a spatially equivalent static maze. We formulated four primary hypotheses:

Engagement (H1) : *We hypothesized that POMS would lead to a* ***greater Time-On-Task*** *(engagement) compared to the static maze, given its potential for theoretically infinite exploration.*

User Experience (H2) : *Recognizing the potential perceptual complexities of a dynamically changing environment, we aimed to determine if POMS could maintain user experience levels comparable to a stable one. Thus, we hypothesized that there would be* ***no significant detriment*** *in User Experience (as measured by the User Experience Questionnaire - UEQ) between the POMS and static maze conditions, suggesting that POMS's dynamic nature would not detract from overall usability and satisfaction.*

Presence (H3): *Similarly, for presence, we hypothesized that there would be* ***no significant detriment*** *in the sense of Presence (as measured by the igroup Presence Questionnaire - iPQ) between the two conditions, indicating that POMS could maintain immersion levels comparable to a stable environment.*

Cybersickness (H4): *For cybersickness, while the dynamic spatial reconfiguration inherent in POMS could introduce novel perceptual stimuli, the preservation of 1:1 natural walking is a known mitigating factor. Therefore, we hypothesized that POMS would achieve cybersickness outcomes* ***comparable to the static maze****, resulting in* ***no significant difference*** *in the change in cybersickness symptoms (as measured by the Simulator Sickness Questionnaire - SSQ) between the POMS and static maze conditions.*

This paper makes two primary contributions:

(1) The design, implementation, and detailed description of the Procedural Overlapping Maze System (POMS), a novel system that realizes and extends the foundational concepts for architecturally consistent maze generation proposed in [Ojha and Reddy, 2024], enabling continuous natural walking through dynamically reconfigured environments.
(2) Robust empirical evidence (N = 17, matched pairs) quantifying the effects of this approach on **user engagement**, **experience**, **presence**, and **cybersickness** compared to a traditional static maze. The findings demonstrate that such procedurally overlapping architectures can maintain experiential quality and, **notably, offer significant comfort advantages**, while also highlighting the need for further research to fully translate extended walking potential into demonstrably increased user engagement.

The remainder of this paper details related work, the POMS framework, the experimental methodology, results, and a discussion of their implications.

2 RELATED WORK

Navigating virtual environments (VEs) is a fundamental interaction in Virtual Reality (VR), yet it presents persistent challenges, primarily stemming from the discrepancy between the desire for expansive exploration and the physical constraints of the user's playspace [12]. Addressing this locomotion problem effectively is crucial for user engagement, immersion, and comfort. Over the years, a diverse range of techniques has emerged, broadly categorizable as supernatural or natural locomotion methods.

2.1 VR Locomotion Techniques: Bridging Virtual and Physical Space

Supernatural locomotion techniques deliberately decouple user actions from realistic physical movement to traverse large VEs. Teleportation, allowing instantaneous travel between points, is perhaps the most common, often favored for its simplicity and tendency to mitigate cybersickness by avoiding continuous visual flow mismatched with vestibular input (cf. [9]). However, teleportation can disrupt spatial understanding and reduce the sense of presence. Controller-based movement, mimicking traditional video game locomotion, provides continuous motion but frequently induces cybersickness due to the visual-vestibular conflict it generates [11]. Other approaches like Walking-in-Place (WiP) utilize physical gestures detected via sensors [27] or head/hand movements [15] to drive virtual motion. While more embodied than teleportation, WiP still presents a sensory mismatch and can lead to fatigue. A common thread among these supernatural methods is the trade-off: they grant freedom from physical boundaries but often at the expense of immersion and physiological comfort.

In contrast, natural locomotion, specifically physical walking, leverages the user's innate ability to move, mapping real-world steps 1:1 into the VE [12]. This approach provides the most congruent sensory experience, strongly enhancing spatial awareness, task performance, and the subjective feeling of presence (cf. [19, 30]). However, its direct dependence on the available physical tracking area is a significant limitation. Exploring a VE larger than the physical room necessitates alternative solutions, leading researchers to investigate methods that either extend the boundaries of natural walking or manipulate the virtual environment itself to accommodate it within limited confines. Our work focuses on the latter, aiming to maximize natural walking benefits by architecturally optimizing the VE for constrained physical spaces.

2.2 Redirected Walking: Extending Natural Locomotion via Imperceptible Manipulation

Redirected Walking (RDW) techniques represent a significant effort to reconcile natural walking with limited physical space by subtly manipulating the user's virtual path without their awareness [18]. The core principle involves introducing small discrepancies, or "gains," between the user's physical movements (translation, rotation) and their corresponding representation in the virtual environment. These gains, when kept below human perceptual thresholds [5, 25], can effectively steer the user away from physical boundaries, enabling them to traverse virtual paths that curve or extend beyond the confines of the tracked area while believing they are walking straight. Common manipulations include translation gains (virtual speed differs from physical speed) [32], rotation gains (virtual turning rate differs from physical turning rate) [25], and curvature gains (injecting slight curves into seemingly straight virtual paths) [18]. Bending gains that warp the entire VE geometry relative to the user have also been explored [23].

RDW offers a compelling advantage by preserving the proprioceptive and vestibular feedback associated with actual walking, thereby maintaining high levels of presence and minimizing cybersickness compared to many supernatural techniques. However, the efficacy of RDW is constrained by several factors. Firstly, the magnitude of applicable gains is limited by human perception; exceeding these thresholds makes the manipulation noticeable, potentially breaking immersion or causing disorientation [5]. Secondly, RDW typically requires a minimum amount of physical space to operate effectively, as sufficient distance is needed to accumulate the necessary virtual path deviations without requiring overly aggressive (and thus perceptible) gains [1].. Studies suggest areas of 6x6m or larger are often needed for robust application [1]. Furthermore, implementing effective RDW necessitates sophisticated steering algorithms to predict user paths and dynamically apply appropriate gains to avoid obstacles and boundaries [14, 34**?**]. These algorithms can become complex, especially in dynamic or multi-user scenarios [2, 4].

When users inevitably approach physical boundaries despite subtle redirection, more overt reorientation techniques may become necessary. These include methods like freeze-turn or freeze-backup maneuvers [33], potentially accompanied by distractors [17**?**], which temporarily interrupt the flow of natural walking to reset the user's position or orientation within the physical space. While sometimes unavoidable, these overt methods can be disruptive to the user experience. RDW, therefore, presents a powerful but bounded solution. Our work explores overlapping architectures as an alternative approach that avoids explicit user path manipulation through gains, instead focusing entirely on manipulating the VE's structure to accommodate continuous walking within the existing physical footprint.

2.3 Overlapping Architectures and Impossible Spaces: Manipulating the Environment Itself

Instead of manipulating the user's perception of their movement, another class of techniques directly manipulates the virtual environment's spatial structure to enable extended exploration within limited physical bounds. These approaches create 'overlapping architectures' or 'impossible spaces' – environments that appear locally coherent and navigable but whose global layout would be physically unrealizable [28]. The fundamental principle relies on the observation that users often fail to notice significant inconsistencies or overlaps in the VE's structure, particularly when their attention is focused on a task or when the changes occur outside their immediate field of view or during moments of distraction like saccades or blinks [3, 24].

Pioneering work by Suma et al. [28] systematically explored detection thresholds for spatial overlap, finding that users could tolerate significant inconsistencies (up to 56% overlap in smaller spaces) before noticing the impossibility. This finding opened avenues for compressing large virtual environments into smaller physical areas. Techniques to achieve this include leveraging 'change blindness' during transitions, such as altering the layout of a room behind a user as they pass through a doorway [26]. Others have explored dynamically bending or warping the VE geometry, like the Space Bender system which curves corridors as the user approaches physical boundaries [23], or the 'Foldable Spaces' concept which employs more overt accordion-like manipulations [6]. Vasylevska and Kaufmann [31] developed algorithms for procedurally generating layouts prioritizing content placement over strict architectural possibility, implicitly allowing for overlap.

Applying these concepts specifically to maze or corridor-like environments, which are naturally suited due to their constrained sightlines, has also been investigated. Mittal et al. [13] designed limitless corridor paths, although not explicitly focusing on overlap for space reuse. Koltai et al. [8] developed procedurally generated, tile-based overlapping mazes, but relied on portals to seamlessly teleport users between overlapping sections rather than creating continuous, architecturally overlapping paths. While effective in maintaining flow, the portal mechanism differs from a purely architectural overlap approach.

