Locomotion Methods and Embodiment in Sequential VR Tasks

Ivan A. Aguilar* — Simon Fraser University
Ammaar Zaman† — Know Center Research GmbH
Aleksandra Krajnc‡ — Know Center Research GmbH
Tim F. Stadlbauer§ — University of Groningen
Andreea I. Sburlea¶ — University of Groningen
Ernst Kruijff‖ — Bonn-Rhein-Sieg University of Applied Sciences
Eduardo E. Veas** — Graz University of Technology
Bernhard E. Riecke†† — Simon Fraser University

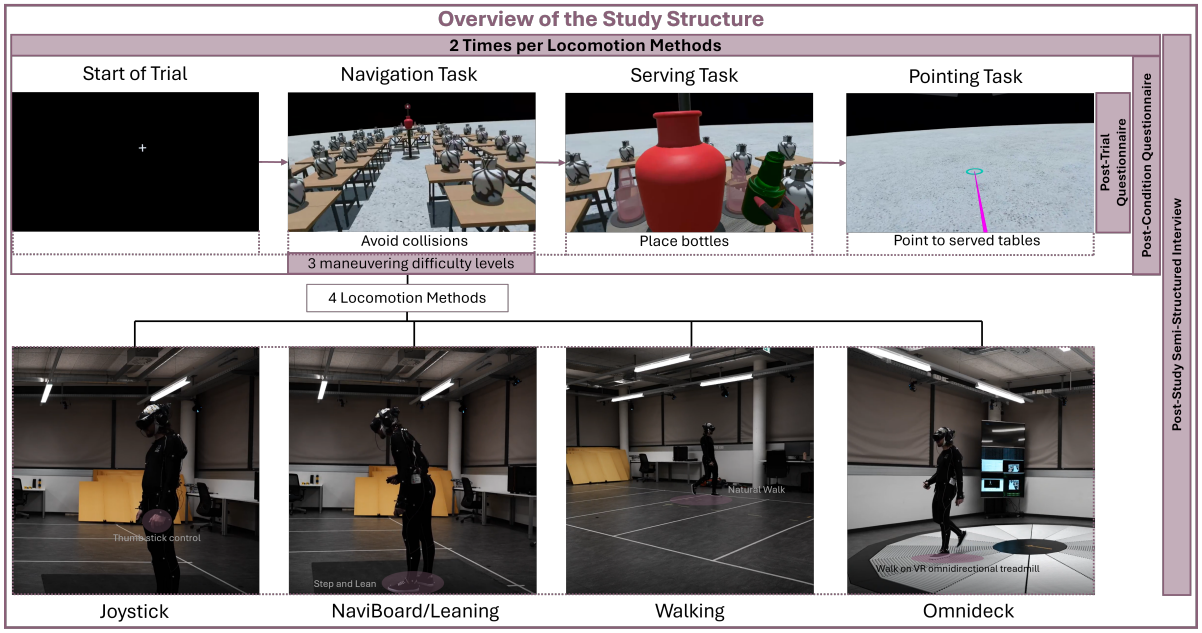


Figure 1: Sequential restaurant task and locomotion conditions. In each level, participants first navigated to target tables and placed bottles on the corresponding coasters. They then returned to the center and pointed to the last four served tables in reverse order.

Abstract

Locomotion in virtual reality shapes not only travel, but also how users coordinate interaction, maintain spatial understanding, and remain comfortable over time. Prior work has compared walking, controller travel, leaning interfaces, and omnidirectional treadmills mostly in isolated navigation tasks, leaving open how they perform when movement must stay coordinated with object interaction and spatial updating. We report a within-subjects study comparing joystick steering, a standing NaviBoard-inspired leaning interface, an Omnideck treadmill, and free walking in a sequential restaurant task. Participants navigated to target tables, placed bottles accurately, and then pointed to the locations of recently served tables across increasing difficulty. Walking provided the strongest overall task performance, lowest sickness and maneuvering difficulty, and highest post-condition comfort, ease of use, naturalness, safety, and usability. Joystick emerged as the clearest non-walking fallback for efficient task execution and control simplicity. Leaning and Omnideck increased bodily involvement, but this added embodiment did not automatically improve integrated task performance. Omnideck's clearest non-walking advantage was engagement rather than efficiency or comfort. Difficulty amplified coordination costs, and repetition improved selected outcomes without reversing the overall ranking. These results show that embodiment is beneficial only when locomotion preserves a coherent relation between movement, task demands, and spatial updating.

Index Terms: Virtual Reality, locomotion, spatial understanding, user study

1 Introduction

Locomotion is one of the central design choices in virtual reality because it shapes more than movement through a scene. It affects how users stay oriented, how easily they interact with objects, how much effort the interface demands, and how comfortably they can continue acting over time. This becomes especially important in applied settings such as training, collaborative virtual environments, and telepresence, where users rarely move for travel alone. They of-

*e-mail: iaguilar@sfu.ca
†e-mail: azaman@know-center.at
‡e-mail: akrajnc@know-center.at
§e-mail: t.f.stadlbauer.1@student.rug.nl
¶e-mail: a.i.sburlea@rug.nl
‖e-mail: ernst.kruijff@h-brs.de
**e-mail: eveas@tugraz.at
††e-mail: ber1@sfu.ca

ten have to navigate while manipulating objects, maintaining task context, avoiding obstacles, and updating spatial memory. In this sense, locomotion is part of the wider 3D interaction problem rather than a separate travel mechanism [34].

Prior locomotion research shows that these requirements do not lead to one universally best technique. Physical walking is a strong baseline because it preserves body based self motion cues that support orientation and spatial updating [43]. Its practical limitation is that many applications cannot provide enough tracked space for unconstrained walking. Controller steering is flexible and familiar, but visual motion without matching physical translation can increase sensory conflict and discomfort [11, 40]. Leaning interfaces and omnidirectional treadmills offer more embodied alternatives by bringing body movement back into the control loop, yet they can also introduce balance demands, gait adaptation, control effort, or precision costs [42, 22, 35].

This creates a problem for applied VR. Many locomotion comparisons focus mainly on travel, target search, or route following. Such tasks are valuable because they isolate movement performance, but they do not fully capture situations in which movement has to remain coordinated with object interaction and retained spatial knowledge. A method that works well for point to point travel may behave differently when users must also avoid obstacles, place objects accurately, remember recently visited locations, and continue acting as task difficulty increases. Recent work similarly shows that locomotion outcomes can diverge across efficiency, orientation, usability, and cybersickness, which makes task context central to interpretation [28, 13].

We examine this issue with a sequential restaurant task that combines navigation, bottle placement, collision avoidance, and later pointing to recently served table locations. The study compares joystick steering, a standing NaviBoard inspired leaning interface, an Omnideck treadmill, and free walking in a within subjects design. All four methods preserve physical rotation, but they differ in how virtual translation is controlled. This allows manual steering, partial bodily control, treadmill based walking, and unconstrained walking to be compared under the same task structure and across increasing difficulty.

The study contributes a task setting for evaluating locomotion beyond travel, a controlled comparison of four practically relevant locomotion methods, and an account of when bodily involvement helps or hinders sequential task performance. The findings show that bodily involvement is beneficial when it helps users coordinate movement, object interaction, spatial recall, and comfort. It can become a cost when the locomotion mapping adds regulation effort that the task does not need.

2 Background and Related Work

Locomotion in VR affects not only how users move through a scene, but also how they remain oriented, manage effort, and coordinate action within the virtual environment. It shapes spatial updating, comfort, presence, and task control. These issues become sharper when navigation is embedded in a task sequence rather than treated as travel alone. The relevant work is therefore not only about moving through virtual space, but about how movement remains coordinated with manipulation and retained spatial knowledge.

2.1 Locomotion methods in VR

VR locomotion techniques can be classified by how travel is controlled, whether movement remains continuous, and which self motion cues are preserved during translation and rotation. The four methods tested here are all active and continuous, and all preserve physical rotation. They differ mainly in the mapping used for virtual translation. Walking provides one to one overground translation, Joystick uses manual rate control without physical translation, NaviBoard uses leaning based body displacement as a travel command, and Omnideck locomotion uses constrained gait based input. This places the comparison within a standard locomotion design space shaped by control mapping, self motion cues, technical constraint, and task demand rather than by naturalness alone [43, 1, 13, 34].

Physical walking is the most direct form of VR locomotion because translation and rotation are accompanied by congruent vestibular, proprioceptive, kinesthetic, visual, and motor cues. These cues support orientation and spatial updating while movement unfolds, which explains why walking is often used as the natural reference condition in navigation studies [43, 53, 48, 49]. Its practical limitation is space. Many VR applications cannot provide a tracked area large enough for unconstrained walking, especially when the task requires repeated travel or larger virtual environments.

Controller based locomotion addresses this space constraint by allowing users to translate through the virtual scene without physically walking. Joystick steering is common because it is compact, familiar, and easy to deploy. It can preserve continuous optic flow, but it also separates visual self motion from physical translation, which can increase sensory conflict and discomfort [11, 40]. Teleportation reduces continuous visual motion and can lower sickness, but it may also disrupt path continuity and spatial updating [8, 10, 30, 62]. Controller based travel therefore remains useful, but its suitability depends on whether continuity, comfort, and spatial updating are more important for the task than bodily self motion.

