

Interaction Under Whole-Body User Rotations in VR Space

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Fig. 1: Interaction under tilted conditions (rotation around the X-axis). **(Left)** Cube insertion during the docking task at a 45° tilt (dominant hand: right; skin tone: 4). **(Right)** Sphere shooting with a laser during the shooting task at a 150° tilt (dominant hand: left; skin tone: 6).

Abstract—Virtual reality (VR) enables interactions beyond real-world limitations, yet many such capabilities remain underexplored due to concerns about user comfort and increased disorientation and cybersickness. This study examined how altering the user's virtual pitch orientation influences interaction performance and subjective ratings. In a within-subject design, 30 seated participants experienced 12 virtual tilts from moderate to extreme ($\pm 180^\circ$). We assessed comfort, simulator sickness, perceptual responses, and performance. Our results revealed no significant increases in nausea, disorientation, or decreased comfort, with mild tilts performing equivalently to baseline. Notably, even extreme tilts maintained low nausea levels. Performance effects were mixed: forward tilts yielded similar or slightly improved performance, whereas backward tilts modestly impaired performance, though not significantly. These findings suggest that VR experiences featuring virtual body orientations distinct from the user's physical posture are feasible without compromising comfort or performance, enabling novel opportunities in simulation, interface design, visualization, creative content creation, and VR gaming.

Index Terms—Beyond-real interaction, Cybersickness, Decoupled user orientation, Incongruent virtual positioning, Interaction performance, Multisensory conflicts, User comfort, User rotation, Virtual reality, Visuo-vestibular conflict

1 INTRODUCTION

Virtual reality (VR) enables the creation of scenarios that are impossible in the physical world. Such “beyond-real” interactions, which offer affordances surpassing real-world limitations, naturally spark curiosity and interest among researchers and users [1, 39]. These scenarios invite novel use cases that may not have been previously considered, as our conceptualization of interaction remains shaped by the constraints of physical reality, such as those imposed by gravity, biomechanics, or materiality.

Among these underexplored possibilities are VR experiences in which the user's virtual body orientation (in pitch or roll) becomes incongruent with their physical posture. In other words, scenarios in which the virtual floor and surrounding environment are tilted relative to the real-world frame.

Such manipulations raise legitimate concerns regarding simulator sickness [15]. A central mechanism is visual-vestibular conflict, a mismatch between visual input (what the user sees) and vestibular input (signals from the inner ear concerning motion and balance), which is considered a special case of the broader sensory conflict theory. According to this theory, cybersickness arises when sensory inputs conflict with one another or with the brain's prior expectations, referred to as an “expectancy conflict” [34, 36]. More specifically, the subjective

vertical conflict theory [11] posits that sickness is particularly likely when discrepancies affect the perception of gravitational vertical. In practice, this implies that virtual environments where the ground plane or horizon is tilted relative to real-world gravity can induce greater nausea and disorientation than environments with aligned verticals [29].

Consequently, prior work has investigated perceptual manipulations such as passive haptics and redirected walking [25], haptic retargeting [4], and hand-based redirection techniques [32, 43], but the effects of whole-body rotational mismatch remain relatively unexplored. Yet allowing users to operate in VR with arbitrary orientations could unlock new affordances, ranging from practical applications in domains requiring non-standard viewpoints to enhanced creative workflows and immersive experiences.

In simulation contexts, such as spaceflight or aerobatic training, mismatched physical-virtual orientations could serve as cost-effective preparation for real-world disorientation through controlled sensory conflict. Consumer VR may benefit from such techniques as well: while lying-down VR applications or VR use from reclining positions (e.g., in medical contexts or for users with chronic fatigue) have been studied [30, 41], novel gameplay based on user or world rotation could exploit more unusual viewpoints, including extreme changes to the user's point of view (e.g., positioning the user upside-down). Additionally, tilting the camera can find applications in cinematic VR and immersive storytelling. In the HCI domain, tasks involving large structures (e.g., architectural visualization, molecular modeling, network graphs, geological models), particularly in collaborative contexts where rotating the object itself is impractical or undesirable, would benefit from the freedom to provide malleable viewpoints. A growing transition of 3D model design and virtual world creation into VR is

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likely, benefiting from designers crafting scene components in situ while they adjust their avatars' virtual orientation to avoid awkward working angles (in sculpting or 3D painting where examining a model from underneath is often necessary).

Validating the feasibility of such configurations, beyond preliminary efforts in prior work [7, 30, 41] may support the development of VR environments where users can remain comfortable and perform effectively even under extreme spatial disorientation (e.g., in zero-gravity collaborative design settings). Confirming the feasibility of arbitrary user orientations in VR could enable also more natural flight-based locomotion and underwater exploration techniques, freeing users from the constraints of upright body positioning.