Building upon foundational principles of generating architecturally consistent, multi-path, right-angled dynamic mazes [16],, the **Procedural Overlapping Maze System (POMS)**, evaluated in this paper, offers a distinct approach. POMS focuses on *continuously unfolding* an architecturally overlapping corridor structure navigated *solely via natural walking*. It achieves this through real-time procedural generation and dynamic pruning of maze sections, aiming to maximize immersion and minimize disorientation within a constrained physical area. However, while local consistency is maintained, the perceptual and cognitive implications of such continuous dynamic reconfiguration in close proximity to a naturally walking user, particularly concerning comfort and the cognitive load of navigating a globally inconsistent space, require thorough investigation.

2.4 Evaluating User Experience in VR Locomotion

Quantifying the user experience (UX) is paramount when assessing the efficacy of different VR locomotion techniques. Given the potential for disorientation and discomfort, **cybersickness** is a critical factor. The **Simulator Sickness Questionnaire (SSQ)**, developed by Kennedy et al. [7], remains the most widely adopted instrument for measuring sickness symptoms, typically categorized into Nausea, Oculomotor, and Disorientation subscales. Numerous studies have employed the SSQ to compare sickness levels across various locomotion methods, often finding higher sickness associated with techniques involving passive visual motion mismatched with physical movement [11] (cf. reviews like [20]).

Beyond comfort, usability and overall user satisfaction are crucial. The **User Experience Questionnaire (UEQ)**, and its short form **UEQ-S** [21], provides standardized metrics for evaluating both pragmatic quality (e.g., efficiency, perspicuity, dependability) and hedonic quality (e.g., stimulation, novelty, attractiveness). These dimensions capture the task-oriented effectiveness and the non-task-oriented enjoyment and appeal of an interactive system, making the UEQ suitable for assessing how well a locomotion technique supports interaction goals while also being subjectively pleasing.

Perhaps the most sought-after quality in VR is presence, the subjective feeling of "being there" in the virtual environment. The **igroup Presence Questionnaire (iPQ)** [22] is a well-validated instrument measuring three key dimensions: Spatial Presence (the sense of being physically located within the VE), Involvement (the degree of attention allocated to the VE and task), and Experienced Realism (the subjective sense of credibility or realism of the VE). Natural locomotion is often posited to enhance presence compared to more artificial methods (cf. [30]), making the iPQ essential for evaluating techniques aiming to preserve or facilitate natural walking.

While these instruments (SSQ, UEQ-S, iPQ) are frequently utilized in VR research to evaluate individual locomotion techniques or compare distinct methods like teleportation versus joystick control (cf. [9]), there is a notable gap in their application to rigorously compare architecturally overlapping environments designed for natural walking against equivalent static layouts. Specifically, a controlled study examining the simultaneous impact of procedural overlapping architectures on engagement, sickness, usability, and presence using this combination of validated measures has been lacking. The present study directly addresses this gap, employing these established instruments within a robust between-group design (Section 4) to provide comprehensive empirical evidence on the user experience benefits afforded by the **Procedural Overlapping Maze System (POMS)** framework.

3 MAZE GENERATION FRAMEWORK:

The Procedural Overlapping Maze System (POMS) is designed to procedurally generate potentially infinite, architecturally consistent right-angled maze corridors in real-time. It is specifically tailored for natural walking locomotion within constrained room-scale VR environments (physical areas $\geq 4{\times}4$ m). POMS achieves this by employing a dynamic tree-based data structure for spatial representation, a collision-driven procedural expansion algorithm, and aggressive visibility management to enable the reuse of physical space. This approach builds upon the core principles of dynamic, architecturally consistent maze generation outlined in [16].

3.1 Data Representation

The core of POMS relies on a tree data structure, managed by a Tree class, where each node represents a significant decision point or termination within the maze topology, such as a junction offering path choices or a dead end. These points are encapsulated by a MazeNode class. Each MazeNode stores critical state information: its world-space Position (Vector3), its Level or depth within the tree hierarchy, references to its Parent, Left child, and Right child nodes, and, crucially, the IncomingDirection vector. This vector represents the direction from which the player entered the node and is fundamental for maintaining local orientation and enforcing the system's right-angled corridor structure.

The Tree class manages the overall collection of MazeNode instances, maintains a reference to the currentNode occupied by the player, and holds references to the necessary Unity GameObject prefabs used for instantiating maze components (e.g., *nodePrefab* for junctions, *wallPrefab* for corridors, *nodewallPrefab* for closing paths). The hierarchical relationship between nodes, combined with the strict ±90-degree rotation applied when generating child nodes from a parent (detailed in Section 3.2), implicitly encodes the maze layout. This embodies the rotational indexing concept from [16],

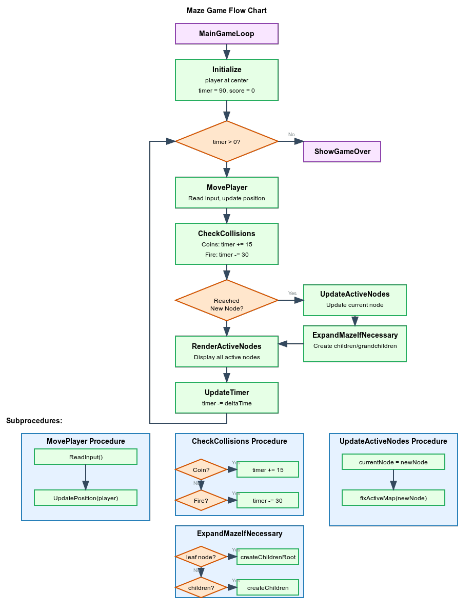


Figure 2: Visualization of the Algorithm

where new corridors are always generated orthogonally to the parent corridor, ensuring local architectural consistency throughout the dynamically generated environment.

3.2 Procedural Expansion Algorithm

The expansion of the maze within POMS is triggered dynamically by the user's physical movement through the VE. Each significant point in the maze (e.g., a potential junction or the end of a corridor) is represented by an instance of a nodePrefab (see Section 3.1), which contains a collider. When the player's VR avatar physically enters this collider, a NodeCollisionHandler component detects the event. This handler then signals a central MazeGenerator script, passing a reference to the MazeNode object associated with the interacted nodePrefab.

The MazeGenerator then queries the Tree structure to determine if the interacted MazeNode is a leaf node (i.e., it currently has no Left or Right child nodes). If it is a leaf node, the Tree class's createChildren method is invoked to generate new pathways. (A similar method, createChildrenRoot, is used exclusively for generating the initial segments from the starting MazeNode of the maze). The createChildren method calculates the world-space positions for potential new Left child and Right child nodes. This calculation is based on the current (parent) node's Position, its IncomingDirection, predefined corridor segment lengths (which were fixed for this study, though POMS allows for randomized lengths via parameters), and strict ±90-degree rotations executed by rotateLeft and rotateRight helper methods, ensuring new paths diverge orthogonally relative to the parent's IncomingDirection. New MazeNode objects are then created for these calculated child positions and are linked hierarchically to the parent MazeNode in the tree.

Following the logical creation and linking of new MazeNode objects, their visual representation is instantiated in the VE (**image to be added**). The parent MazeNode object calls its createLeftWall and createRightWall methods. These methods are responsible for instantiating wallPrefab GameObjects, which form the corridor segments connecting the parent node to its newly created left and right child nodes, respectively. The methods calculate the appropriate midpoint position and scale for each wallPrefab based on the distance between the connected nodes. Crucially, to maintain the illusion of a continuous, architecturally sound environment and to prevent users from seeing into areas that might be subsequently pruned (as detailed in Section 3.3), a nodewallPrefab is also instantiated. This nodewallPrefab visually closes off the path from which the user just arrived, effectively appearing behind the parent node of the newly generated segment(s), perpendicular to its IncomingDirection.

This real-time, collision-driven expansion process ensures that new pathways seamlessly appear as the user explores, facilitating continuous natural walking and creating the experience of navigating a dynamically unfolding, depth-first exploration of the potential maze space.

3.3 Visibility Management & Pruning

To enable the architectural overlap necessary for theoretically infinite maze generation within a finite physical space, and to maintain computational efficiency, POMS employs a dynamic visibility management and pruning strategy. Only a small, local subset of the maze surrounding the player is kept active (i.e., visible and collidable) at any given time. This active subset is managed by the Tree class's fixActiveMap method, which is invoked after each significant node interaction (typically when the player enters a new MazeNode's collider).

The fixActiveMap method dynamically updates an internal list of activeNodes. Typically, this list includes the currentNode (the MazeNode the player currently occupies), its immediate Parent node (if one exists), and its direct Left child and Right child nodes (if they exist). All GameObjects visually representing MazeNode instances (i.e., nodePrefabs) and their associated corridor segments (wallPrefabs, nodewallPrefabs) that are *not* part of this activeNodes list are deactivated within the Unity scene (set to inactive, thus neither rendered nor processed by physics). Conversely, GameObjects corresponding to nodes that enter the activeNodes list are enabled.