Artificial translation is not equally disruptive in every configuration, because some body based cues can remain available. Preserving real body rotation while using artificial translation can improve navigation compared with fully artificial movement, because heading changes remain tied to the user's own body [44]. In the present experiment, all four locomotion conditions preserved one to one physical rotation. The comparison focuses on how translation method affects task coordination when body based turning is held constant.

Omnidirectional treadmills and related walking simulators try to preserve more of the walking experience within limited space. Prior work distinguishes passive slip style systems from larger active systems with belts, rollers, or other recentering mechanisms [55, 14, 29]. These systems can provide walking like input, but their benefits are not automatic. Gait can become slower, more effortful, or less stable than overground walking, and performance depends strongly on the treadmill design and task demands [35, 54, 61, 26]. Treadmill based locomotion is therefore most informative in tasks that reveal whether added gait involvement supports the task or becomes another control demand.

Across these method families, the literature points to a common tradeoff rather than a simple ranking. Walking often gives strong spatial and experiential benefits, but it requires space. Joystick steering is practical and efficient, but can increase sensory conflict. Teleportation can reduce sickness, but may weaken continuous updating. Treadmills and other embodied systems can increase body involvement, but may add learning and control costs. Locomotion evaluations are therefore strongest when they are grounded in the task users must perform, not only in naturalness or embodiment level [1, 13, 34].

2.2 Embodied locomotion and leaning interfaces

Embodied locomotion interfaces use the user's body as part of the movement command rather than relying only on abstract manual input. In VR, such mappings can support presence, self motion perception, orientation, and interaction with the surrounding scene [50, 25]. At the same time, bodily involvement can also introduce effort, balance demands, and control uncertainty. Bodily involvement is valuable when the mapping supports the task, and costly when it adds effort, balance demands, or control uncertainty.

Leaning based locomotion shows this tradeoff clearly. These interfaces map head, torso, or body displacement to virtual translation, which can keep the hands available for object interaction while still using the body to guide movement [20, 42, 22]. This makes leaning attractive for tasks in which movement and manipulation occur together. A user can move through the scene while keeping the controllers available for reaching, grasping, or placing objects.

Prior work shows that leaning interfaces can improve presence, vection, or usability compared with handheld control when the mapping is well tuned and physical rotation remains available [23, 22, 33]. Their benefits, however, are sensitive to gain, dead zones, stability, and physical effort [32]. If users have to monitor posture too carefully or correct unintended motion, the embodied mapping can become part of the task burden rather than a support for it.

Similar tradeoffs appear across wheelchair, leaning, walking in place, treadmill, and joystick interfaces. These interfaces each distribute control cost differently across comfort, intuitiveness, physical effort, and spatial performance [2, 39, 57, 17]. The present study therefore does not treat more bodily involvement as automatically better. Instead, it asks whether each locomotion method preserves coordination when users must move, serve objects, avoid obstacles, and later recall locations.

2.3 Sequential tasks, manipulation, and spatial updating

In many applied VR tasks, movement unfolds while the user is also acting on the environment. Users may have to navigate while selecting or manipulating objects, maintaining awareness of task goals, and remembering where relevant places were encountered. Work on 3D object interaction shows that manipulation itself brings tradeoffs between directness, precision, and control complexity [3, 38, 36]. When locomotion and manipulation occur together, the interface has to support both without forcing users to constantly pause, switch attention, or repair the control relation.

Locomotion work increasingly treats this interference as a design problem rather than a side effect. Interfaces that leave the hands free can reduce interference with object manipulation, but only when the locomotion mapping is itself easy to regulate [22]. Work on locomotion during concurrent object manipulation further shows that travel techniques must preserve the ability to select, manipulate, and act without excessive interference [60]. In the restaurant task, this issue appears when participants must move and place bottles within one continuous sequence.

The task also depends on spatial updating. Reaching a destination is not the only spatial demand in VR navigation. Users must also maintain an updated relation between their body, the path taken, the objects encountered, and the places that may need to be recalled later [48, 44, 4]. Many locomotion studies use target search, path following, or maze traversal because these tasks isolate travel effectively. Those paradigms are valuable, but they do not fully capture situations where navigation, object placement, collision avoidance, and memory have to remain coupled over time [6, 52, 58].

The resulting gap is a task setting in which locomotion, object placement, obstacle avoidance, and later recall remain linked rather than measured separately. The present study uses a task in which participants move through changing paths, place bottles at target tables, avoid obstacle tables, and then point to recently served locations. The comparison therefore tests locomotion under conditions closer to applied VR than isolated travel alone.

2.4 Gap and motivation

Prior work shows that locomotion affects spatial updating, comfort, presence, and user experience, and that embodied input can be beneficial when it fits the task. What remains less clear is how these tradeoffs appear when movement must stay coordinated with object placement, obstacle avoidance, and retained spatial knowledge in one sequential VR task. This gap matters for applied domains such as training, collaborative VR, and telepresence, where locomotion is rarely the only demand.

To address this gap, the study uses a restaurant inspired testbed that combines navigation, serving, and exploratory spatial updating across increasing difficulty. Rather than asking which locomotion method is best in general, we ask which methods best preserve coordinated task performance when movement, action, and memory must work together over time.

3 Research Focus and Contributions

Prior work has examined many locomotion techniques, but less is known about how these techniques behave when movement, object interaction, obstacle avoidance, and memory are combined within one task sequence. The present study examines this problem by comparing four locomotion methods in a task where navigation must remain coordinated with object placement, obstacle avoidance, and later spatial recall.

The study addresses four research questions.

- **RQ1.** How do the locomotion methods influence performance across navigation, object placement, collision avoidance, and spatial updating?
- **RQ2.** How do the methods affect user experience, including workload, comfort, engagement, cybersickness, and perceived control?
- **RQ3.** What practice and adaptation effects emerge across repeated exposure to the locomotion methods?
- **RQ4.** How does task difficulty interact with locomotion method to affect performance and user experience?

The study contributes in three ways. First, it introduces a sequential VR task that evaluates locomotion as part of navigation, object placement, collision avoidance, and exploratory spatial updating. Second, it provides a controlled within subjects comparison of joystick steering, NaviBoard inspired leaning, Omnideck treadmill locomotion, and free walking under the same task demands. Third, it shows that embodied locomotion depends on task fit rather than on bodily involvement alone. The findings show that bodily involvement helps when it keeps movement, interaction, spatial updating, and comfort easy to coordinate, but becomes costly when the mapping adds effort that the task does not need.

4 Experimental Setup

The study compared four locomotion methods in a shared virtual restaurant task. The task, environment, object interaction, and physical rotation were kept consistent across conditions, while the method for controlling virtual translation was varied.

4.1 Locomotion Interfaces and Equipment

The study was implemented in Unity 2020.3 and rendered on a desktop computer with an Intel Core i7 14700K processor, 32 GB of DDR4 memory, and an NVIDIA GeForce RTX 4070 graphics card with 12 GB of GDDR6X memory. Visuals were displayed on a Meta Quest Pro headset at 1800×1920 pixels per eye and 90 Hz, with a field of view of 106° horizontally and 96° vertically. Audio was delivered through Sony WH CH720N noise canceling headphones. Interaction used Meta Quest Touch Pro controllers with onboard cameras for inside out six degrees of freedom tracking. This supported bottle grasping and placement even when the controllers moved outside the headset camera view.

Across all locomotion methods, physical body rotation was mapped one to one to virtual rotation. Preserving physical rotation was intended to maintain body based heading cues and avoid the additional confound of artificial turning, which prior work has linked to spatial cognition and cybersickness outcomes [59, 46, 47, 44, 45, 41]. The experimental manipulation therefore focused on the method used for virtual translation.

Joystick steering. Participants translated through the scene with a controller thumbstick. Translation direction followed controller orientation, and movement speed scaled with thumbstick deflection. Motion smoothing was applied to reduce abrupt acceleration and support comfort during continuous movement [24].

NaviBoard leaning. Participants stood on a circular platform and controlled translation by leaning or stepping away from the center. A rigid 24 cm central plate with a tactile cylindrical stub helped participants identify the neutral position by feel. A fixed 12 cm dead zone reduced unintended translation. Once the estimated head rotation center moved beyond that zone, virtual translation was applied in the corresponding direction, with speed increasing nonlinearly as displacement increased. Spatialized audio conveyed movement speed. Compared with the original NaviBoard implementation, our version used a smaller dead zone, relied on the head rotation center rather than raw HMD position to allow head turns without unintended translation, and added audio cues for speed feedback [42, 23].

Omnideck treadmill. Participants walked on an Omnideck omnidirectional treadmill with a diameter of approximately 5.0 m. Rollers beneath the surface helped keep users near the center and responded to displacement and speed estimated from the HMD position. A flat central region without rollers provided stable footing at the center of the treadmill.

Walking. Free walking served as the natural control condition. Participants walked inside a tracked area of 8.45 $\times$ 5.25 m that was mapped one to one to the virtual environment. This condition preserved the closest correspondence between physical and virtual translation and required minimal additional interface learning.

Full body motion capture and electroencephalography were recorded during the study, but they are not analyzed in this paper. The present analysis focuses on behavioral logs, level summary ratings, and retained questionnaire data.