To advance understanding of VR interaction under whole-body rotations, we analyzed task performance and subjective responses across 12 pitch tilt conditions – forward-backward rotations of the user's virtual position. These tilts ranged from mild inclinations of $\pm 15^\circ$ to fully inverted orientations of $\pm 180^\circ$, tested in a within-subject study involving 30 participants. Subjective assessments (administered per-condition in VR and after the experiment) included comfort, spatial perception, and simulator sickness, while performance metrics encompassed task completion time and positional accuracy. After completing the quantitative phase, qualitative data were collected using semi-structured, open-ended questions. The responses were then analyzed thematically to contextualize and deepen the interpretation of the quantitative results.

The following research questions (RQs) guided this exploratory study:

- RQ₁* (Subjective measures) To what extent are the subjective measures of comfort, spatial understanding, dizziness, and nausea under varying tilt conditions equivalent to those in the baseline (0°) condition?
- RQ₂* (Task performance) How does task performance under varying tilt conditions compare to baseline performance?
- RQ₃* (Perceptual disturbances) How does tilted virtual body orientation influence perception of the VR environment and the physical body?

Our results provide compelling evidence for the feasibility of VR interaction where users' virtual orientation differs from their physical posture, revealing only minimal decreases in user comfort and negligible cybersickness levels throughout the experiment. Surprisingly, even extreme user orientations (between $\pm 90^\circ$ and $\pm 180^\circ$) received high comfort ratings and produced no notable nausea. Through comprehensive statistical analysis, visual presentation of subjective and objective data per condition, and thematic analysis of qualitative responses, we outline concrete actionable implications for VR developers seeking to implement physically unconstrained user orientations into their designs.

2 RELATED WORK

2.1 Cybersickness in Tilted VR

Simulator sickness (or cybersickness) in VR originates predominantly in cases of mismatched stimuli between the real and the virtual world, particularly in cases of perceived self-movement when the users stays stationary [5, 15, 18, 21]. In relation to tilted ground in VR, cybersickness arises from the visuo-vestibular conflict. This was first suggested by sensory conflict theories by Reason and Brand (1975) [37], stating that motion- or cyber-sickness appears whenever the brain receives sensory input (visual, vestibular, proprioceptive) that deviate from its internal model. The accumulated magnitude \times duration of the mismatch drives symptoms.

More recently, subjective vertical conflict theory [11, 12] maintains the same principles but argues that all sickness-inducing situations can be reduced to one type of error; the angular difference between sources of information on gravito-inertial vertical (based on visual, vestibular, and proprioceptive sensors).

Based on these theories and empirical practice, manipulating the user tilt and roll rotation is not recommended in VR experiences. For example, camera-placement recommendations for immersive video from Meta state: "Maintain a steady horizon to help prevent motion

sickness" [23]. Consequently, this area remains underresearched. Cybersickness in relation to tilted orientation in VR has been studied solely with the incorporation of movement, finding that even short exposures to walking in a tilted VR environment can make 25% of participants experience notable cybersickness (simulator sickness questionnaire, SSQ with scores > 25) [33]. This effect is not unique to VR and can also be observed in still positions in physical reality, for example when riding trains that tilt on curves [17].

The effects of VR-induced sickness tend to diminish with the length of the VR session [28] and a repeated exposure [2, 10]. The underlying mechanisms for this reduction are often attributed to sensory adaptation and habituation processes [20].

2.2 Perception Manipulation

Perceptual manipulation is the deliberate alteration or control of sensory input to influence a user's perception in a targeted way. Redirected-walking work combines visual gains with passive haptics to bend physical paths [25], and later dynamic repurposing of surfaces is known as haptic retargeting [4]. In confined passenger spaces, Medeiros et al. [32] rotated and scaled virtual work areas by up to 60° while reporting stable workload, framing these techniques explicitly as perception manipulation. A complementary line of research redirects virtual hands. Zenner et al. quantified undetectable displacement thresholds [44] and released an open-source toolkit (HaRT) that implemented body-, world-, and hybrid warps [43]. These studies collectively show that angle or gain changes smaller than users' detection thresholds can be exploited to reuse limited physical space without breaking presence.

Our work extends this framework from yaw-based redirection and hand-centric warps into the pitch axis, introducing full-body orientation conflicts that engage vestibular cues more strongly than earlier approaches.

2.3 Interaction and Self-Perception under Spatial Orientation Conflict

A growing body of research has investigated how the human perceptual system adapts to environments where gravitational, proprioceptive, and visual cues conflict. Early work in zero-gravity simulations highlighted the fundamental role that vision plays in spatial orientation when gravitational cues are absent, as demonstrated by Aoki et al. [3]. Their study showed that, without gravity, individuals rely primarily on visual references, with performance strongly linked to the consistency of these cues.

A study comparing upright-positioned, passively guided walk-throughs in a virtual 3D maze with conditions involving participant rotation in tilt and pitch showed that the absence or misalignment of gravity impairs spatial cognition [42]. The findings underscore the critical interplay between vestibular input and visual perception, with implications for interaction techniques that deviate from conventional gravitational alignment.

Research into the influence of body posture further illustrates this dynamic. Studies examining VR experiences in supine positions [30, 41] indicate that while immersion can be maintained through adapted interaction techniques, changes in body orientation notably alter spatial perception. For instance, supine users tend to underestimate distances compared to standing users, again pointing to the role of graviceptive cues in spatial orientation.