This dynamic activation and deactivation process effectively prunes distant or unseen branches of the maze tree from the current view. This strategy is crucial for several reasons:

- It ensures that the user only perceives a locally consistent and architecturally sound segment of the environment at any moment.
- It prevents the user from seeing potentially contradictory geometry that would arise if distant, physically overlapping but virtually distinct sections of the maze were simultaneously visible.
- It significantly reduces the rendering and physics load on the system, contributing to stable performance and high frame rates.

- By managing changes on deactivated elements, it contributes to the seamlessness of the experience, as corridors appear to extend naturally without the user witnessing abrupt generation or deconstruction of the environment.

This visibility management and pruning mechanism is therefore fundamental to how POMS achieves the seamless reuse of physical space, allowing for extended natural walking experiences beyond the physical boundaries of the tracked area.

3.4 Interactive Element Integration

To provide a structured task context for the experimental evaluation and to enhance player engagement, POMS integrates interactive elements into its procedural generation process. During the instantiation of each new corridor segment (i.e., when the createLeftWall or createRightWall methods are called, as described in Section 3.2), instances of interactive element prefabs are placed based on probabilistic criteria. Specifically, a coinPrefab has a 50% chance of being placed, and a firePrefab (representing a fireball) also has a 50% chance of being placed within any given new segment. Coins, when spawned, are stationary and typically positioned midway along the corridor's length. Fireballs, however, are dynamic and move within the confines of the corridor segment they occupy, presenting a moving obstacle for the player.

A PlayerManager script, attached to the user's VR avatar, utilizes Unity's physics system (specifically, OnTriggerEnter events) to detect collisions between the player and these interactive elements. Interacting with a coin triggers a positive gameplay consequence: a predefined amount of time (referenced by the variable coin_add) is added to the game timer. Conversely, colliding with a fireball results in a negative consequence: a predefined amount of time (referenced by fire_subtract) is subtracted from the game timer.The overall flow of player interaction, including these timed elements and their consequences within the game loop, is visualized in Figure 2. By incorporating these elements with clear, measurable goals and immediate consequences, POMS transforms the basic navigation framework into a playable game environment, making it suitable for the comparative user studies conducted in this research.

Associated visual feedback mechanisms, such as a DamageEffect upon collision with a fireball, and animations managed by handlers like CoinAnimationHandler (for coin collection) and DynamicFireBalls (for the fireballs' appearance and movement), further enhance the interactivity and feedback to the player. By incorporating these elements with clear, measurable goals and immediate consequences, POMS transforms the basic navigation framework into a playable game environment, making it suitable for the comparative user studies conducted in this research.

3.5 Implementation & Performance Considerations

The POMS framework was implemented using the Unity Engine (version 2022.3.5f1 LTS) with C# as the primary scripting language. The target platform for development and evaluation was the Meta Quest 3, leveraging its standalone processing capabilities and inside-out tracking features suitable for room-scale VR applications. All environmental components within POMS, including nodes, corridor walls, and interactive elements, are instantiated from optimized prefabs during runtime. These prefabs consist of simple, low-polygon models, similar to those used in the foundational [16] framework, ensuring efficient rendering.

A key design goal for POMS is to maintain consistently high and stable frame rates, which is critical for minimizing latency and ensuring user comfort in VR. For the Meta Quest 3, the target was to achieve $\geq$ 72 Hz. This performance is achieved through the combination of the efficient tree-based data structure for managing the maze logic (Section 3.1) and the aggressive visibility pruning performed by the fixActiveMap method (Section 3.3), which significantly reduces the number of active GameObjects requiring processing at any given time.

POMS is designed to function robustly in physical tracked areas of 4×4 meters or larger. The experimental evaluation detailed in this paper was conducted within an 8×8 meter physical space, demonstrating the system's capability in such an environment.

4 EVALUATION METHODOLOGY

To rigorously assess the impact of the Procedural Overlapping Maze System (POMS) on user experience compared to a traditional static maze architecture, we designed and conducted a controlled laboratory experiment. This section details the methodological choices made to ensure valid and reliable comparisons between the two conditions.

4.1 Study Design

We employed a **between-group experimental design** with a total of 34 participants (forming 17 matched pairs) to evaluate the effects of the maze architecture (**POMS vs. Static**) on user engagement (measured as time-on-task), usability (User Experience Questionnaire - UEQ), presence (igroup Presence Questionnaire - iPQ), and simulator sickness (Simulator Sickness Questionnaire - SSQ). This between-group approach was chosen primarily to prevent potential **carry-over effects** that could arise in a within-subjects design. Specifically, initial exposure to the unique spatial characteristics of the POMS condition might influence a participant's perception, navigation strategy, or sickness tolerance when subsequently experiencing the static condition (or vice versa). A between-group design ensures that each participant experiences only one experimental condition, thereby isolating the effect of the independent variable (maze architecture) and providing a cleaner comparison.

Furthermore, recognizing that individual differences can significantly influence outcomes in VR studies, we incorporated a **matched-pairs procedure**. Participants were matched based on two key self-reported factors: **frequency of weekly video gaming hours** and **prior VR usage experience**.

- **Gaming hours** were considered a relevant covariate as extensive gaming experience might influence navigational efficiency, problem-solving within the maze, and thus potentially affect engagement metrics like time-on-task.
- **Prior VR usage experience** was deemed important as familiarity with VR systems can impact subjective ratings of usability (UEQ), the reported sense of presence (iPQ), and susceptibility to or reporting of cybersickness symptoms (SSQ).

By forming pairs of participants with similar levels on these experience factors and then randomly assigning one member of each pair to either the POMS or the Static condition, we aimed to balance these key potential confounds across the experimental groups. This matching strategy enhances the statistical power of the study by reducing error variance attributable to these pre-existing individual differences, allowing for a more sensitive detection of true differences between the POMS and Static conditions.

4.2 Participants

A total of **34 participants** (Mean age = 21.2 years, SD = 2.96, range = 18-28 years; 27 Males + 7 Females) were recruited for this study from the local university campus community. Standard inclusion criteria were applied: participants were required to have normal or corrected-to-normal vision and self-report no history of significant vestibular disorders or heightened susceptibility to motion sickness. All participants provided written informed consent before commencing the study, which had received ethical approval from the Institutional Review Board (IRB).

Prior to the experimental session, participants completed a **background questionnaire**. This questionnaire collected demographic information (including age and gender) and assessed their experience levels relevant to the study, which formed the basis for creating **17 matched pairs**. The matching criteria from the questionnaire were operationalized as follows:

- **Prior VR Experience:** Participants indicated their experience, categorized as "never used," "used fewer than 5 times," or "used more than five times."
- **Frequency of Gaming:** Participants reported their gaming habits, categorized as "daily," "several times a week," "once a week," "occasionally," or "never."

Participants were paired such that both individuals within a given pair reported similar levels of experience across these two dimensions. Following the pairing process, one member of each pair was randomly assigned to the **Static** condition group (N=17), and the other member was assigned to the **POMS** condition group (N=17).

4.3 Apparatus

The experiment utilized the **Meta Quest 3**, a standalone Head-Mounted Display (HMD). This device was chosen for its robust inside-out tracking capabilities, which are well-suited for room-scale VR, and its capacity to run the experimental application without requiring external computing hardware.

The virtual environments (for both the **Static** and **POMS** maze conditions) and the associated gameplay logic, including the timer and interactions with coins and fireballs, were implemented as a custom application. This application was developed using the **Unity Engine** (version 2022.3.5f1 LTS).

All experimental sessions took place within a precisely measured **8 × 8 meter physical tracking area**. This area was clearly marked on the floor to ensure consistent spatial boundaries for all participants. The chosen space comfortably accommodated the natural walking required by both experimental conditions and exceeded the minimum 4×4 meter operational requirement of the POMS framework. Standardizing the HMD, the software build, and the physical environment across all participants was crucial to ensure that any observed differences between the groups could be primarily attributed to the assigned maze condition (Static vs. POMS).

4.4 Task

Participants in both the Static and POMS conditions engaged in an identical **time-constrained maze navigation and exploration task**. The task was designed to encourage continuous engagement and provide quantifiable performance metrics related to exploration depth. The primary objective for participants was to achieve the highest possible "Star Level" within the limited time budget, while simultaneously preventing their game timer from running out.

Participants began the task with an initial **90 seconds** displayed on a virtual timer, typically shown on their virtual left-hand controller display. Their current "Star Level" was displayed on their virtual right-hand controller, starting at zero stars. For every 60 seconds a participant actively remained in the game environment, an additional star was added to their display, serving as a direct indicator of their exploration persistence and depth.