4.2 Virtual Environment and Task

The virtual environment resembled a restaurant and measured 8.45 $\times$ 5.25 m. The scene intentionally avoided strong global orientation cues. Lighting was directed downward to avoid directional shadows, no walls or landmarks were present, and the floor used a neutral cement texture inside a circular boundary with an 8 m radius. The task narrative was inspired by restaurant service scenes in *Ratatouille* [5] and by prior work on teleoperated service robots in restaurant settings [56].

Each level combined a serving phase and a pointing phase, as shown in Figure 1. In the serving phase, participants started at the center of the environment and navigated along paths delimited by obstacle tables. Their task was to serve drinks as quickly and accurately as possible while avoiding collisions. Target bottle locations were indicated by coasters and semitransparent bottles. Each target table required two bottles. When participants approached a table, the bottles appeared. After correct placement, an audio cue confirmed success and the served table disappeared. New paths and target tables appeared until the level was completed. At the beginning of the session, participants chose the hand used for bottle manipulation and, where relevant, the hand used for movement control. These assignments remained fixed throughout the study.

The pointing phase began when participants returned to the center marker and waited for three seconds. They then pointed, using a ray cast from the manipulation hand, to the last four tables served in that level in reverse order. During the serving phase, the tables that had to be remembered were marked with a red vase and number. An audio cue reinforced the instruction once the first target table appeared.

Task difficulty increased across three levels. Level 1 contained straight paths and four tables. Level 2 contained curved paths and seven tables. Level 3 contained curved paths with narrow sections and eight tables. After each level, participants viewed a leaderboard showing their performance for that locomotion condition and level. They then answered short in VR questions about sickness, disorientation, and difficulty, followed by a thirty second quiet standing period while posture was recorded. Participants were told that performance depended on obstacle avoidance, bottle placement precision, minimizing extra bottles, accurate pointing, and overall completion time.

5 Experimental Design and Procedure

5.1 Participants and Ethical Considerations

The analysis included 32 participants. Age ranged from 18 to 36 years ($M = 27.06$, $SD = 4.54$). Twenty participants identified as male and 12 as female. Participants completed a pre study questionnaire covering vision, vestibular issues, gaming habits, prior VR experience, and experience with game controllers. Participants received 60 euro vouchers as compensation. The study protocol was approved by the institutional ethics committee.

5.2 Repeated Measures Design

The experiment used a 4x2x3 within-subjects design with locomotion method, repetition, and difficulty level as repeated factors. Each participant experienced four locomotion methods: joystick steering, NaviBoard leaning, Omnideck locomotion, and free walking. Locomotion order was counterbalanced with a Latin square to reduce order and carryover effects.

For each locomotion method, participants first completed one short practice trial containing only the first difficulty level, followed by two full experimental trials (repetitions), resulting in eight full trials in total. Each full trial contained the three difficulty levels in ascending order. Level layouts were drawn from a larger pool and varied between trials, with the constraint that the same layout set could not occur in immediately consecutive trials.

5.3 Training and Familiarization

At the beginning of the session, participants reviewed and signed the informed consent form, completed the pre study questionnaire, read an illustrated instruction sheet, and watched a gameplay video showing the task flow. The researcher then demonstrated the three task levels so that participants could become familiar with the restaurant scenario, controller mappings, collisions, bottle placement, pointing phase, and the short in VR questions shown after each level. Interpupillary distance was adjusted with the Meta Quest Pro setup tool and recorded so that it could be restored whenever the headset was worn.

Participants then completed short familiarization sessions with all four locomotion methods. Only the first task level was demonstrated and practiced for each method. During Omnideck familiarization, treadmill speed was adjusted to a comfortable preferred speed for each participant and recorded for later use. During NaviBoard leaning and joystick familiarization, the researcher demonstrated the platform setup, movement mapping, and control boundaries. Participants continued to the experimental trials after confirming that they understood the locomotion method and felt able to perform the task.

After familiarization, participants changed into the motion capture suit, were fitted with the EEG cap, and completed the calibration steps required for marker placement and skeleton tracking.

5.4 Experimental Procedure

Participants completed the counterbalanced sequence of locomotion conditions. Within each condition, they first completed the short practice trial and then two full trials. Each level followed a fixed sequence. Participants completed the serving phase, returned to the center, completed the pointing phase, viewed leaderboard feedback, answered the short in VR questions, and then stood quietly for thirty seconds while posture was recorded.

After each full trial, participants completed a post trial questionnaire on a tablet. The questionnaire included the Simulator Sickness Questionnaire [31], the NASA Task Load Index [21], a vection rating [19], and a rating of real environment awareness. After the second full trial for each locomotion condition, participants completed a post condition questionnaire covering usability, comfort, presence, spatial presence, perceived control, tiredness, and related user experience factors. Presence and spatial presence items were derived from the Igroup Presence Questionnaire [51]. Short breaks were provided between conditions as needed.

After the final locomotion condition, participants completed a comparative survey ranking the four methods. They were then debriefed and thanked.

6 Measures

Measures covered task execution, spatial recall, and user experience. Task execution measures were derived from the behavioral logs. They included completion time, total distance traveled, extra bottles used, bottle placement error, obstacle collision incidence, obstacle collision count, and average collision time for trials with a collision. These measures captured efficiency, route behavior, serving precision, obstacle contact, and recovery from collisions.

Spatial recall was assessed during the pointing phase. The retained measures were absolute pointing error, absolute ego orientation error, configuration error, absolute distance estimation error, and pointing response time [15]. Absolute pointing error captured directional accuracy toward remembered table locations. Absolute ego orientation error captured errors in the participant's estimated facing direction relative to the remembered targets. Configuration error captured the consistency of remembered target directions. Absolute distance estimation error captured the accuracy of remembered target distance. Pointing response time captured how quickly participants produced a pointing response after the prompt. Because pointing errors were generally large, these outcomes are treated as exploratory rather than as the primary basis for interpreting differences between locomotion methods.

Subjective measures included standardized questionnaires and brief in VR ratings. Cybersickness was assessed with the Simulator Sickness Questionnaire [31], and workload was assessed with the NASA Task Load Index [21]. Presence related experience was assessed with items derived from the Igroup Presence Questionnaire [51]. After each level, brief in VR questions captured sickness, spatial disorientation, pointing difficulty, maneuvering difficulty, and serving difficulty. After each locomotion condition, the post condition questionnaire assessed usability, comfort, engagement, perceived control, tiredness, and related user experience factors. After all conditions, participants completed comparative rankings of the four locomotion methods.

Full body motion capture and electroencephalography were recorded during the study, but they are not analyzed in this paper. The present paper focuses on behavioral logs, level summary ratings, and retained questionnaire data.

7 Analysis

Level summary outcomes were analyzed with mixed effects models including repetition, locomotion condition, difficulty level, and their interactions as fixed effects. Participant was modeled as a random intercept. Each outcome was fit with a distribution and link function appropriate to its scale and distribution.

Completion time and distance traveled were continuous outcomes with heavier tailed variation, so they were modeled with Student t identity link models. Bottle placement error and non zero average collision time were positive and skewed, so they were modeled with Gamma log link models. Extra bottle use and collision count were overdispersed count outcomes and were modeled with negative binomial log link models. Collision incidence was modeled with a binomial logit link model. Bounded in VR rating responses were modeled with ordered beta models using logit or complementary log log links depending on the response distribution. Post condition Likert type items were modeled with ordinal logit mixed models using locomotion condition as the fixed effect.

Omnibus effects are reported with Wald χ^2 tests. Follow up contrasts to significant omnibus effects use unadjusted pairwise p values because the condition comparisons are planned follow ups to the corresponding omnibus model terms and are used to interpret the pattern shown in the estimated marginal means. The interpretation focuses on task performance, immediate in VR ratings, and post condition user experience. The large pointing errors make the spatial-updating measures most useful as exploratory context rather than as the main basis for interface ranking.

8 Results

The results separate three aspects of locomotion quality: movement efficiency, route compactness, and coordination cost. Walking produced the strongest full-task profile, while Joystick emerged as the strongest non-walking method for efficient task execution. Leaning and Omnideck showed different costs: Leaning kept travel distance compact but increased control and recovery burden, whereas Omnideck increased bodily involvement but produced longer paths and more extra bottles. Table 1 summarizes the selected level summary models and their main patterns. The interpretation emphasizes task execution, immediate in-VR ratings, and post-condition user experience. Pointing and spatial recall outcomes are treated as exploratory because pointing errors were generally large.

8.1 Objective Performance

The main task-performance outcomes are shown in Figure 2. Completion time was modeled with a Student t identity link model. A Wald χ^2 (Type III) test showed significant effects of repetition, $\chi^2(1) = 31.67$, $p < .001$, condition, $\chi^2(3) = 566.24$, $p < .001$, difficulty level, $\chi^2(2) = 1946.03$, $p < .001$, and condition by difficulty level, $\chi^2(6) = 65.04$, $p < .001$. Participants were faster in the second repetition (91.67 s, $SE = 2.64$) than in the first (99.70 s, $SE = 2.66$). Walking showed the clearest efficiency advantage (76.66 s, $SE = 2.56$), followed by Joystick (91.71 s, $SE = 3.16$), Omnideck (107.15 s, $SE = 2.87$), and Leaning (107.23 s, $SE = 2.78$). Unadjusted pairwise contrasts separated Walking from all non-walking interfaces and separated Joystick from both Leaning and Omnideck. Leaning and Omnideck were not significantly different. Difficulty increased completion time from Level 1 (58.62 s, (SE=2.53)) to Level 2 (99.24 s, (SE=2.76)) and Level 3 (129.20 s, (SE=2.95)). The significant condition by difficulty interaction shows that locomotion differences became more pronounced as the task became harder. Walking remained fastest at every level, while Joystick stayed the strongest non-walking method and Leaning and Omnideck became increasingly costly in the more demanding levels.