The effects of multisensory conflicts have also been explored in the context of self-motion and motor responses. McManus and Harris [31] found that when visual and gravitational cues are misaligned, individuals susceptible to reorientation illusions experience altered perceptions of self-motion. Similarly, Scotto di Cesare et al. [16] showed that discrepancies between visual scene orientation and body tilt lead to systematic errors in tasks such as arm pointing. Later, Luo et al. (2023) [27] investigated VR locomotion techniques for reclining and lying positions, identifying limitations and reduced performance that arose from the sensory integration conflicts between visual, vestibular, and proprioceptive inputs.

Studies focusing on locomotion and unconventional VR scenarios suggest advanced adaptability of the human brain. Becker et al.

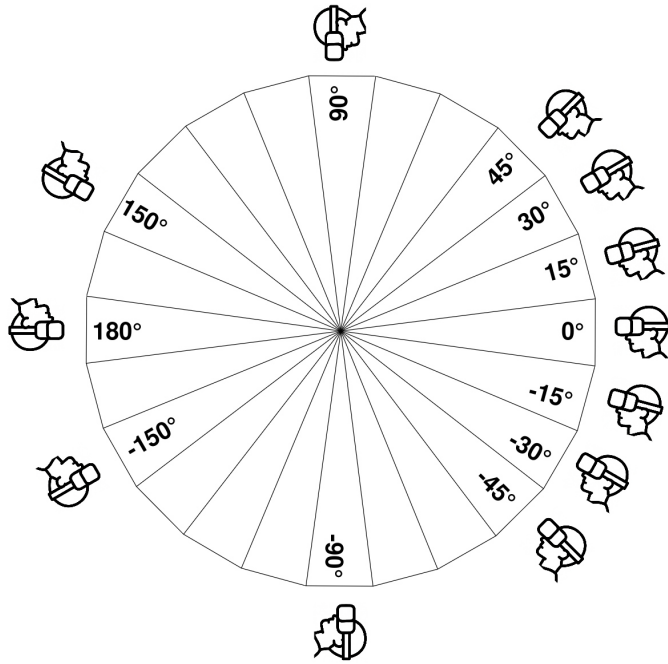


Fig. 2: Side-view schematics of the experimental manipulation. Users, while seated in a chair, experienced a range of virtual pitch tilts between 0° and $\pm 180^\circ$, shown in the figure.

(2019) [7] explored environments where users could walk up walls and across ceilings, discovering that such radical spatial transformations were often perceived as self-induced rotations with minimal cybersickness. Nevertheless, changes to visual body orientation weakened full-body illusions, demonstrating the role of graviceptive cues in embodiment and spatial perception [40].

2.4 Research Gaps

While prior work confirms that the orientation system adapts to multi-sensory conflict, most perception-manipulation studies are constrained to horizontal yaw or to hand-scale displacements. The limits of pitch misalignment, where the virtual gravity vector is deliberately decoupled from the physical one, remain largely unexplored. We address this gap by examining a wide range of pitch tilts (up to $\pm 180^\circ$) and analysing both performance and sickness.

Recent evidence suggests that immersion can survive moderate tilts [30, 41] and that repeated exposure yields adaptation [2, 10]. Building on these insights and the detection-threshold work for hand redirection [44], we seek psychophysical and subjective boundaries for whole-body pitch manipulation. Our findings aim to guide future perception-manipulation designs that repurpose limited physical space without compromising comfort.

3 METHODOLOGY

3.1 Study Design

This study employed a within-subject design, with each participant experiencing 12 tilt conditions including a baseline (0°) condition (all conditions shown in Figure 2). As it was reasonable to expect excessive disorientation or nausea based on previous studies, we opted for a counter-balanced progressive manipulation of the tilted conditions (rather than full randomization) to reduce the risks of participant discomfort and drop-out. Variant A began with forward tilts (15°, 30°, 45°, 90°, 150°, 0°, -15°, -30°, -45°, -90°, -150°, $\pm 180^\circ$), while Variant B started with backward tilts (-15°, -30°, -45°, -90°, -150°, 0°, 15°, 30°, 45°, 90°, 150°, $\pm 180^\circ$). In both variants, the baseline was positioned centrally (6th condition), to minimize the effects of novelty or training. The number of conditions and trials was a compromise between maximizing data collection and keeping the experiment duration manageable.

3.2 Participants

Thirty participants (14 female, 16 male; median age = 34 years, SD = 12.02, range = 20–69) took part, following the guidelines on the design of VR interaction studies [8]. Participants were recruited from the institutional staff, via ads placed in local libraries, and using the local university’s bulletin board system. Most (27 participants) had prior VR experience, but very limited. The majority (18) rarely played video games (less than monthly, or never). The work was conducted under the oversight of the local ethics committee.

3.3 Apparatus

Participants used standalone Meta Quest 3S head-mounted displays (HMDs) featuring bare-hand tracking. The HMD provided Fresnel lenses with visible fields of view of 97° horizontally and 93° vertically, a per-eye resolution of 1832x1920, and refresh rate of 120 Hz. The VR application ran directly on the HMD, with screen casting to a mobile phone during experimentation.