Navigation was performed exclusively via **natural walking** within the **8 × 8 meter physical tracking area**; no artificial locomotion methods (e.g., teleportation, controller-based joystick movement) were permitted. Throughout the maze corridors, instances of interactive elements were placed, following the probabilistic rules outlined in Section 3.4, with their placement density and logic kept consistent across both conditions:

- **Coins:** Collecting a stationary coin (by walking into it) added **15 seconds** to the remaining game timer.
- **Fireballs:** Colliding with a moving fireball subtracted **30 seconds** from the remaining game timer.

The task concluded under one of two conditions: either when the participant's game timer reached zero (ending their exploration attempt), or if the participant chose to **voluntarily quit** the experiment at any point before the timer expired. This latter option was made available to ensure participant comfort and respect ethical considerations.

This standardized task provided participants with clear objectives (maximize Star Level by managing exploration time), offered immediate feedback via the timer and the accumulating Star Level display, and incentivized continuous movement. The primary behavioral measure of engagement was the total **Time-On-Task**. The task also provided a consistent interactive context for evaluating usability (UEQ), presence (iPQ), and cybersickness (SSQ), while respecting participant autonomy.

4.5 Conditions

Participants were assigned to one of two experimental conditions, both experienced within a shared 8×8 meter virtual room that was mapped 1:1 to the physical 8×8 meter tracking area. The conditions differed solely in the underlying architecture of the maze contained within this virtual room. All other aspects—including visual assets (corridor style, width), interaction mechanics (coins, fireballs, timer based on the rules in Section 3.4), task goals (Section 4.4), and the physical/virtual room environment—were held constant across conditions.

- **POMS Condition (Experimental Condition):** Participants in this group experienced a maze generated by the **POMS** framework (detailed in Section 3) *within the 8×8 meter virtual room.* This environment featured potentially infinite, right-angled corridors generated procedurally in real-time. Critically, POMS employed architectural overlap, dynamically activating and deactivating maze sections (via the fixActiveMap mechanism) to continuously reuse the physical and virtual 8×8 meter space. This allowed for the generation of extended virtual paths that created the illusion of an environment larger than the 8x8m confines, without relying on artificial locomotion methods.
- **Static Maze Condition (Control Condition):** Participants in this group navigated a pre-generated, non-overlapping maze layout, which was also entirely contained *within the 8×8 meter virtual room.* While designed to be visually similar to the POMS condition in terms of corridor style and width, and employing the same probabilistic rules for interactive element placement, this maze represented a fixed, architecturally consistent virtual space with a finite explorable area strictly limited to the 8x8m virtual room. Participants navigating this maze would encounter the predefined walls of the static maze structure or the boundaries of the 8x8m virtual room itself if they attempted to proceed further. This condition did not employ any space-reusing techniques such as overlapping sections or procedural regeneration.

The core distinction between conditions was thus the presence (POMS condition) versus absence (Static condition) of the procedural, space-reusing overlapping architecture within the same defined 8x8m virtual environment.

4.6 Procedures:

Interested individuals who responded to recruitment materials were first sent the **background questionnaire** (as described in Section 4.2). Data from this questionnaire regarding prior VR experience and gaming frequency were used to create matched pairs of participants. Subsequently, participants were scheduled for individual experimental sessions. The assignment of which condition (Static or POMS) each member of a pair would experience was pre-determined through random allocation before their session.

Upon arrival at the laboratory, participants were first briefed on the general nature of the study, the VR equipment they would be using (Meta Quest 3), and the overall task they would perform. Care was taken not to reveal the specific research hypotheses or the differences between the two experimental maze conditions. Following this briefing, participants provided written informed consent.

Once consent was obtained, participants completed the **pre-exposure Simulator Sickness Questionnaire (SSQ)** to establish a baseline measure of their well-being.

The experimenter then prepared the VR system according to the participant's pre-assigned condition (Static or POMS). The participant was subsequently assisted in donning the Meta Quest 3 HMD. Standardized verbal instructions were provided, explaining:

- The primary objective of the maze navigation task: to achieve the highest possible "Star Level" by exploring the maze and managing their game time effectively, while trying to prevent the timer from running out.
- How Star Levels were earned through sustained exploration and displayed on their virtual controller.
- The locomotion method: exclusively natural walking within the 8x8m area.
- The function of the in-game timer (starting at 90 seconds).
- The consequences of interacting with coins (+15 seconds) and fireballs (-30 seconds).
- Crucially, the in-game mechanism to voluntarily quit the experiment at any time if they felt uncomfortable or wished to stop for any reason, and how to activate it.

Following these instructions, participants underwent a brief **practice session**. This involved navigating a simple, neutral VR environment using natural walking, allowing them to acclimatize to the HMD, the feeling of movement in VR, and basic interaction, including practicing the use of the in-game quit mechanism, before commencing the main task.

Once the participant confirmed they were comfortable, they began the main experimental task in their assigned maze condition. During the task, the experimenter monitored the participant's progress and ensured their safety from outside the tracked physical area. The task continued until either the in-game timer reached zero or the participant utilized the in-game mechanism to quit the experiment.

Immediately after the VR exposure concluded and the HMD was removed, participants completed a set of post-experimental questionnaires in the following fixed order:

- The **post-exposure Simulator Sickness Questionnaire (SSQ)**.
- The **User Experience Questionnaire (UEQ)**.
- The **igroup Presence Questionnaire (iPQ)**.

Finally, participants were fully debriefed. This included explaining the study's purpose, the comparison between the POMS and Static maze types, and answering any questions they had. The entire experimental session for each participant lasted approximately 20 minutes.

4.7 Measures:

To address our research questions and test our hypothesis, we collected behavioral data during the VR task and subjective data via standardized questionnaires administered before and/or after the VR exposure.

(1) **Time-On-Task (H1: Engagement)** This primary behavioral measure captured the total duration, in seconds, that each participant actively spent navigating within their assigned maze condition before the game timer expired or they chose to quit using the in-game mechanism. It served as the principal indicator of engagement and exploration persistence.
(2) **Simulator Sickness Questionnaire (SSQ) (H4: Sickness):** The standard SSQ [7] was administered both immediately before (pre-exposure) and immediately after (post-exposure) the VR task. This 16-item questionnaire assesses symptoms on a 4-point scale (0=none, 1=slight, 2=moderate, 3=severe). Following standard practice, scores were calculated for its

three subscales: **Nausea (N)**, **Oculomotor (O)**, and **Disorientation (D)**. To control for baseline individual differences and isolate sickness induced specifically by the VR exposure, the **difference score (Δ Score = Post-score - Pre-score)** for each subscale was computed for each participant.

(3) **User Experience Questionnaire (UEQ) (H2: User Experience):** The full version of the User Experience Questionnaire (UEQ) [10] was administered post-exposure. This 26-item instrument measures user experience across six distinct dimensions using a 7-point semantic differential scale:
 (a) **Attractiveness:** Overall impression of the product.
 (b) **Perspicuity:** Ease of getting familiar with and understanding the product.
 (c) **Efficiency:** Ability to solve tasks without unnecessary effort.
 (d) **Dependability:** Feeling in control of the interaction.
 (e) **Stimulation:** Extent to which the product is exciting and motivating.
 (f) **Novelty:** Degree to which the product is innovative and creative. Mean scores were calculated for each of the six dimensions per participant.

(4) **igroup Presence Questionnaire (iPQ) (H3: Presence):** The igroup Presence Questionnaire (iPQ) [22] was administered post-exposure to assess various facets of the participants' subjective experience of presence in the virtual environment. This 14-item questionnaire utilizes a **7-point Likert-type scale** for its core items. Scores were aggregated into the four standard subscales:
 (a) **General Presence (GP):** The overall sense of "being there".
 (b) **Spatial Presence (SP):** The sense of being physically located within the VE.
 (c) **Involvement (INV):** The degree of attention allocated to the VE and task.
 (d) **Experienced Realism (REAL):** The subjective sense of credibility or realism of the VE.

Mean scores were calculated for each subscale per participant.

4.8 Statistical Analysis Plan

The primary goal of the statistical analysis was to compare the outcome measures (Time-On-Task, UEQ subscales, iPQ subscales, and SSQ subscale Δscores) between participants in the POMS condition and their matched counterparts in the Static condition. Given the matched-pairs design, analyses focused on comparing these paired observations. A significance level of $\alpha = 0.05$ was adopted for all primary hypothesis tests and research question evaluations.