Distance traveled was also modeled with a Student t identity link model. A Wald χ^2 (Type III) test showed significant effects of repetition, $\chi^2(1) = 13.54$, $p < .001$, condition, $\chi^2(3) = 970.56$, $p < .001$, difficulty level, $\chi^2(2) = 16767.84$, $p < .001$, and condition by difficulty level, $\chi^2(6) = 80.21$, $p < .001$. Paths were shorter in Repetition 2 (34.18 m, $SE = 0.24$) than in Repetition 1 (34.88 m, $SE = 0.25$). Joystick (31.53 m, $SE = 0.26$) and Leaning

(31.70 m, $SE = 0.29$) produced the shortest paths and were not significantly different from each other. Walking required more travel (36.24 m, $SE = 0.25$), and Omnideck produced the longest paths (38.63 m, $SE = 0.33$). Unadjusted contrasts separated Joystick and Leaning from Walking and Omnideck, and separated Walking from Omnideck. Difficulty increased distance from Level 1 (20.73 m, $SE = 0.22$) to Level 2 (33.50 m, $SE = 0.28$) and Level 3 (49.35 m, $SE = 0.30$). Distance traveled separated route compactness from task efficiency. Joystick and Leaning produced the shortest paths, but Walking remained fastest overall. This suggests that compact movement was not sufficient for coordinated task performance when users also had to serve bottles, avoid obstacles, and maintain the task sequence.

Serving outcomes showed a clear precision and interaction-cost pattern. Extra-bottle use was modeled with a negative binomial log link model. A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 24.76$, $p < .001$, and difficulty level, $\chi^2(2) = 19.19$, $p < .001$. Omnideck required the most extra bottles (0.92, $SE = 0.14$), followed by Leaning (0.61, $SE = 0.10$), Joystick (0.55, $SE = 0.10$), and Walking (0.42, $SE = 0.09$). Unadjusted contrasts showed higher extra-bottle use for Omnideck than Joystick, Leaning, and Walking. Extra-bottle use also increased from Level 1 (0.42, $SE = 0.07$) to Level 2 (0.64, $SE = 0.11$) and Level 3 (0.82, $SE = 0.13$). Bottle placement error was modeled with a Gamma log link model. A Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 251.79$, $p < .001$. All six unadjusted condition contrasts were significant, although the response-scale estimates were small and tightly clustered around 0.02 m. This indicates reliable but practically compact differences in placement precision across locomotion interfaces.

The collision results were analyzed through collision probability, collision count, and average collision duration. Collision incidence was modeled with a binomial logit link model. A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 10.59$, $p = .014$, and difficulty level, $\chi^2(2) = 181.34$, $p < .001$. Walking had the lowest estimated probability of collision (0.56, $SE = 0.07$), followed by Leaning (0.64, $SE = 0.06$), Joystick (0.76, $SE = 0.06$), and Omnideck (0.79, $SE = 0.06$). Unadjusted contrasts separated Walking from Joystick and Omnideck, and separated Leaning from Omnideck. Collision count was modeled with a negative binomial log link model. A Wald χ^2 (Type III) test showed significant effects of repetition, $\chi^2(1) = 7.92$, $p = .005$, condition, $\chi^2(3) = 17.58$, $p < .001$, and difficulty level, $\chi^2(2) = 448.52$, $p < .001$. Walking had the lowest estimated collision count (0.80, $SE = 0.15$), followed by Omnideck (1.30, $SE = 0.20$), Leaning (1.47, $SE = 0.22$), and Joystick (1.74, $SE = 0.25$). Average collision time was modeled with a Gamma log link model after excluding zero-collision responses, so it estimates recovery duration when a collision occurred.

A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 81.99$, $p < .001$, and difficulty level, $\chi^2(2) = 9.77$, $p = .008$. Joystick had the shortest average collision time (0.46 s, $SE = 0.04$), followed by Walking (0.58 s, $SE = 0.07$), Omnideck (0.63 s, $SE = 0.05$), and Leaning (1.12 s, $SE = 0.09$). Unadjusted contrasts showed longer average collision time for Leaning than Joystick, Omnideck, and Walking, and longer average collision time for Omnideck than Joystick. Together, the collision measures show different safety profiles rather than one single collision pattern. Walking produced the safest overall profile, with the lowest collision probability and lowest collision count. Joystick produced the highest estimated collision count, but its contacts were brief when they occurred. Leaning was not the most collision-prone condition, but it produced the longest recovery time after contact. Omnideck combined high collision probability with longer travel and higher extra-bottle use. Difficulty increased collision probability and collision count, while the non-zero collision-duration model estimated shorter average contact duration at higher levels. This suggests that harder levels produced more frequent contacts rather than necessarily longer individual contact episodes.

8.2 Immediate In-VR Ratings

Immediate in-VR ratings are shown in Figure 3. Higher values indicate worse sickness, disorientation, or difficulty. Sickness severity was modeled with an ordered beta complementary log log link model after zero responses were excluded, so the model estimates non zero sickness severity. A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 80.53$, $p < .001$, and difficulty level, $\chi^2(2) = 23.91$, $p < .001$. The repetition term did not reach the conventional significance threshold, $\chi^2(1) = 3.02$, $p = .082$. Walking produced the lowest sickness estimate (13.19, $SE = 0.02$), followed by Omnideck (21.84, $SE = 0.03$), Joystick (27.34, $SE = 0.03$), and Leaning (30.38, $SE = 0.03$). Unadjusted contrasts separated Walking from each non-walking interface and separated Omnideck from Joystick and Leaning. Joystick and Leaning were not significantly different. Sickness severity increased from Level 1 (18.98, $SE = 0.02$) to Level 2 (21.83, $SE = 0.03$) and Level 3 (26.55, $SE = 0.03$).

Spatial disorientation was modeled with an ordered beta logit link model. A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 44.09$, $p < .001$, and difficulty level, $\chi^2(2) = 27.83$, $p < .001$. Walking was lowest (35.18, $SE = 0.06$), followed by Joystick (42.70, $SE = 0.06$), Omnideck (44.73, $SE = 0.06$), and Leaning (45.96, $SE = 0.06$). Unadjusted contrasts showed that Walking was lower than each non-walking interface. Joystick and Omnideck were not significantly different, and Leaning and Omnideck were not significantly different. Difficulty increased disorientation from Level 1 (37.78, $SE = 0.06$) to Level 2 (42.85, $SE = 0.06$) and Level 3 (45.71, $SE = 0.06$).

Task-specific ratings separated the locomotion interfaces most strongly for maneuvering and serving. Maneuvering difficulty was modeled with an ordered beta logit link model. A Wald χ^2 (Type III) test showed significant effects of repetition, $\chi^2(1) = 5.58$, $p = .018$, condition, $\chi^2(3) = 364.69$, $p < .001$, and difficulty level, $\chi^2(2) = 100.25$, $p < .001$. Walking was lowest (16.30, $SE = 0.02$), followed by Joystick (35.37, $SE = 0.04$), Omnideck (46.83, $SE = 0.04$), and Leaning (53.05, $SE = 0.04$). All six unadjusted condition contrasts were significant. Serving difficulty was also modeled with an ordered beta logit link model. A Wald χ^2 (Type III) test showed significant effects of condition, $\chi^2(3) = 397.23$, $p < .001$, and difficulty level, $\chi^2(2) = 15.61$, $p < .001$. Walking was lowest (13.12, $SE = 0.02$), Joystick was next (19.36, $SE = 0.03$), and Leaning (37.35, $SE = 0.05$) and Omnideck (40.38, $SE = 0.05$) were higher. Unadjusted contrasts separated Walking from all non-walking interfaces and separated Joystick from Leaning and Omnideck. Leaning and Omnideck were not significantly different. These ratings show that locomotion costs were most visible in sickness, disorientation, maneuvering, and serving difficulty. Walking was consistently lowest, and Joystick was the least costly non-walking option for task control.