3.4 VR Environment

The VR environment was designed to maximize ecological validity. Participants interacted in a neutrally toned modernist interior – a virtual room measuring 8x8 m, with a height of 4 m. Central to the room was a large (4m diameter) 24-sided wheel with working panels on the sides, serving as the primary workspace during the tasks. The application was optimized to ensure stable maximal frames-per second (72 FPS) performance throughout the whole run.

Only hand models (wrist cutoff), rather than full-body avatars, were used in the VR environment. This choice aimed to minimize cognitive load, disorientation, and nausea associated with the experimental manipulation. Incorporating a complete avatar could introduce confounding variables, such as height-related anxiety in conditions where participants appeared elevated in virtual space.

Mixed lighting (one light at the top of the room, one behind the starting position of the user in the scene) was used in the scene; pre-computed baked lights for efficiency and real-time lights for hand shadows. The scene was created in Unity 2022.3.54f1 with universal rendering pipeline (defaults from “Very high” quality settings were used).

3.4.1 Upward cues

Based on the prior literature, gravitational references were provided, including asymmetrical furniture arrangements (desk, shelves, sofa) to facilitate orientation and to reinforce the effect of different positioning in the virtual room. Additional vertical cues included a door, curtains, a ceiling light fixture, and the working wheel in the center of the room. Three framed, AI-generated images depicted upright human figures interacting with HMDs. Crown moldings in the corners and a distinctly textured ceiling further enhanced vertical orientation cues.

3.4.2 Participant positioning

Participants started above the ground, outside the central wheel, transitioning to task locations via fade-out/fade-in sequences lasting 4 seconds to mitigate nausea from unexpected movement. Each position placed participants 32.5 cm from the wheel’s working panel, which occupied roughly 50% of their field of view. The user-panel distance was based on internal testing, aiming to balance environmental visibility with comfort during prolonged interaction.

3.4.3 Interfaces and interaction

Participants interacted via simple button-based interfaces for selecting the dominant hand and skin color from the 7 steps of the Fitzpatrick scale [22] (implemented using the Hafnia hands package, with the goal of facilitating embodiment by maximizing visual congruency [19, 35]). They also responded to in-VR questionnaires by selecting numbered buttons (1–7) and confirmed responses using a “Next” button, and controlled the transitions to each next tilt condition.

<i>In-VR Questionnaire</i>	
Comfort	How comfortable do you feel in the current tilt condition?
Spatial perception	How easy is it to understand the spatial layout and orientation of your surroundings?
Disorientation	To what extent do you feel dizzy or disoriented?
Nausea	To what extent do you feel nauseous?
Gravity pull illusion	To what extent does it feel like the gravity is pulling you in a direction other than downward?
Body orientation illusion	To what extent do you feel that this condition has affected your sense of your body orientation?

Table 1: In-VR questionnaire items

3.4.4 Tasks

Two interaction tasks were employed in the experimental design. First, a docking task inquiring into sustained hand-eye coordination, mental rotation, and precision alignment under altered egocentric pitch orientation. Second, a shooting task focused on pointing/selection, continuous stabilization, and visuomotor correction over a wide angular workspace. Participants underwent training before being positioned in the tilt conditions. The task interactables were rotated in line with the user rotations, aiming to model VR scenarios where users would opt to rotate their virtual posture to match interaction demands.

The docking task involved picking and rotating a 0.1 m cube mid-air to align a red-marked face towards the participant, then inserting it into a matching hollow in the wheel’s panel (Figure 1, left). Gravity was disabled, allowing re-grasping. Three trials occurred per tilt condition, with randomized initial cube orientations. Performance metrics were trial completion time (from first grasp to final placement) and positional accuracy (top-down and left-right displacement). Placement precision (SD) in the baseline condition was recorded for later usage as equivalency bounds in the statistical testing.

In the shooting task, participants aimed at spheres (0.5 m diameter) randomly positioned horizontally (30-60° from both sides of the central wheel) and vertically (-30-30°) relative to the HMD, at depths of 1-3.5 m. This positioning avoided sphere collisions with the wheel or walls, while maximizing the usable free space in the virtual room for sphere placement. Successful hits required maintaining an uninterrupted ray contact with a sphere for 1 second, indicated by color transition from blue to red and accompanied by auditory feedback (Figure 1, right). Each condition involved seven simultaneous trials. Performance was measured by mean trial time (excluding the initial trial in the set).

3.5 Questionnaires

Prior to the experiment, participants reported demographics, VR experience, gaming frequency (7-step Likert scales), and baseline simulator sickness (SSQ, 4-step Likert scale, [24]). Following recommendations [9, 14], we gathered the SSQ scores before and after the experiment and used the difference for assessment.

In VR, participants completed brief, custom questionnaires, based on previous work (detailed in Table 1) on a 7-step Likert scale.