Data preparation and test input: To prepare the data for statistical testing, several transformations were conducted. For the Simulator Sickness Questionnaire (SSQ), a difference score (ΔScore = Post-exposure score − Pre-exposure score) was calculated for each participant across the Nausea, Oculomotor, Disorientation, and Total Score subscales. Each of the 17 matched pairs was then compared using these ΔScores. Similarly, for the User Experience Questionnaire (UEQ) and the igroup Presence Questionnaire (iPQ), mean scores were computed for each relevant subscale for every participant, and these were compared pairwise across the 17 matched dyads. Time-On-Task was recorded in total seconds, and comparisons between the two conditions were made for 17 matched participant pairs.

Normality testing: For each outcome measure, the distribution of the *differences between the paired observations* (e.g., POMS_Score – Static_Score) was assessed using the Shapiro-Wilk test. If the resulting p-value exceeded 0.05, the difference scores were considered to be normally distributed. This normality assessment informed the appropriate choice of statistical test for each outcome.

Statistical test selection: The choice between parametric and non-parametric tests was based on the results of the Shapiro-Wilk test. If the paired differences were found to be normally distributed, a paired-samples t-test was employed. Conversely, if the data violated the normality assumption, the Wilcoxon signed-rank test, a non-parametric alternative for paired data, was used.

Evaluating research questions and hypotheses: Each research question was addressed using tests tailored to the expected directional outcomes. For H1 (Engagement: Time-On-Task), where a directional increase was hypothesized for the POMS condition, a one-sided test was conducted to determine whether Time-On-Task was significantly greater in the POMS condition. For H2 (User Experience: UEQ subscales), H3 (Presence: iPQ subscales), and H4 (Cybersickness: SSQ subscale Δscores), where no directional difference was predicted, two-sided tests were used. In all cases, paired-samples t-tests were applied when normality was met; otherwise, Wilcoxon signed-rank tests were used. These analyses evaluated whether the observed differences between POMS and Static conditions were statistically significant.

Effect sizes: To supplement hypothesis testing with a measure of practical significance, effect sizes were computed for all comparisons. For paired-samples t-tests, Cohen's d_z, calculated from the mean and standard deviation of the paired differences, was reported. For Wilcoxon signed-rank tests, the rank-biserial correlation (r_{rb}) was used to quantify the effect magnitude. These metrics provided an interpretable estimate of the strength of the observed effects.

5 RESULTS

This section presents the outcomes of the statistical analyses comparing the POMS (Dynamic) and Static maze conditions based on the matched-pairs design. Normality of the difference scores (POMS - Static) for each measure was assessed using the Shapiro-Wilk test. Based on these normality checks, appropriate paired statistical tests were employed. An alpha level of $\alpha = 0.05$ was used for all significance testing.

5.1 Time-On-Task (H1)

We hypothesized (H1) that participants would spend significantly more time engaged in the POMS condition compared to the Static condition. The data for Time-On-Task involved N=17 matched pairs. The distribution of the difference scores for Time-On-Task (POMS Time - Static Time) was assessed for normality using the Shapiro-Wilk test. The test indicated that the differences were normally distributed (W = 0.9587, p = 0.6064). Figure 4 shows visualization of the difference score distribution.

The distribution of Time-On-Task for both POMS (Dynamic) and Static conditions is visualized in Figure 3. Participants in the POMS condition (M = 447.35s, SD = 402.53s) spent numerically more time on average than those in the Static condition (M = 396.06s, SD = 251.87s).

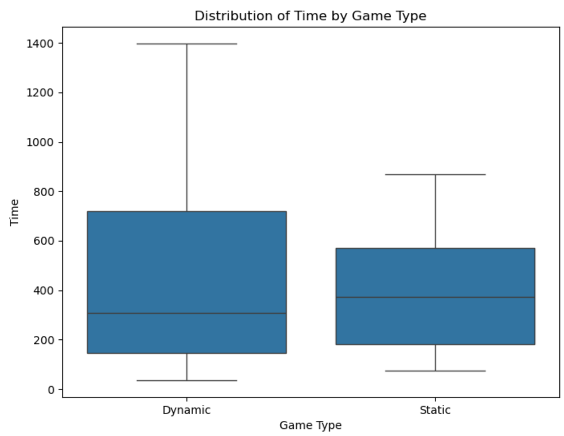
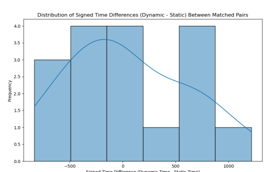
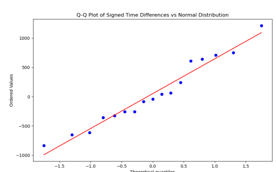


Figure 3: Boxplot comparing the distribution of Time-On-Task (seconds) between POMS (Dynamic) and Static conditions (N=17 pairs).



(a) Histogram of differences.



(b) Q-Q plot of differences.

Figure 4: Distribution of difference scores for Time-On-Task (POMS Time - Static Time, in seconds) for $N = 17$ matched pairs: (a) Histogram and (b) Q-Q plot.

Given the normality of the difference scores, a one-sided paired-samples t-test was conducted to compare Time-On-Task, testing if POMS > Static. While participants in the POMS condition spent numerically more time on average, this difference did not reach statistical significance (t(16) = 0.3701, one-sided p = 0.3581). Cohen's d for paired samples was calculated as 0.0898, indicating a negligible effect size.

Conclusion for H1: Hypothesis 1, predicting significantly longer Time-On-Task in the POMS condition, was **not supported** by the statistical analysis.

5.2 User Experience (UEQ) (H2)

We hypothesized (H2) that there would be no significant difference in user experience between the POMS and Static maze conditions, as assessed by the User Experience Questionnaire (UEQ). The analysis for UEQ subscales involved N=17 matched pairs. Difference scores (POMS - Static) for each UEQ subscale were tested for normality using the Shapiro-Wilk test.

Based on normality assessments, paired-samples t-tests were used for Attractiveness, Perspicuity, Efficiency, Stimulation, Novelty, and the UEQ Total score, as their difference scores were normally distributed. A Wilcoxon signed-rank test was used for Dependability, as its difference scores were not normally distributed (Shapiro-Wilk W = 0.8703, p = 0.0275). All tests were two-sided.

The results of these comparisons were as follows:

Table 1: Comparison Results Between POMS and Static Conditions

Measure	Test Statistic	p-value	Effect Size
Attractiveness	$t(16) = -0.7116$	0.4877	Cohen's $d_z = -0.1779$
Perspicuity	$t(16) = -0.6920$	0.4995	Cohen's $d_z = -0.1730$
Efficiency	$t(16) = 0.1687$	0.8683	Cohen's $d_z = 0.0422$
Dependability	$W = 52.0$	0.4031	$r_{rb} = -0.2090$
Stimulation	$t(16) = 0.1974$	0.8461	Cohen's $d_z = 0.0494$
Novelty	$t(16) = -1.1125$	0.2834	Cohen's $d_z = -0.2781$
UEQ Total Score	$t(16) = -0.4574$	0.6539	Cohen's $d_z = -0.1144$

The results of these comparisons are summarized in Figure 5. As hypothesized, no statistically significant differences were found between the POMS and Static conditions for any of the UEQ subscales or the total UEQ score (all p > 0.28, N=17 pairs).

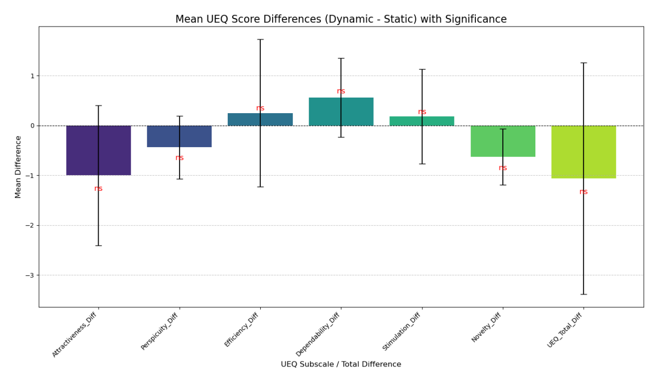


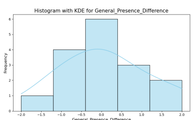
Figure 5: Mean differences (POMS - Static) for UEQ subscales and total score (N=17 pairs). Error bars represent the standard error of the mean. Significance indicators ns for not significant are shown above each bar.

Conclusion for H2: Hypothesis 2, predicting no significant difference in user experience as measured by the UEQ, was **supported**. None of the UEQ subscales nor the total score showed a statistically significant difference between the POMS and Static conditions.