8.3 Post-Condition User Experience

Post-condition items were analyzed with ordinal logit mixed models because they were Likert-type responses with ordered categories (Table 2). Figure 4 shows the items most directly tied to comfort, control, usability, and engagement. For comfort, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 50.77$, $p < .001$. Comfort was highest for Walking (3.48, $SE = 0.48$), followed by Joystick (0.66, $SE = 0.37$), Omnideck (0.21, $SE = 0.34$), and Leaning (-0.87, $SE = 0.35$). Unadjusted contrasts separated Walking from all non-walking conditions, separated Joystick from

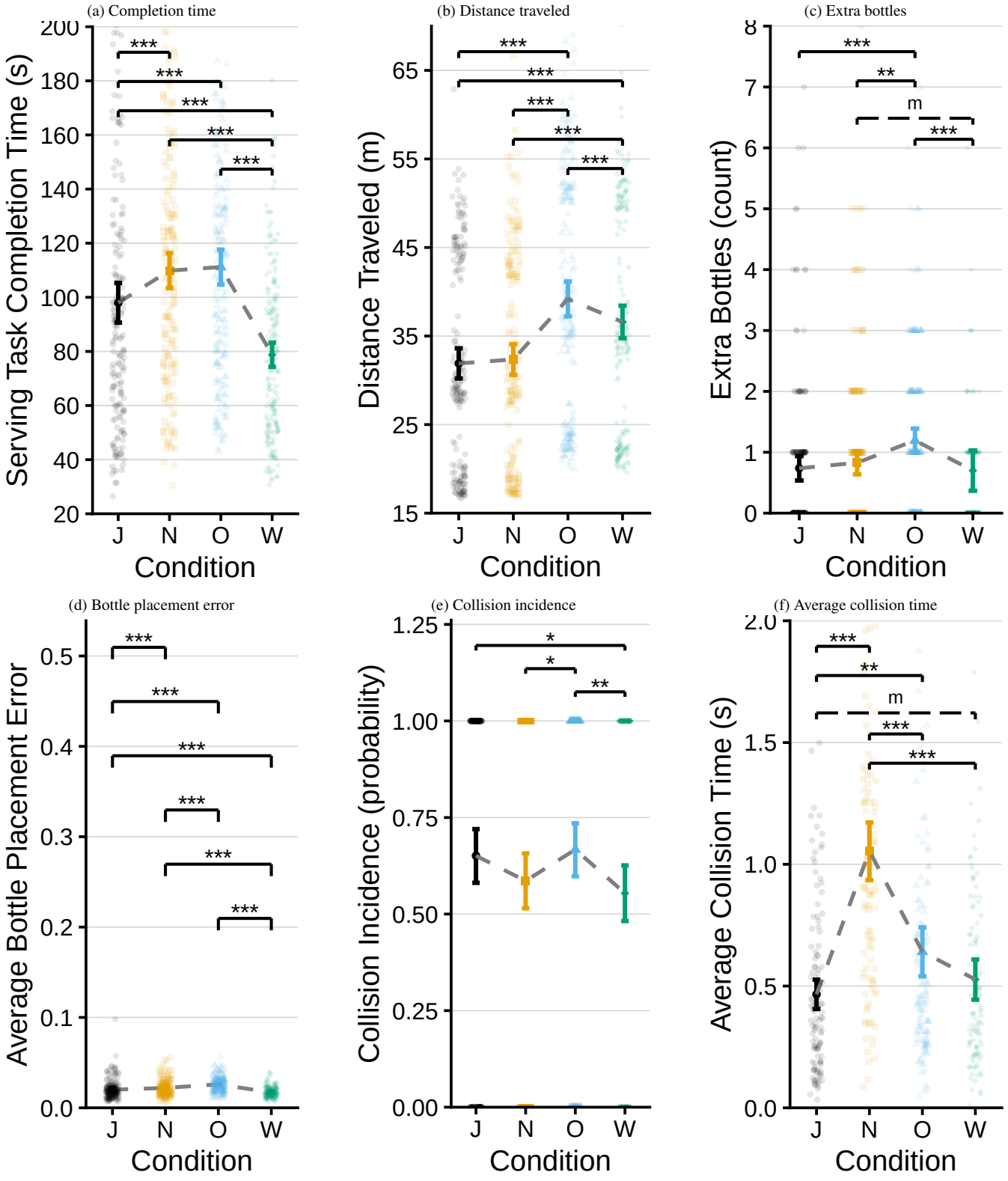


Figure 2: Objective task-performance outcomes by locomotion condition. Points show means, raw data points, and error bars show confidence intervals. Brackets indicate significant unadjusted pairwise condition contrasts. Asterisks denote the significance level: m $p < .1$ * $p < .05$, ** $p < .01$, *** $p < .001$. Lower values indicate better performance for completion time, distance traveled, extra bottles, bottle placement error, and collision outcomes.

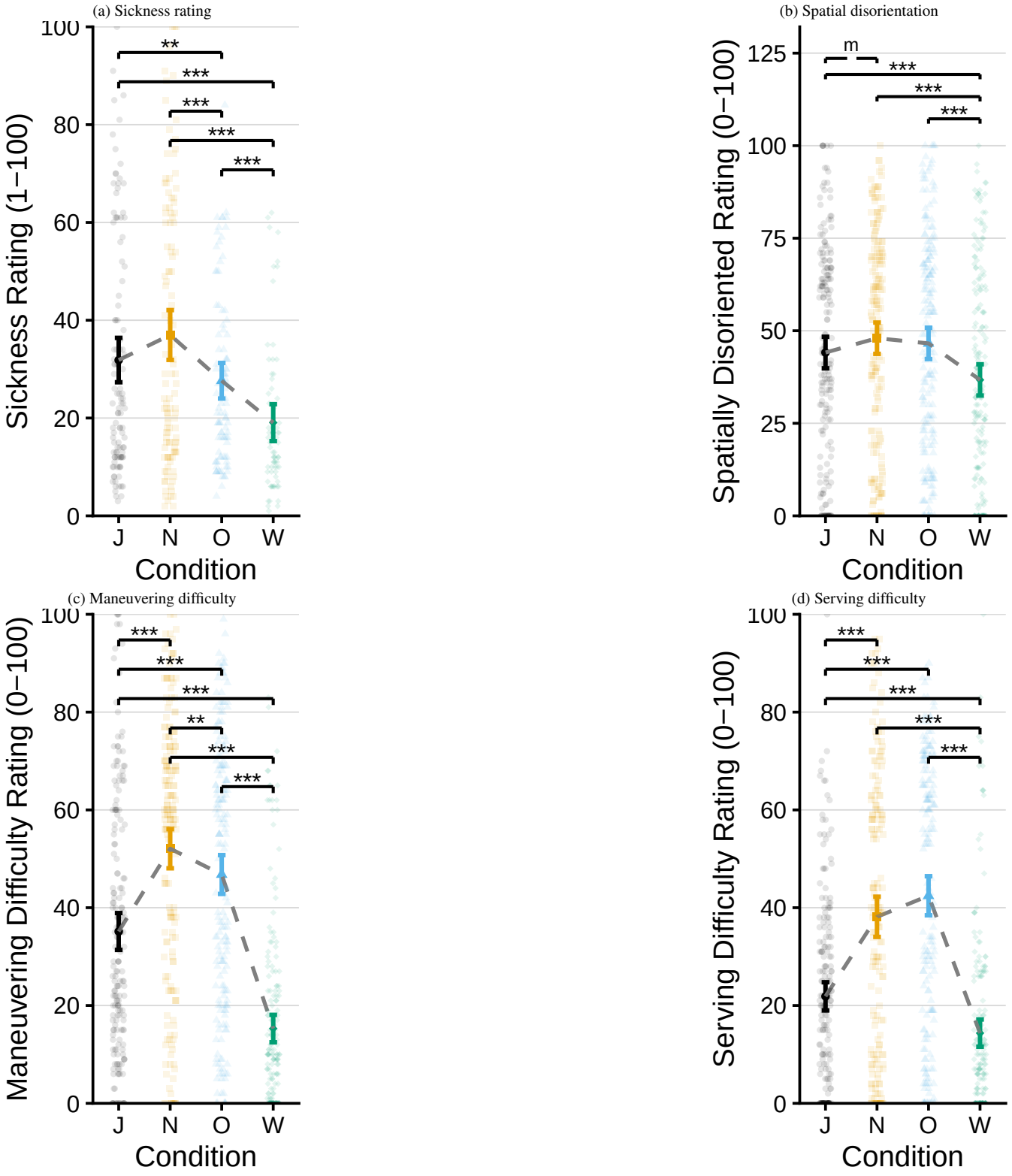


Figure 3: Immediate in-VR ratings by locomotion condition. Points show means, raw data points, and error bars show confidence intervals. Brackets indicate significant unadjusted pairwise condition contrasts. Asterisks denote the significance level: m $p < .1$ * $p < .05$, ** $p < .01$, *** $p < .001$. Lower values indicate lower sickness, disorientation, or task difficulty.

Leaning, and separated Omnideck from Leaning. Joystick and Omnideck were not significantly different. For ease of use, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 59.46$, $p < .001$. Walking was highest (4.92, $SE = 0.62$), Joystick was

Table 1: Summary of selected level summary models for objective outcomes and immediate in VR ratings. Omnibus effects are based on Wald χ^2 (Type III) tests. Pairwise interpretation follows the unadjusted contrasts shown in the corresponding figures.