Post-experiment questionnaires assessed post-experimental SSQ (the original study’s formula [24] was used for the computation of the per-category and the total score), embodiment (based on [38], occurrences of the word “body” were replaced with “hands”), and perceptual distortions on 7-step Likert scales. The latter questionnaire inquired into the perceptual effects: postural aftereffects, body tilt illusion, disorientation, inverse illusion (the feeling that the virtual room rotated around the user, instead of the user rotating within the room), visual capture (whether the virtual environment overrode the physical sensations of

posture or orientation), multisensory conflicts, and sense of ownership and agency metrics. The custom items of the post-experimental questionnaire are available in supplementary materials of this paper. Additionally, participants provided written open-ended reflections on cognitive load, adaptation, emotional and psychological reactions, and open feedback and general comments.

3.6 Procedure

Participants provided informed consent, which emphasized that they could terminate the experiment prematurely in case of nausea or discomfort. After pre-experiment questionnaires (answered on a laptop using Google Forms), participants received instructions and adjusted the HMD (inter-pupillary distance, strap fit). In VR, initial training and practice questionnaires were completed first. After that, participants completed ordered (based on experimental variant) 12 tilt conditions, each including both tasks (in randomized order) and in-VR questionnaires. Upon exiting VR, participants filled out post-experiment questionnaires. In total, participants spent on average 22.43 minutes (SD = 6.18 minutes) in the VR.

3.7 Data Evaluation

First, performance data were pruned per-metric using the 1.5× interquartile range (IQR) criterion. Statistical testing of equivalence involved two one-sided t-tests (TOSTs). The smallest effect size of interest (SESOI) was set to one questionnaire point in questionnaire responses, representing the lowest meaningful difference. For positional accuracy, a standard approach to estimating the SESOI was selected – SD of per-participant baseline condition. For temporal performance metrics, a fixed SESOI of 20% was used. This value is arbitrary, based on margins of error commonly reported for task-time metrics in usability research, and aligns with the 0.80–1.25 bioequivalence criterion accepted by the FDA. We acknowledge that various equivalence bounds were evaluated during exploratory analysis, with SESOI for temporal metrics finalized based on distribution characteristics. Null-hypothesis significance tests (NHSTs) were applied to performance metrics to identify significant differences across conditions. Each family of tests employed a multiple comparison correction using the Holm method. All statistical testing was performed in R.

Because our data demonstrated non-normality, we evaluated non-parametric equivalence tests alongside traditional TOST procedures. The nonparametric tests produced results that were largely consistent with those from the parametric analyses. Given that TOSTs based on t-tests are widely used, offer a well-established framework for interpreting equivalence, and are relatively robust to violations of normality, we report the parametric TOST outcomes here.

For qualitative analysis, participants’ open responses were analyzed using a thematic approach. The initial open coding captured key reactions, which were iteratively clustered into themes following standard procedures [13]. The themes were refined to align with the patterns in subjective descriptions and performance data, focusing on the salient aspects of the experience.

4 RESULTS

4.1 Subjective Responses

To test RQ_1 (comfort, spatial understanding, dizziness, and nausea equivalence to baseline), equivalence tests (TOSTs) were performed on in-VR questions 1–4 (see Table 2). These tests indicate the equivalency of the four variables in conditions between -45° and 45° , with the exception of a decreased comfort in the 30° condition.

Moreover, disorientation remained equivalent to baseline in conditions up to $\pm 90^\circ$, and nausea was equivalent to baseline in all conditions tested (up to $\pm 180^\circ$). In conditions where the equivalency tests did not turn out statistically significant, the 90% confidence intervals did not exceed a 1.5-point difference. Subjective responses across conditions are visualized in Figure 3.

SSQ scores (Figure 4) indicated “minimal” symptoms overall (total: 9.10 ± 17.81 , nausea: 3.82 ± 10.51 “negligible”, oculomotor disturbance:

Cond.	Comfort	Spatial perception	Disorientation	Nausea
-150°	1.03 [0.62, 1.44] p = 1.000	1.03 [0.59, 1.48] p = 1.000	-0.77 [-1.10, -0.43] p = 0.854	-0.27 [-0.48, -0.05] p < 0.001
-90°	0.47 [0.10, 0.83] p = 0.108	0.50 [0.21, 0.79] p = 0.045	-0.37 [-0.56, -0.18] p < 0.001	0.03 [-0.07, 0.13] p < 0.001
-45°	0.33 [-0.01, 0.67] p = 0.018	0.10 [-0.16, 0.36] p < 0.001	-0.20 [-0.46, 0.06] p < 0.001	-0.07 [-0.23, 0.09] p < 0.001
-30°	0.33 [0.13, 0.54] p < 0.001	0.10 [-0.16, 0.36] p < 0.001	0.03 [-0.17, 0.24] p < 0.001	-0.10 [-0.25, 0.05] p < 0.001
-15°	0.23 [0.08, 0.39] p < 0.001	0.03 [-0.23, 0.30] p < 0.001	0.07 [-0.13, 0.27] p < 0.001	0.07 [-0.05, 0.18] p < 0.001
15°	0.31 [0.07, 0.55] p < 0.001	0.00 [-0.22, 0.22] p < 0.001	-0.14 [-0.28, 0.00] p < 0.001	-0.03 [-0.17, 0.10] p < 0.001
30°	0.60 [0.30, 0.90] p = 0.165	0.33 [0.04, 0.63] p < 0.001	-0.13 [-0.34, 0.08] p < 0.001	-0.13 [-0.33, 0.06] p < 0.001
45°	0.53 [0.27, 0.80] p = 0.045	0.40 [0.11, 0.69] p = 0.018	-0.37 [-0.56, -0.18] p < 0.001	-0.23 [-0.41, -0.06] p < 0.001
90°	0.63 [0.28, 0.98] p = 0.344	0.47 [0.13, 0.80] p = 0.065	-0.47 [-0.73, -0.20] p = 0.018	-0.23 [-0.43, -0.04] p < 0.001
150°	0.97 [0.52, 1.41] p = 1.000	1.10 [0.75, 1.45] p = 1.000	-0.80 [-1.12, -0.48] p = 0.888	-0.23 [-0.41, -0.06] p < 0.001
±180°	0.77 [0.29, 1.24] p = 1.000	0.57 [0.24, 0.89] p = 0.165	-0.63 [-0.93, -0.33] p = 0.207	-0.10 [-0.27, 0.07] p < 0.001

Table 2: TOST results for in-VR questions 1-4, showing which conditions are equivalent (equivalency bounds ± 1 questionnaire point on the 7-point Likert scale) to the 0° baseline condition. First line shows the effect size with 90% CI, second line shows the Holm-adjusted p-value.

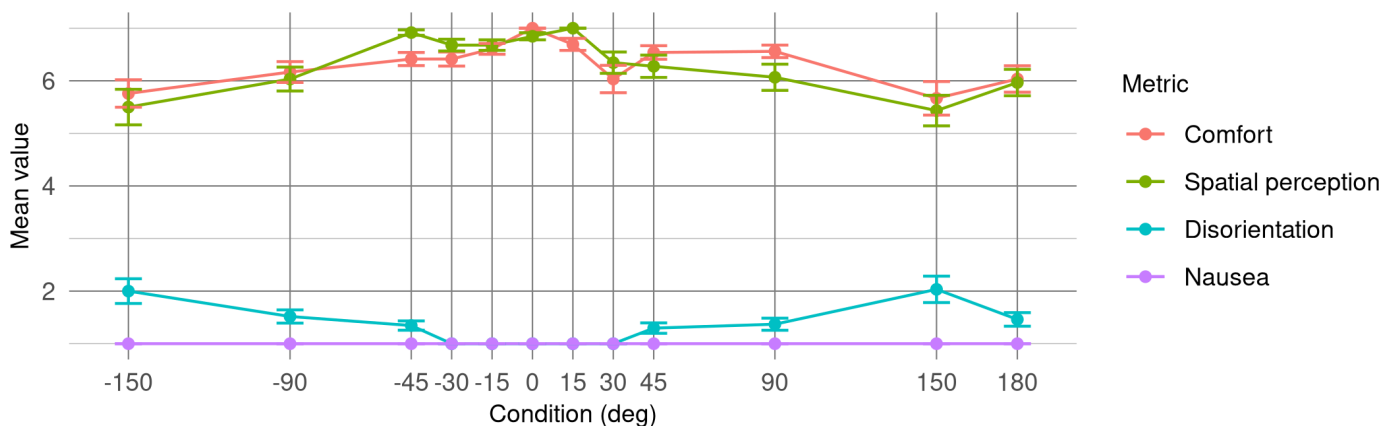


Fig. 3: Mean values of the answers to in-VR questions 1-4 over tilt conditions with 90% CI error bars.

7.58±17.12 “minimal”, disorientation: 14.38±26.48 “significant”). Despite strict reference values (see subsection 5.1.1), simulator sickness remained low.

4.2 Performance

To test RQ_2 (performance comparison to baseline), TOSTs (Table 3) were applied to docking task completion times and positional errors, and shooting task completion times. Additionally, Holm-corrected NHST tests were performed to find conditions where the performance significantly differed from baseline.

$\pm 15^\circ$ conditions often showed negative spikes in performances, which were not observed with $\pm 30^\circ$ conditions, likely a result of initial exposure to the test task under tilted orientation. In larger tilts, shooting task times were equivalent or non-significantly better than baseline (Figure 7).

The positional accuracy in the docking task (Figure 6) was equivalent to baseline mainly in positive tilts. In the 45° condition, the equivalency test was not statistically significant, while the accuracy showed a slight improvement. In negative tilts, the positional error was larger (the positional accuracy was poorer). However, none of these trends resulted in statistically significant differences.