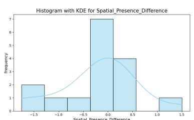
5.3 Presence (iPQ - H3)

We hypothesized (H3) that there would be no significant difference in the reported sense of presence between the POMS and Static maze conditions, as measured by the igroup Presence Questionnaire (iPQ). The analysis for iPQ subscales involved N=17 matched pairs. Difference scores (POMS - Static) for all iPQ subscales were found to be normally distributed based on Shapiro-Wilk tests. Consequently, two-sided paired-samples t-tests were conducted.

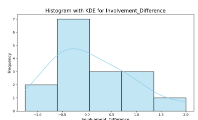
The Shapiro-Wilk tests indicated that the difference scores (POMS - Static) for all iPQ subscales were normally distributed (all p > 0.05), justifying the use of two-sided paired-samples t-tests. Figure 6 illustrates the distributions of these difference scores for each subscale.



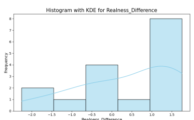
(a) GP Diff.



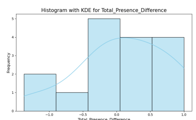
(b) SP Diff.



(c) INV Diff.



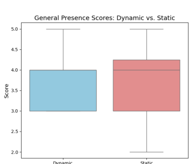
(d) REAL Diff.



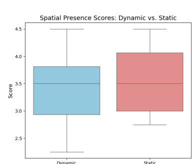
(e) TP Diff.

Figure 6: Histograms of difference scores (POMS - Static) for iPQ subscales ($N = 17$ pairs), illustrating normality: (a) General Presence, (b) Spatial Presence, (c) Involvement, (d) Experienced Realism, (e) Total Presence.

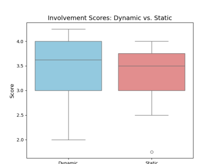
The comparison of iPQ scores between the POMS and Static conditions is shown in Figure 7. As hypothesized, the results of the t-tests revealed no significant differences for any iPQ subscale or the total presence score.



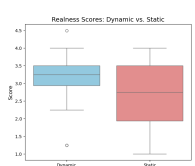
(a) GP Scores.



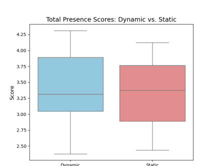
(b) SP Scores.



(c) INV Scores.



(d) REAL Scores.



(e) TP Scores.

Figure 7: Boxplot comparison of iPQ subscale scores between POMS (Dynamic) and Static conditions ($N = 17$ pairs): (a) General Presence, (b) Spatial Presence, (c) Involvement, (d) Experienced Realism, (e) Total Presence.

Conclusion for H3: Hypothesis 3, predicting no significant difference in the sense of presence as measured by the iPQ, was **supported**. None of the iPQ subscales nor the total presence score

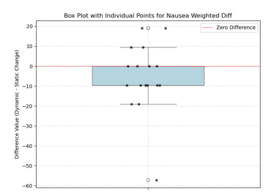
Table 2: Presence Measures: POMS vs Static Conditions

Measure	Statistic	p	Effect Size
GP	$t(16) = 0.2225$	0.8269	$d_z = 0.0556$
SP	$t(16) = -1.0000$	0.3332	$d_z = -0.2500$
INV	$t(16) = 0.3810$	0.7085	$d_z = 0.0953$
REAL	$t(16) = 1.2585$	0.2274	$d_z = 0.3146$
Total	$t(16) = 0.4909$	0.6306	$d_z = 0.1227$

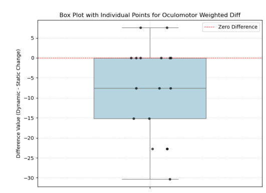
showed a statistically significant difference between the POMS and Static conditions.

5.4 Simulator Sickness (SSQ - H4)

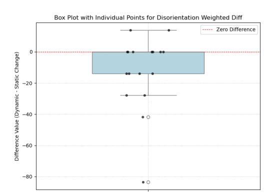
We hypothesized (H4) that there would be no significant difference in the change in cybersickness symptoms (Δ Score = Post-exposure - Pre-exposure) between the POMS and Static maze conditions, as assessed by the Simulator Sickness Questionnaire (SSQ). The analysis involved N=17 matched pairs. Difference scores for the SSQ subscale Δscores (POMS ΔScore - Static ΔScore) were calculated. Figure 8 presents boxplots illustrating the distribution of these difference scores for Nausea, Oculomotor, Disorientation, and Total SSQ. A score below zero on these plots indicates a smaller increase in symptoms for the POMS condition compared to the Static condition. These differences were then tested for normality.



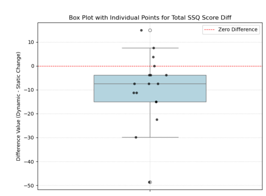
(a) Nausea Δ Score Differences.



(b) Oculomotor Δ Score Differences.



(c) Disorientation Δ Score Differences.

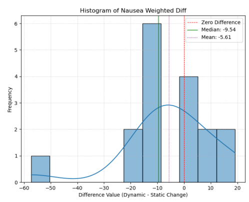


(d) Total SSQ Δ Score Differences.

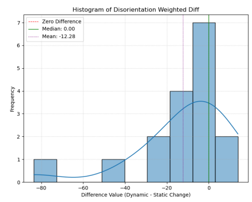
Figure 8: Boxplots of the differences in SSQ Δ Scores (POMS Δ Score – Static Δ Score; $N = 17$ pairs, n_{eff} varies). A difference below zero indicates a smaller increase in sickness for POMS. (a) Nausea, (b) Oculomotor, (c) Disorientation, (d) Total SSQ.

The distributions of the differences in SSQ Δ Scores (POMS Δ Score - Static Δ Score) for each subscale, initially presented as boxplots in Figure 8, were further examined for normality. Shapiro-Wilk tests indicated that the difference scores for Nausea Scores

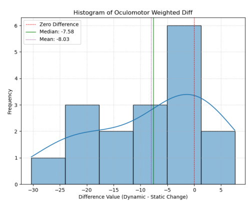
(W=0.8581, p=0.0143) and Disorientation Δ Scores (W=0.8037, p=0.0023) were not normally distributed. In contrast, Oculomotor Δ Score differences (W=0.9064, p=0.0871) and Total SSQ Δ Score differences (W=0.9279, p=0.2005) were found to be normally distributed. Figure 9 displays histograms of these difference scores



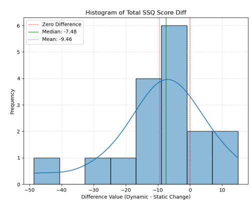
(a) Nausea Δ Score Differences.



(b) Disorientation Δ Score Differences.



(c) Oculomotor Δ Score Differences.



(d) Total SSQ Δ Score Differences.

Figure 9: Histograms of the differences in SSQ Δ Scores (POMS Δ Score − Static Δ Score; $N = 17$ matched pairs), illustrating the distributions used for normality assessment. (a) Nausea (non-normal), (b) Disorientation (non-normal), (c) Oculomotor (normal), (d) Total SSQ (normal).

Consequently, to assess H4, two-sided Wilcoxon signed-rank tests were conducted for the Nausea and Disorientation subscales, while two-sided paired-samples t-tests were conducted for the Oculomotor and Total SSQ subscales, as per the provided analysis protocol. The results of these initial two-sided tests, along with subsequent one-sided tests and effect sizes, are summarized in Table 3.

Given that significant differences were observed for Oculomotor, Disorientation and Total SSQ with the initial two-sided tests (thus not supporting H4 for these measures), one-sided tests were subsequently examined to explore the specific direction of these differences and assess potential comfort benefits of POMS (testing if POMS Δ Scores < Static Δ Scores). Figure 9 illustrates the non-normal distributions for Nausea and the normal distribution for Total SSQ difference scores. The results of these one-sided tests (see Table 3) revealed:

(1) The increase in Oculomotor symptoms was significantly smaller in the POMS condition compared to the Static condition.
(2) The increase in Disorientation symptoms was significantly smaller in the POMS condition.
(3) The increase in Nausea symptoms in the POMS condition remained non-significant.
(4) The increase in the Total SSQ score was significantly smaller in the POMS condition.

The effect sizes for the statistically significant results (Table 3) indicated large effects for the reduction in Oculomotor (Cohen's d = -0.6968), Disorientation (r_{rb} = -0.7455), and Total SSQ (Cohen's d = -0.6448) symptoms in the POMS condition compared to the Static condition. For Nausea, where the difference was not statistically significant, a medium effect size (r_{rb} = -0.3407) was observed, suggesting a trend towards reduced symptoms in the POMS condition. The negative effect size values indicate that lower difference scores (representing a smaller increase in sickness for POMS or a greater increase for Static) are associated with the POMS condition.