Outcome	Model family and link	Reliable omnibus effects	Main pattern
Completion time	Student-t, identity	Repetition, Condition, Difficulty, Condition × Difficulty	Walking was fastest. Joystick was the strongest non-walking condition, and difficulty increased completion time.
Distance traveled	Student-t, identity	Repetition, Condition, Difficulty, Condition × Difficulty	Joystick and Leaning produced the shortest paths. Omnideck produced the longest paths, and difficulty increased distance.
Extra bottles	Negative binomial, log	Condition, Difficulty	Omnideck required the most extra bottles. Walking required the fewest.
Bottle placement error	Gamma, log	Condition	Placement error showed reliable condition differences, but absolute errors were small and clustered around approximately 2 cm.
Collision incidence	Binomial, logit	Condition, Difficulty	Walking had the lowest estimated probability of collision, while Omnideck and Joystick were higher.
Collision count	Negative binomial, log	Repetition, Condition, Difficulty	Walking produced the fewest collisions. Joystick produced the highest estimated collision count.
Average collision time	Gamma, log	Condition, Difficulty	Leaning produced the longest average collision time for trials with collisions. Joystick was lowest.
Sickness	Ordered beta, cloglog	Condition, Difficulty	Walking produced the lowest sickness ratings. Sickness increased with difficulty.
Spatial disorientation	Ordered beta, logit	Condition, Difficulty	Walking produced the lowest disorientation ratings. Non-walking conditions were higher.
Maneuvering difficulty	Ordered beta, logit	Repetition, Condition, Difficulty	Walking was easiest to maneuver. Joystick was the least difficult non-walking condition.
Serving difficulty	Ordered beta, logit	Condition, Difficulty	Walking was easiest for serving, followed by Joystick. Leaning and Omnideck were higher.

next (1.80, $SE = 0.43$), and Omnideck (0.26, $SE = 0.39$) and Leaning (-0.41, $SE = 0.39$) were lower. Unadjusted contrasts separated Walking from all non-walking conditions and separated Joystick from both Omnideck and Leaning, while Omnideck and Leaning were not significantly different.

For naturalness, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 56.99$, $p < .001$. Naturalness strongly favored Walking (4.55, $SE = 0.63$), followed by Joystick (-0.27, $SE = 0.35$), Omnideck (-0.36, $SE = 0.34$), and Leaning (-1.45, $SE = 0.36$). Unadjusted contrasts separated Walking from all non-walking conditions, separated Joystick from Leaning, and separated Omnideck from Leaning. Joystick and Omnideck were not significantly different. For safety, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 35.71$, $p < .001$. Safety was highest for Walking (3.21, $SE = 0.48$), followed by Joystick (1.93, $SE = 0.42$), Leaning (0.68, $SE = 0.39$), and Omnideck (0.15, $SE = 0.36$). Unadjusted contrasts separated Joystick from Leaning and Omnideck, separated Walking from Leaning and Omnideck, and separated Walking from Joystick. Leaning and Omnideck were not significantly different.

For overall usability, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 53.86$, $p < .001$. Overall usability again placed Walking highest (3.76, $SE = 0.49$), with Joystick and Omnideck close together (both 0.66, $SE = 0.35$ and $SE = 0.34$) and Leaning lowest (-0.81, $SE = 0.34$). Unadjusted contrasts separated Walking from all non-walking conditions and separated Leaning from Joystick and Omnideck. Joystick and Omnideck were not significantly different. For involvement and engagement, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 47.08$, $p < .001$. Walking was highest (3.38, $SE = 0.47$), followed by Omnideck (0.90, $SE = 0.36$), Joystick (0.41, $SE = 0.37$), and Leaning (-0.52, $SE = 0.36$). Unadjusted contrasts separated Walking from all non-walking conditions and separated Omnideck from Leaning. Omnideck did not differ significantly from Joystick. The post-condition results partly mirrored the objective pattern while also showing where experience and task efficiency separated. Walking was the most comfortable, usable, natural, and safe interface. Joystick remained the clearest non-walking fallback for ease and control, whereas Omnideck's relative advantage appeared mainly in engagement rather than task efficiency or comfort.

8.4 Supportive Workload, Vection, and Sickness Measures

The pre-post trial questionnaire measures provide additional context for the task and post-condition results. They are not plotted as primary outcomes because they describe broader workload, vection, immersion, and sickness responses rather than the task-specific coordination measures shown. Table 3 summarizes the condition-level EMMs.

Overall workload was consistent with the task-control pattern. A Wald χ^2 (Type III) test showed a significant condition effect for Overall NASA-TLX, $\chi^2(3) = 48.58$, $p < .001$. Walking and Joystick had the lowest estimated workload, Omnideck was higher, and Leaning was highest, indicating that the more embodied non-walking interfaces did not reduce perceived workload in this task. Unadjusted contrasts separated Joystick from Leaning and Omnideck, and separated Walking from Leaning and Omnideck. Joystick and Walking were not significantly different.

Vection and immersion showed why embodiment alone does not explain the task-performance results. For vection, a Wald χ^2 (Type III) test showed a significant condition effect, $\chi^2(3) = 95.45$, $p < .001$. Walking produced the strongest vection estimate, followed by Omnideck, while Joystick and Leaning were lower and not significantly different. For immersion, a Wald χ^2 (Type III) test showed a smaller but significant condition effect, $\chi^2(3) = 8.17$, $p = .043$. Walking and Leaning were higher than Joystick, while Omnideck was intermediate. These results show that bodily involvement did not produce a single experiential pattern. Walking produced the strongest vection and high immersion. Omnideck showed its clearest non-walking advantage in vection and engage-

Table 2: Summary of selected post condition ordinal logit mixed models. Omnibus effects are based on Wald χ^2 (Type III) tests. Each item was modeled with condition as the fixed effect and participant as a random intercept. Pairwise interpretation follows unadjusted planned condition contrasts.

Outcome	Model family and link	Omnibus condition effect	Main pattern after unadjusted contrasts
Comfort	Ordinal, logit	$\chi^2(3) = 50.77$, $p < .001$	Walking was highest. Joystick and Omnideck were not significantly different, and Leaning was lowest.
Ease of use	Ordinal, logit	$\chi^2(3) = 59.46$, $p < .001$	Walking was highest, followed by Joystick. Omnideck and Leaning were lower.
Naturalness	Ordinal, logit	$\chi^2(3) = 56.99$, $p < .001$	Walking was highest. Joystick and Omnideck were not significantly different, and Leaning was lowest.
Safety	Ordinal, logit	$\chi^2(3) = 35.71$, $p < .001$	Walking was highest, Joystick was next, and Omnideck and Leaning were lower.
Overall usability	Ordinal, logit	$\chi^2(3) = 53.86$, $p < .001$	Walking was highest. Joystick and Omnideck were not significantly different, and Leaning was lowest.
Involvement and engagement	Ordinal, logit	$\chi^2(3) = 47.08$, $p < .001$	Walking was highest. Omnideck showed the strongest non-walking engagement pattern, but did not differ significantly from Joystick.

Table 3: Supportive pre-post trial questionnaire outcomes by locomotion condition. Values are estimated marginal means with standard errors on the response scale. Omnibus effects are based on Wald χ^2 (Type III) tests.

Outcome	Model family and link	Joystick	Leaning	Omnideck	Walking
Overall NASA-TLX	Student-t, identity	46.16 (2.41)	52.48 (2.43)	50.19 (2.40)	45.07 (2.42)
Vection	Ordered beta, logit	50.57 (0.05)	53.06 (0.05)	68.58 (0.04)	84.26 (0.03)
Immersion	Ordered beta, logit	67.09 (0.06)	74.41 (0.05)	70.04 (0.05)	75.54 (0.05)
Post Total SSQ	Gamma, log	22.41 (3.79)	26.85 (4.48)	24.38 (4.09)	16.67 (2.81)

ment, whereas Leaning was closer to Joystick for vection despite higher immersion. The experiential benefits of bodily involvement therefore did not automatically translate into better task performance.

Post Total SSQ was modeled with a Gamma log link after excluding zero responses. A Wald χ^2 (Type III) test showed significant effects of repetition, $\chi^2(1) = 6.54$, $p = .011$, and condition, $\chi^2(3) = 22.02$, $p < .001$. Walking had the lowest estimated SSQ total, followed by Joystick, Omnideck, and Leaning. Unadjusted contrasts separated Walking from Joystick, Omnideck, and Leaning. This broader sickness severity measure is consistent with the immediate in-VR sickness ratings, where Walking was also lowest.

8.5 Exploratory Pointing and Spatial Measures

The pointing-related measures are interpreted as exploratory because pointing errors were generally large. Absolute pointing error, absolute ego-orientation error, configuration error, pointing response time, and absolute distance-estimation error each showed some condition-sensitive structure. However, the measurement noise in the pointing task limits how strongly these outcomes can rank the locomotion interfaces. The main conclusion therefore rests on task execution, serving accuracy, collision cost, immediate comfort, and post-condition user experience. The spatial results still provide useful secondary evidence because they document directional trends and response-timing patterns without carrying the main interface ranking.

8.6 Repetition and Task Demand

Across outcomes, repetition effects were selective rather than global. Repetition improved completion time, distance traveled, maneuvering difficulty, and collision count, but it did not reverse the condition ranking. Difficulty had broader effects and increased completion time, distance traveled, extra-bottle use, collision incidence, collision count, sickness, disorientation, maneuvering difficulty, and serving difficulty. Participants adapted with exposure, but the locomotion mappings still produced stable differences in how easily users coordinated movement, serving, and comfort under increasing task demand.

9 Discussion

This study compared four locomotion methods in a sequential VR task that combined navigation, object placement, obstacle avoidance, and later recall of served table locations. The results do not support a simple progression in which more bodily involvement automatically produced better performance. Walking produced the strongest integrated profile, but Joystick remained the most effective alternative to walking for efficient task execution. Leaning and Omnideck increased bodily involvement in different ways, yet both introduced coordination costs that limited their benefit in the full task. The main implication is that embodied locomotion has to be judged through task fit. Bodily involvement helped when it kept movement, interaction, spatial updating, and comfort easy to coordinate. It became less useful when the mapping added regulation demands that competed with the task.