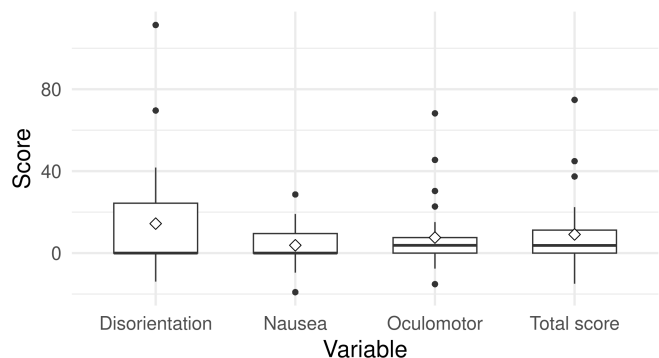


Fig. 4: Boxplot with differential SSQ results per condition, and the total score. Whiskers extend to the 1.5 × IQR, diamond marks mean value.

Cond.	Docking time	Pos. error	Shooting time
-150°	-0.08 [-0.72 0.56] p = 0.090	-0.10 [-0.25 0.05] p = 0.156	0.08 [-0.09 0.24] p = 0.022
-90°	-0.29 [-0.92 0.35] p = 0.209	-0.07 [-0.23 0.09] p = 0.130	-0.02 [-0.18 0.15] p < 0.001
-45°	-0.39 [-0.99 0.22] p = 0.243	-0.02 [-0.19 0.16] p = 0.090	0.03 [-0.14 0.20] p < 0.001
-30°	-0.99 [-1.66 -0.32] p = 1.000	-0.01 [-0.17 0.15] p = 0.042	-0.03 [-0.20 0.13] p < 0.001
-15°	-0.63 [-1.33 0.07] p = 0.660	-0.17 [-0.30 -0.05] p = 0.315	-0.11 [-0.28 0.07] p = 0.060
15°	-2.16 [-3.08 -1.24] p = 1.000	0.02 [-0.09 0.13] p < 0.001	0.12 [-0.06 0.29] p = 0.076
30°	-0.83 [-1.54 -0.11] p = 1.000	-0.01 [-0.14 0.11] p < 0.001	-0.01 [-0.18 0.16] p < 0.001
45°	-0.58 [-1.23 0.06] p = 0.552	0.06 [-0.09 0.21] p = 0.090	0.09 [-0.04 0.23] p < 0.001
90°	-1.16 [-1.94 -0.39] p = 1.000	0.04 [-0.07 0.15] p < 0.001	0.16 [0.01 0.32] p = 0.090
150°	-0.35 [-0.95 0.25] p = 0.220	0.00 [-0.12 0.12] p < 0.001	0.10 [-0.04 0.24] p < 0.001
±180°	-0.22 [-0.97 0.53] p = 0.243	0.05 [-0.05 0.15] p < 0.001	0.19 [0.03 0.34] p = 0.009

Table 3: TOST results for performance metrics, showing which conditions are equivalent to the 0° baseline condition. Equivalency bounds: docking task trial time ± 1.10 s, docking task positional error ± 0.31 cm, shooting task trial time ± 0.42 s. First line shows the effect size with 90% CI, second line shows the Holm-adjusted p-value.

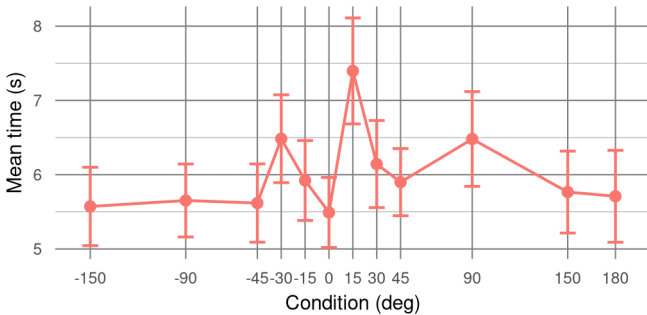


Fig. 5: Mean docking task trial times over tilt conditions with 90% CI error bars.

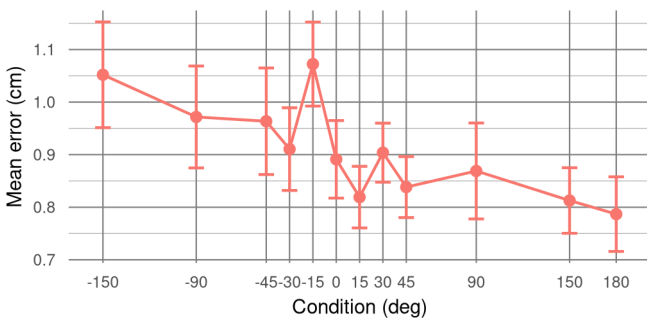


Fig. 6: Mean docking task positional error over tilt conditions with 90% CI error bars.

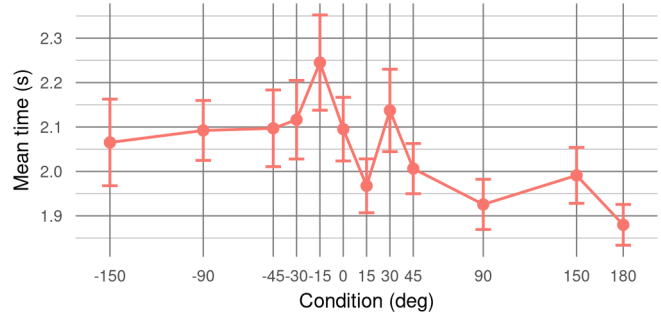


Fig. 7: Mean shooting task trial times over tilt conditions with 90% CI error bars.