Conclusion for H4: Hypothesis 4, predicting no significant difference in cybersickness, was **supported for Nausea**. For Oculomotor, Disorientation, and Total SSQ scores, H4 was not supported as significant differences were found.

However, **these differences indicated a benefit for the POMS condition**, with participants experiencing significantly smaller increases in these sickness symptoms compared to the Static maze. This suggests POMS offered improved comfort regarding these specific aspects of cybersickness.

6 DISCUSSIONS

This study provided a controlled, empirical comparison of the Procedural Overlapping Maze System (POMS) against a traditional static maze, evaluating user engagement, experience (UEQ), presence (iPQ), and simulator sickness (SSQ). The findings reveal POMS as a promising technique that not only extends natural walking capabilities in limited physical spaces but also offers significant comfort benefits without compromising core experiential qualities.

6.1 Hypotheses and Key Findings:

Our hypotheses regarding user experience (H2) and presence (H3) predicting no significant differences between POMS and the static maze—were supported. Both UEQ and iPQ scores indicated that POMS's dynamic architectural changes did not negatively impact usability, satisfaction, hedonic qualities, or the sense of presence compared to a stable environment. This crucial outcome suggests that POMS's real-time generation and pruning maintained an immersive experience, aligning with research showing that locally consistent, subtly changing environments can be well-tolerated [3, 24, 28].

Regarding cybersickness (H4), we initially hypothesized no significant difference. This was supported for Nausea symptoms. However, for Oculomotor, Disorientation, and Total SSQ scores, POMS demonstrated a **significant advantage, resulting in markedly smaller increases in symptoms** compared to the static maze, with these benefits associated with large effect sizes.

For user engagement (H1), while POMS participants numerically spent more time on average (M = 447.35s, an increase of approximately 51 seconds over the Static condition's M = 396.06s), this difference was not statistically significant with the current task and sample size. Notably, the standard deviation for Time-On-Task in POMS was considerably larger (SD = 402.53s vs. Static SD = 251.87s), with some individuals engaging for up to 23 minutes, suggesting a varied response to the theoretically infinite environment.

Table 3: Comparison of SSQ ΔScores (POMS ΔScore - Static ΔScore) between POMS and Static Conditions ($N = 17$ matched pairs)

Subscale	Normality (S-W p)	Test Used	Test Statistic	p (2-sided)	p (1-sided, POMS < Static)	Effect Size
Nausea	0.0143	Wilcoxon	$W = 30.0$ ($n_{\text{eff}} = 13$)	0.2645	0.1323	$r_{\text{rb}} = -0.3407$
Oculomotor	0.0871	Paired t-test	$t(16) = -2.8731$	0.0110*	0.0055*	$d = -0.6968$
Disorientation	0.0023	Wilcoxon	$W = 7.0$ ($n_{\text{eff}} = 10$)	0.0323*	0.0162*	$r_{\text{rb}} = -0.7455$
Total SSQ	0.2005	Paired t-test	$t(16) = -2.6585$	0.0172*	0.0086*	$d = -0.6448$

Note: * indicates $p < 0.05$. n_{eff} refers to the number of pairs with non-zero differences used in the Wilcoxon signed-rank test.

6.2 Interpretation of Results:

The most compelling finding is the significant reduction in Oculomotor, Disorientation, and Total SSQ symptoms with POMS. This is particularly encouraging, as dynamic environmental changes might intuitively be expected to exacerbate sickness. This benefit likely stems from the continuous natural walking afforded by POMS, which may foster more fluid and predictable movement patterns with fewer abrupt stops or sharp turns compared to navigating a physically bounded static maze. Such smoother navigation can mitigate visual-vestibular conflicts often linked to Oculomotor and Disorientation symptoms [14]. This outcome robustly counters initial concerns that POMS's spatial remapping might itself induce discomfort, instead highlighting a distinct advantage of architecturally managed continuous walking.

The maintained levels of user experience and presence, coupled with these substantial comfort benefits, underscore POMS's potential. While increased Time-On-Task was not statistically confirmed in this study, the **markedly lower cybersickness achieved with POMS is a critical factor that directly facilitates the possibility of longer interaction durations.** It is intuitive that users experiencing less discomfort, particularly less disorientation and oculomotor strain, would be more willing and able to continue engaging with a VR experience for extended periods. **Therefore, the enhanced comfort demonstrated by POMS provides a strong and direct foundation for future applications to achieve demonstrably increased engagement, especially if integrated with more compelling and diverse game mechanics** beyond the basic coin collection and fireball avoidance used here. The current task design may not have fully capitalized on the extended play potential that is inherently unlocked by a more comfortable and theoretically limitless system.

6.3 Implications and Potential Applications:

The primary implication of this research for VR design is that architectural overlap, when carefully implemented as in POMS, can effectively reuse physical space not only without degrading user experience or presence but also by significantly enhancing user comfort. This combination of maintained experiential quality and improved comfort, particularly the reduction in cybersickness, unlocks considerable potential across diverse application domains. Here are a few examples to illustrate potential use cases:

- **Expansive Exploration and Visualization:** Virtual showrooms and commercial spaces (e.g., multi-level car dealerships, sprawling retail environments, or architectural walkthroughs) can be comfortably navigated within limited physical footprints. Immersive tourism applications, such as large-scale virtual museums or historical sites, also benefit from more natural and extended walking tours.
- **Engaging Gaming and Entertainment:** POMS is well-suited for endless runners and procedurally generated maze games, enabling longer, more immersive sessions through sickness-free, theoretically infinite paths. The comfort benefits also support broader overlapping reality techniques for large-scale or open-world game experiences.
- **Therapeutic, Rehabilitation, and Cognitive Applications:** POMS supports engaging walking exercises for physiotherapy in constrained clinical environments, where reduced cybersickness may increase adherence. It also serves cognitive training and spatial memory tasks, particularly for older adults, and can enable remote, embodied 'walk and talk' therapy as an alternative to video calls.

7 LIMITATIONS

This study's findings, while promising, should be considered in light of several limitations. The generalizability of our results is inherently constrained by the relatively modest sample size (N=17 matched pairs for most measures) drawn from a university community, which may not fully capture the diversity of all potential VR users. Future research with larger and more varied populations would be essential for broader validation. Furthermore, the outcomes are context-dependent, tied to the specific time-constrained maze navigation task, the 8x8m tracked area, and the particular algorithmic implementation of POMS. Variations in these experimental parameters could lead to different user experiences and comfort levels. Our reliance on subjective self-report measures, though standard, also presents a limitation; complementing these with objective physiological data in subsequent studies would offer a more multifaceted understanding. Finally, the variable duration of VR exposure, while ecologically valid as it reflected natural task completion, introduced an element of inconsistency that could influence cumulative effects like cybersickness, warranting consideration in future experimental designs.

8 CONCLUSION AND FUTURE WORKS

This study demonstrates that the Procedural Overlapping Maze System (POMS) effectively extends natural walking in VR within limited physical spaces, maintaining user experience and presence comparable to static mazes while significantly reducing key cybersickness symptoms (Oculomotor, Disorientation, Total SSQ). This enhanced comfort is a critical advancement for VR locomotion. While POMS facilitated numerically longer engagement, translating this improved comfort and theoretically infinite exploration into statistically significant increases in Time-On-Task requires further investigation into task design.

Future work should focus on three primary areas. Firstly, enhancing user engagement by exploring richer task mechanics and environmental cues that capitalize on POMS's extended walking capabilities. Secondly, deepening our understanding of the underlying mechanisms by analyzing movement kinematics and cognitive load to further optimize comfort and interaction. Thirdly, broadening validation and application, which involves studies with larger, diverse samples, incorporating objective physiological measures, and exploring POMS's efficacy in specific domains such as therapeutic interventions, cognitive training, and procedural entertainment.

In conclusion, POMS offers a robust method for comfortable, extended natural walking in VR. Addressing the interplay between advanced locomotion techniques, engaging content, and user comfort will be pivotal in realizing the full potential of boundless virtual exploration.

ACKNOWLEDGMENTS

We are grateful to all the participants who generously volunteered their time for this study. This research received ethical approval from the Institutional Review Board of the International Institute of Information Technology, Hyderabad.

REFERENCES

[1] Mahdi Azmandian, Timofey Grechkin, Mark T. Bolas, and Evan A. Suma. 2015. Physical Space Requirements for Redirected Walking: How Size and Shape Affect Performance. In *ICAT-EGVE*.