Walking supported integrated task execution, not only travel. Walking was fastest, produced the lowest sickness and disorientation ratings, was easiest for maneuvering and serving, and received the strongest post condition ratings for comfort, ease of use, naturalness, safety, usability, and engagement. This broad advantage is consistent with work showing that physical walking provides body based information that supports orientation, distance estimation, and spatial updating in virtual environments [43, 53, 48, 49]. Ruddle et al. [48] are especially relevant because they separate body based translational and rotational information and show how such information contributes to cognitive map accuracy. The present study extends this logic to a task in which users were not only moving through space, but also serving objects, avoiding obstacle tables, managing a changing route, and responding to increasing task difficulty.

The distance result makes this interpretation more specific. Joy-

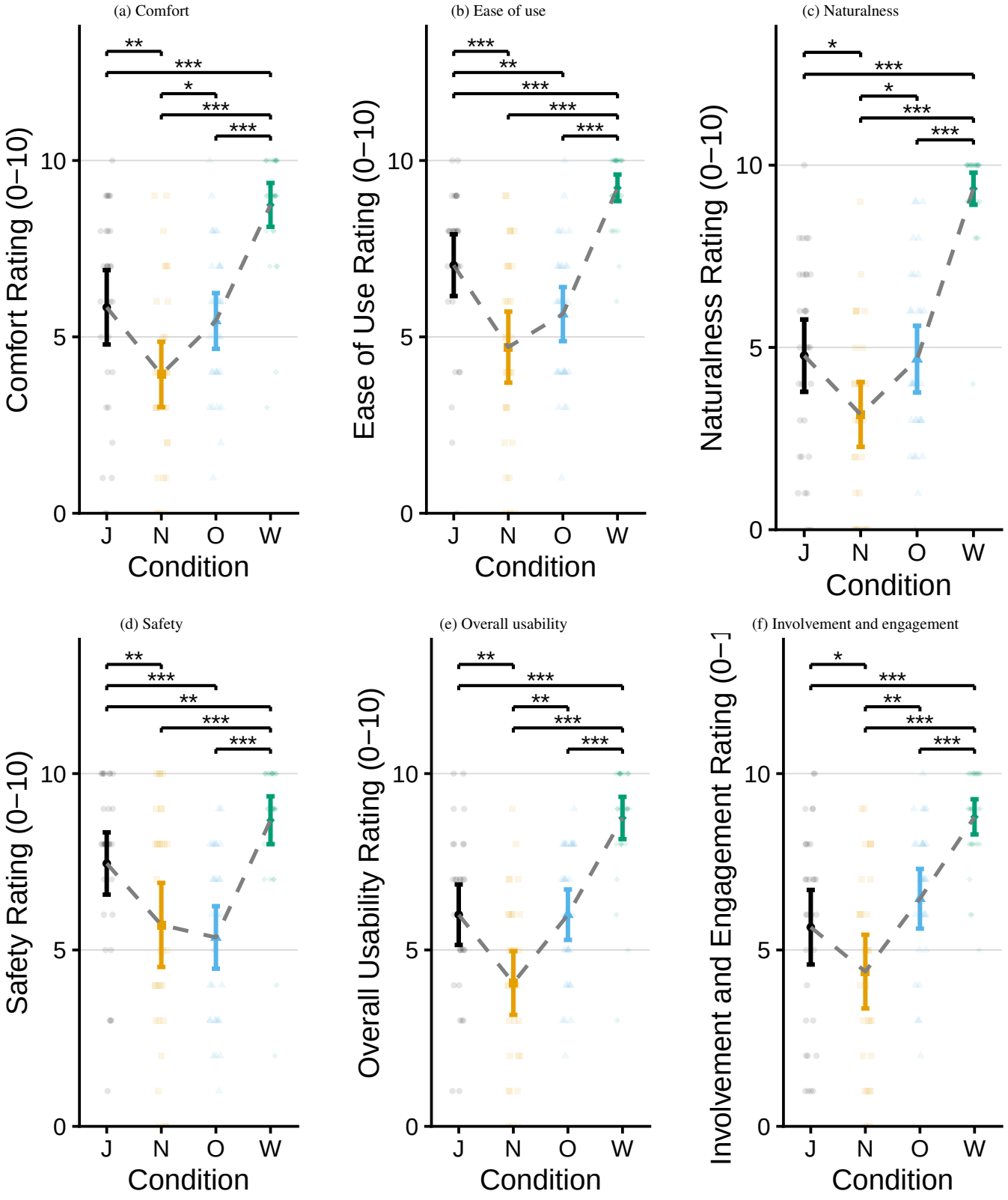


Figure 4: Post condition user experience ratings by locomotion condition. Points show means, raw data points, and error bars show confidence intervals. Brackets indicate significant unadjusted pairwise condition contrasts. Asterisks denote the significance level: * $p < .05$, ** $p < .01$, *** $p < .001$. Higher values indicate stronger endorsement of the item.

stick and Leaning produced shorter paths than Walking, but Walking still produced the strongest overall task profile. Route compactness therefore did not equal task efficiency. In a pure travel task, a shorter path might appear to be the better outcome. In the restaurant task, participants also had to approach tables, place bottles, avoid contact, and maintain the serving sequence. Walking seems to have supported these concurrent demands because the relation between physical movement, visual motion, and local action remained direct. Its advantage was not simply that it felt natural. It helped participants move and act without having to manage a separate translation rule.

This distinction is important for interpreting embodied locomotion more generally. Physical walking is often treated as the natural reference condition in VR, but its value depends on what the task requires. In the present task, walking supported not only spatial updating but also local maneuvering and object placement. The benefit therefore came from the way walking preserved coordination across several task components at once. When space is available, this makes walking a strong choice for applied tasks that require navigation and action to unfold together.

Joystick shows why lower bodily involvement can still be effective. Joystick did not match Walking in comfort, naturalness, sickness, or overall experience, but it remained the most effective alternative to walking for task execution. It was the second fastest method, produced compact routes, and was rated easier for serving than Leaning and Omnideck. This result qualifies a simple embodiment account. A less bodily interface can outperform more embodied alternatives when its mapping is familiar, predictable, and easy to coordinate with the rest of the task.

A key design feature in the present study is that all locomotion methods preserved one to one physical rotation. Prior work shows that physical rotation can support orientation and navigation even when virtual translation is controlled artificially [44]. This helps explain why Joystick remained competitive. Although translation was manual, heading still came from the user's own body. The interface therefore preserved an important part of body based orientation while avoiding the posture regulation of Leaning and the gait adaptation of Omnideck. Joystick control was less embodied, but it imposed fewer additional demands during serving and obstacle avoidance.

This does not mean that joystick locomotion is generally superior to embodied locomotion. Controller based travel is still associated with sensory conflict and discomfort in many settings, especially when visual self motion is not matched by vestibular and proprioceptive translation [11, 40]. The result is more specific. In a standing task where physical rotation is preserved and object placement must remain easy, a stable manual translation mapping can be a practical and robust design choice. It may be less immersive than walking or treadmill based movement, but it can preserve task flow when the alternatives require more regulation than the task can comfortably absorb.

Leaning provided body based control, but also made movement a regulation task. Leaning based locomotion is attractive because it uses body displacement for travel while keeping the hands available for object interaction. This makes it relevant for tasks in which users must move and manipulate objects in the same sequence [20, 42, 22]. Prior work has shown that leaning interfaces can improve presence, vection, usability, or navigation performance when the mapping is well tuned and physical rotation remains available [23, 22, 33]. The present results show the other side of the same design choice.

Leaning produced compact paths, but it did not translate this compactness into better task performance. It was slow, difficult for maneuvering, difficult for serving, and produced the longest average collision time when collisions occurred. This profile suggests that participants could keep movement spatially constrained, but had to spend additional effort regulating the body-to-motion mapping. Leaning required them to control posture, displacement, stopping, and local alignment while also placing bottles and avoiding obstacle tables. The body became part of the control channel, but it also became something that had to be managed.

This interpretation fits work showing that leaning benefits depend strongly on gain, dead zones, stability, and physical effort [32, 22]. A leaning interface can be effective when body displacement gives users a simple and reliable movement command. It becomes more costly when users have to monitor their posture too closely or correct unintended translation during local interaction. In the present task, the cost appeared most clearly in maneuvering difficulty and collision recovery. Leaning was therefore not a failure of embodied input in general. It showed that partial embodiment has to be tuned to the precision and interruption demands of the task.

Omnideck increased bodily involvement and engagement, but did not convert this into task efficiency. Omnideck locomotion produced a different pattern from Leaning. It offered constrained gait based movement and showed its clearest relative advantage in engagement and vection among the non walking conditions. This is important because it indicates that the treadmill was not simply worse in every respect. Participants experienced stronger bodily involvement and self motion than with Joystick or Leaning, and this may be valuable in applications where engagement, exertion, or bodily participation are central design goals.