[2] Mahdi Azmandian, Timofey Grechkin, and Evan Suma Rosenberg. 2017. An evaluation of strategies for two-user redirected walking in shared physical spaces. In *2017 IEEE Virtual Reality (VR)*. 91–98. https://doi.org/10.1109/VR.2017.7892235

[3] Benjamin Bolte and Markus Lappe. 2015. Subliminal Reorientation and Repositioning in Immersive Virtual Environments using Saccadic Suppression. *IEEE Transactions on Visualization and Computer Graphics* 21, 4 (2015), 545–552. https://doi.org/10.1109/TVCG.2015.2391851

[4] Tianyang Dong, Xianwei Chen, Yifan Song, Wenyuan Ying, and Jing Fan. 2020. Dynamic Artificial Potential Fields for Multi-User Redirected Walking. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 146–154. https://doi.org/10.1109/VR46266.2020.00033

[5] Timofey Grechkin, Jerald Thomas, Mahdi Azmandian, Mark Bolas, and Evan Suma. 2016. Revisiting detection thresholds for redirected walking: combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception (SAP '16)*. ACM, New York, NY, USA, 113–120. https://doi.org/10.1145/2931002.2931018

[6] Jihae Han, Andrew Vande Moere, and Adalberto L. Simeone. 2022. Foldable Spaces: An Overt Redirection Approach for Natural Walking in Virtual Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 167–175. https://doi.org/10.1109/VR51125.2022.00034

[7] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[8] Balázs Gyula Koltai, Jakob Elkjær Husted, Ronny Vangsted, Thomas Noes Mikkelsen, and Martin Kraus. 2020. Procedurally Generated Self Overlapping Mazes in Virtual Reality. In *Interactivity, Game Creation, Design, Learning, and Innovation*, Anthony L. Brooks and Eva Irene Brooks (Eds.). Springer International Publishing, Cham, 229–243. https://doi.org/10.1007/978-3-030-62500-5_19

[9] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology (VRST '18)*. ACM, New York, NY, USA, 1–2. https://doi.org/10.1145/3234253.3234291

[10] Bettina Laugwitz, Theo Held, and Martin Schrepp. 2008. UEQ: An EUser Experience Questionnaire: An instrument for measuring the user experience of interactive products. In *HCI and Usability for Education and Work (Lecture Notes in Computer Science, Vol. 5298)*, Andreas Holzinger (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 63–76. https://doi.org/10.1007/978-3-540-89350-9_6

[11] Joseph J. LaViola, Jr. 2000. A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin* 32, 1 (Jan. 2000), 47–56. https://doi.org/10.1145/333329.333344

[12] Joseph J. LaViola, Jr., Doug A. Bowman, Ernst Kruijff, and Ivan Poupyrev. 2004. *3D User Interfaces: Theory and Practice* (1st ed.). Addison-Wesley Professional, Boston, MA, USA.

[13] Raghav Mittal, Sai Anirudh Karre, and Y. Raghu Reddy. 2021. Designing Limitless Path in Virtual Reality Environment. In *Virtual, Augmented and Mixed Reality*, Jessie Y. C. Chen and Gino Fragomeni (Eds.). Lecture Notes in Computer Science, Vol. 12765. Springer International Publishing, Cham, 80–95. https://doi.org/10.1007/978-3-030-77599-5_6

[14] Thomas Nescher, Ying-Yin Huang, and Andreas Kunz. 2014. Planning redirection techniques for optimal free walking experience using model predictive control. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*. 111–118. https://doi.org/10.1109/3DUI.2014.6798851

[15] Niels C. Nilsson, Stefania Serafin, Morten H. Laursen, Kasper S. Pedersen, Erik Sikström, and Rolf Nordahl. 2013. Tapping-In-Place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. 31–38. https://doi.org/10.1109/3DUI.2013.6550193

[16] Puru Ojha and Y. Raghu Reddy. 2024. ACMGVR: Architecturally Consistent Mazes for Games in Virtual Reality. In *Companion Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY Companion '24)*. ACM, New York, NY, USA, 221–226. https://doi.org/10.1145/3665463.3678818 Tampere, Finland, October 14-17, 2024.

[17] Tabitha C. Peck, Mary C. Whitton, and Henry Fuchs. 2008. Evaluation of Reorientation Techniques for Walking in Large Virtual Environments. In *2008 IEEE Virtual Reality Conference*. 121–127. https://doi.org/10.1109/VR.2008.4480761

[18] Sharif Razzaque, Zachariah Kohn, and Mary C. Whitton. 2001. Redirected Walking. In *Proceedings of Eurographics (Short Presentation) (EG '01)*, C. Roberts Jonathan (Ed.).

[19] Roy A. Ruddle, Ekaterina Volkova, and Mazyar Mohamad. 2011. The Effect of Visual Realism on the Ability to Learn a Virtual Route. *Presence: Teleoperators and Virtual Environments* 20, 1 (2011), 76–90. https://doi.org/10.1162/PRES_a_00038

[20] Dimitrios Saredakis, Ancret Szpak, Brandon Birckhead, Hannah A.D. Keage, Albert Rizzo, and Tobias Loetscher. 2020. Factors Associated With Cybersickness in Virtual Reality—A Systematic Review and Meta-Analysis. *Frontiers in Human Neuroscience* 14 (2020), 96. https://doi.org/10.3389/fnhum.2020.00096

[21] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2017. Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). *International Journal of Human–Computer Interaction* 33, 4 (2017), 275–283. https://doi.org/10.1080/10447318.2017.1300003

[22] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The Igroup Presence Questionnaire (IPQ): A Measure of the Subjective Experience of Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments* 10, 3 (2001), 266–281. https://doi.org/10.1162/105474601300343603

[23] Adalberto L. Simeone, Niels Christian Nilsson, André Zenner, Marco Speicher, and Florian Daiber. 2020. The Space Bender: Supporting Natural Walking via Overt Manipulation of the Virtual Environment. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 598–606. https://doi.org/10.1109/VR46266.2020.00082

[24] Daniel J. Simons and Christopher F. Chabris. 1999. Gorillas in Our Midst: Sustained Inattentional Blindness for Dynamic Events. *Perception* 28, 9 (1999), 1059–1074. https://doi.org/10.1068/p2952

[25] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2010. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1 (2010), 17–27. https://doi.org/10.1109/TVCG.2009.79

[26] Evan A. Suma, Seth Clark, David Krum, Samantha Finkelstein, Mark Bolas, and Zachary Warte. 2011. Leveraging change blindness for redirection in virtual environments. In *2011 IEEE Virtual Reality Conference*. 159–166. https://doi.org/10.1109/VR.2011.5759455

[27] Evan A. Suma, Belinda Lange, Albert Skip Rizzo, David M. Krum, and Mark Bolas. 2011. FAAST: The Flexible Action and Articulated Skeleton Toolkit. In *2011 IEEE Virtual Reality Conference*. 247–248. https://doi.org/10.1109/VR.2011.5759483

[28] Evan A. Suma, Zachary Lipps, Samantha Finkelstein, David M. Krum, and Mark Bolas. 2012. Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (2012), 555–564. https://doi.org/10.1109/TVCG.2012.47

[29] Jerald Thomas and Evan Suma Rosenberg. 2019. A General Reactive Algorithm for Redirected Walking Using Artificial Potential Functions. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 56–62. https://doi.org/10.1109/VR.

2019.8797983

[30] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks, Jr. 1999. Walking > Virtual Walking > Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 359–364. https://doi.org/10.1145/311535.311589

[31] Khrystyna Vasylevska, Hannes Kaufmann, Mark Bolas, and Evan A. Suma. 2013. Flexible spaces: Dynamic layout generation for infinite walking in virtual environments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. 39–42. https://doi.org/10.1109/3DUI.2013.6550194

[32] Betsy Williams, Gayathri Narasimham, Timothy P. McNamara, Thomas H. Carr, John J. Rieser, and Bobby Bodenheimer. 2006. Updating orientation in large virtual environments using scaled translational gain. In *Proceedings of the 3rd Symposium on Applied Perception in Graphics and Visualization (APGV '06)*. ACM, New York, NY, USA, 21–28. https://doi.org/10.1145/1140491.1140495

[33] Betsy Williams, Gayathri Narasimham, Björn Rump, Timothy P. McNamara, Thomas H. Carr, John Rieser, and Bobby Bodenheimer. 2007. Exploring large virtual environments with an HMD when physical space is limited. In *Proceedings of the 4th Symposium on Applied Perception in Graphics and Visualization (APGV '07)*. ACM, New York, NY, USA, 41–48. https://doi.org/10.1145/1272582.1272590

[34] Michael A. Zmuda, Joshua L. Wonser, Eric R. Bachmann, and Eric Hodgson. 2013. Optimizing Constrained-Environment Redirected Walking Instructions Using Search Techniques. *IEEE Transactions on Visualization and Computer Graphics* 19, 11 (2013), 1872–1884. https://doi.org/10.1109/TVCG.2013.88

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009