At the same time, Omnideck did not produce the strongest task performance. It led to longer paths, more extra bottles, higher collision probability, and lower comfort than Walking. This pattern is consistent with treadmill literature showing that walking like input can increase bodily involvement while still changing gait, effort, stability, and control compared with overground walking [35, 54, 37, 61, 26]. Lewis et al. [35], for example, show that omnidirectional treadmill walking can differ from natural gait in speed and step characteristics. Such changes matter because a treadmill is not only an embodiment device. It is also a movement interface that users must learn to control.

The present findings therefore separate engagement from task efficiency. Omnideck may be a strong candidate when the design goal is to create a physically involved experience in a constrained space. It may be less suitable when the task requires repeated precise approach, quick local correction, and low effort object placement. In this study, added gait involvement did not remove the need for interface adaptation. The treadmill gave users a more bodily way to move, but it also introduced mechanical and control constraints that affected task coordination.

Task difficulty exposed coordination costs that were less visible in simple movement. Difficulty increased completion time, distance traveled, extra bottle use, collision probability, collision count, sickness, disorientation, maneuvering difficulty, and serving difficulty. This pattern is central to the interpretation because it shows that locomotion methods did not differ only under easy travel conditions. Their differences became more pronounced when the task required tighter coordination among movement, placement, and obstacle avoidance.

The significant condition by difficulty effects for completion time and distance traveled support this point. Walking remained fastest at every level, while Joystick remained the strongest alternative to walking. Leaning and Omnideck became increasingly costly in the more demanding levels. This suggests that the critical limitation of partial embodiment was not only initial unfamiliarity. The mappings carried additional control demands that became more consequential when paths curved, spaces narrowed, and the task required more careful local action.

This finding aligns with recent locomotion work that evaluates techniques inside concrete task structures rather than as isolated

movement mechanisms. Cannavo et al. [9] argue for locomotion evaluation through task scenarios, objective measures, subjective measures, and application requirements. Croucher et al. [12] similarly classify locomotion through task, technique, and modality, which reflects the fact that the same interface can behave differently depending on the activity it supports. The present study follows this logic by showing that locomotion quality changed when users had to move, place, avoid, and remember within one sequence.

Repetition improved performance but did not remove the interface differences. Participants improved with exposure on selected outcomes, including completion time, distance traveled, maneuvering difficulty, and collision count. This indicates that participants adapted to the task and to the locomotion methods. However, repetition did not reverse the overall condition pattern. Walking remained strongest, Joystick remained the most effective alternative to walking, and the partial embodiment methods continued to carry costs.

This pattern is important because locomotion interfaces often improve with practice. Prior work suggests that repeated exposure can change comfort, control confidence, and user response to artificial or embodied movement [40, 22, 26]. The present results are compatible with that view, but they do not reduce the condition effects to novelty or first exposure. Participants had familiarization and repeated trials, and still the same broad interface profile remained. Longer training might improve Leaning and Omnideck, especially for smooth movement and local alignment. The current results show that under practical familiarization, their additional bodily involvement was not enough to overcome the coordination costs introduced by the mappings.

Workload, vection, and engagement separated experience from task performance. The supportive questionnaire outcomes clarify why embodiment should not be interpreted through a single experiential scale. Walking and Joystick produced the lowest overall workload, while Leaning and Omnideck were higher. The NASA-TLX pattern therefore supports the task execution results. More bodily involvement in the non walking methods did not reduce perceived workload in this task. Instead, Leaning appears to have increased control effort and frustration, while Omnideck added physical and adaptation demands.

Vection and immersion showed a different pattern. Walking produced the strongest vection, and Omnideck showed the clearest non walking advantage in vection and engagement. Leaning was closer to Joystick for vection despite stronger bodily input. These outcomes show that bodily involvement did not produce a single experiential profile. A method can improve self motion experience or engagement without producing the best task performance. Conversely, a method such as Joystick can remain efficient and usable even when it is less bodily and less engaging.

This separation is important for applied VR design. If a study examined only engagement or vection, Omnideck would appear more competitive. If it examined only distance traveled, Leaning would appear stronger. If it examined only naturalness, Walking would dominate for a broad and unsurprising reason. The combined result is more informative. Locomotion methods distribute costs and benefits across performance, control effort, sickness, engagement, and comfort. Selecting a method therefore requires knowing which of these dimensions matters most for the application.

Pointing outcomes constrain the spatial updating claim. The restaurant task included a pointing phase because retained spatial knowledge was part of the intended task demand. Participants had to remember recently served table locations and point to them after returning to the center. This made the task richer than travel or serving alone, but the pointing errors were generally large. The pointing measures should therefore be treated as exploratory indicators rather than as the primary basis for ranking locomotion methods.

Prior work links walking and body based movement to improved spatial updating, orientation, and cognitive map formation in virtual environments [48, 49, 44, 4]. The present study is compatible with that literature because the task required participants to maintain relations among movement, served tables, and later pointing responses. However, the strongest evidence in this dataset comes from integrated task execution, serving accuracy, collision behavior, immediate ratings, workload, and post condition experience. The spatial recall measures add useful secondary context, but they do not carry the main claim.

Future work should improve this part of the design. Pointing tasks may be sensitive to instruction, target salience, delay, viewpoint reset, response method, and participants' interpretation of what is being asked. Additional memory probes, map reconstruction tasks, route recall, landmark recognition, or repeated pointing trials could provide a more stable picture of how locomotion methods affect retained spatial knowledge. Such measures would be especially useful for separating path integration, landmark memory, and survey knowledge.

The design implication is task fit rather than maximum embodiment. The results support a task fit view of embodied locomotion. The most bodily method was not automatically the strongest, and the least bodily method was not automatically the weakest. Walking succeeded because it preserved a direct relation between physical movement, visual feedback, and local action. Joystick succeeded as an alternative to walking because it was predictable, familiar, and easy to coordinate with serving. Leaning and Omnideck showed that partial embodiment can increase bodily involvement while also increasing regulation demands.

This implication aligns with broader 3D user interface design, where interaction techniques should be selected in relation to task requirements rather than technical richness alone [34, 7]. It also aligns with recent locomotion studies showing that the suitability of a technique depends on usability, workload, accessibility, sickness, task structure, and concurrent interaction demands [60, 18, 16, 27]. Wan et al. [60] make this point clearly by treating locomotion and object manipulation as competing demands when they occur together. Gao et al. [18] show that body part and transfer function choices shape performance, overshoot, collision behavior, usability, and sickness in body centric locomotion. These studies support the central lesson of the present work. Embodiment is not a guarantee of better interaction. It becomes useful when the body based mapping fits the task.

For applied VR, the practical recommendation is therefore conditional. Walking is the strongest option when sufficient physical space is available and when the task requires continuous navigation, local action, and spatial updating. Joystick remains a robust alternative when the priority is efficiency, simplicity, and low physical demand. Leaning interfaces need careful calibration of gain, dead zone, stopping behavior, and training so that posture regulation does not interfere with precise local action. Omnidirectional treadmills may be most useful when engagement, exertion, or physically involved navigation are central design goals, but their task benefit depends on gait naturalness, control response, comfort, and the amount of training available.

Limitations Several boundaries should be considered when interpreting the results. First, the study used one sequential restaurant task with a specific combination of navigation, serving, obstacles, and recall. Other tasks may weigh the outcome dimensions differently. A training task that prioritizes physical exertion or engagement might favor Omnideck more strongly, while a precise manipulation task might place even greater weight on control stability and local maneuvering. Second, all conditions preserved physical rotation. This was a deliberate design choice because it kept heading control comparable, but it also means the results should not be generalized to joystick conditions with artificial snap or smooth turning. Third, participants received practical familiarization rather

than extended multi day training. Longer training may change the balance for Leaning and Omnideck, although the present results show the costs that appear under realistic first-session use.

A further limitation concerns the spatial recall component. The pointing phase made retained spatial knowledge part of the task, but the large pointing errors limited the strength of the spatial updating conclusions. Finally, full body motion capture and electroencephalography were recorded but not analyzed in this paper. These data could help explain why some interfaces imposed higher control costs, for example through posture regulation, gait adaptation, movement variability, or attentional state. Future analyses could therefore connect behavioral outcomes with movement and physiological measures to better explain how locomotion mappings affect task coordination.

Lastly, some participants were excluded because of high motion sickness, meaning the remaining sample may under-represent users who are most sensitive to virtual reality systems.

10 Conclusion

This study compared joystick steering, NaviBoard inspired leaning, Omnideck treadmill locomotion, and free walking in a sequential VR task that combined navigation, bottle placement, collision avoidance, and later pointing to remembered locations. Walking produced the strongest overall profile across task performance, sickness, maneuvering difficulty, comfort, usability, naturalness, and perceived safety. Joystick was the strongest alternative to walking for efficient task execution and simple control. Leaning and Omnideck introduced more bodily input, but this did not consistently improve integrated task performance. Omnideck's clearest non-walking advantage was engagement rather than efficiency or comfort.

The main conclusion is that locomotion should be judged by how well it fits the task, not by bodily involvement alone. Physical movement is valuable when it keeps visual feedback, body movement, object interaction, and comfort easy to coordinate. Less embodied control can still be effective when it is predictable and leaves users free to focus on the task. Partially embodied systems need careful tuning and training so that body based input supports movement instead of becoming an additional control demand. For applied VR, the most suitable locomotion method is not necessarily the most embodied one. It is the method that keeps movement, action, spatial updating, and comfort aligned across the task.

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