Finally, the trial times in the docking task were neither equivalent nor different from baseline in any of the tilt conditions. The opposite trend from positional accuracy appeared; the trial times were comparable to baseline in negative tilts and worsened in positive tilts, although with a large SD (Figure 5).

Although the equivalency of conditions is difficult to assess due to the apparent effect of training or adaptation, there does not seem to be a systematic worsening in task performance. Additionally, the results suggest a speed-accuracy trade-off and direction-specific effects.

4.3 Perceptual effects

In terms of the perceptual disturbances (RQ_3), perceptual distortions to gravity pull and body orientation peaked between $\pm 45^\circ$ and $\pm 150^\circ$, with a slight decline at $\pm 180^\circ$ (Figure 8). However, these effects were modest, rarely surpassing 3 points on a 7-point Likert scale. These results

The results of the post-experimental questionnaire (Figure 9) showed low to moderate perceptual disturbances. This collectively indicates rather weak perceptual illusions originating in the interaction in tilted virtual body positions. The perceived changes in the orientation of the physical body varied notably, showing that some participants felt this effect strongly, while others did not feel it at all. The embodiment results confirmed a strong sense of ownership and agency despite the experimental manipulation.

4.4 Qualitative analysis

4.4.1 Sensory and perceptual experience

Participants described how the tilts influenced their perception of gravity and spatial orientation. In general, two major themes emerged: one centered on the “believability” of the environment, including the induced sensation of physical body tilting; the other emphasized a persistent connection to the physical body, with little to no influence of visual stimulation on perceived body position or gravity.

In the first group, participants reported, for example, that “tilts were experienced as tilts”, “some tilts were really immersive”, or referred to specific positions, such as “the bottom looking up felt like I was lying on the floor”. Some participants described the illusion of their bodies being repositioned, along with a distorted sense of gravitational pull (“felt like I’m floating & sometimes pull of gravity”). Others noted a mismatch between visual and vestibular signals (“it felt convincing apart from gravity”, or commented that gravity was still perceived as “pushing downward” in the usual way).

Finally, some participants did not experience the body tilt illusion at all, remarking (about the tilts) that “they mostly weren’t noticeable”. One participant summarized: “I felt normally, did not sense the tilting”.

Additional responses touched on visual fidelity. For instance, positive comments on the “good graphics” or how the “brown panel” (the working wheel) served as an orientation cue. Others critiqued aspects of the physical arrangement, such as the closeness of the questionnaire panel or the absence of additional body parts.

4.4.2 Emotional and psychological reactions

Many participants characterized the experience as engaging and immersive. Descriptors such as “immersive”, “convincing”, “engaging”, and

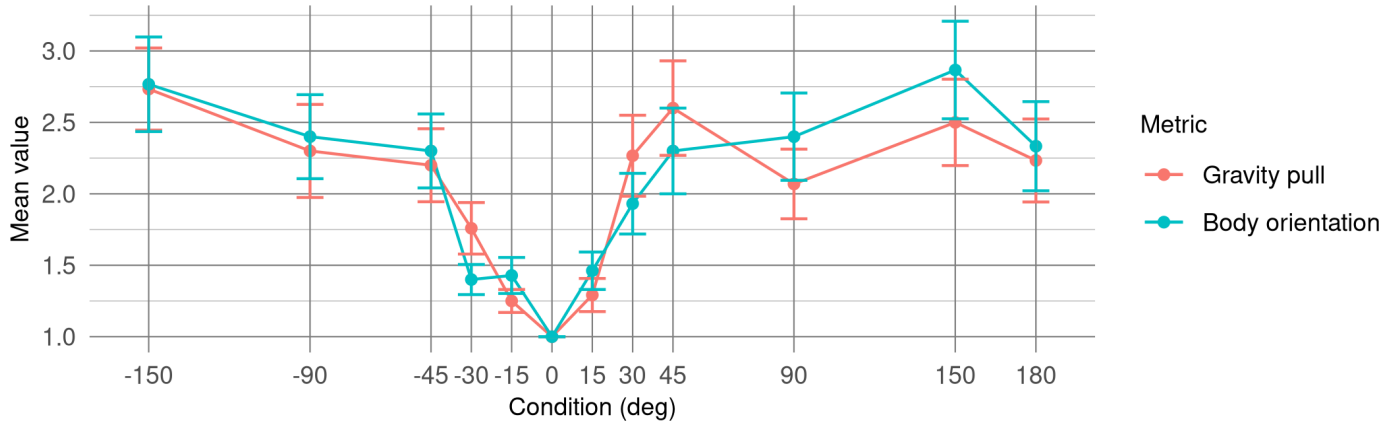


Fig. 8: Mean values of the answers to in-VR questions 5-6 over tilt conditions with 90% CI error bars.

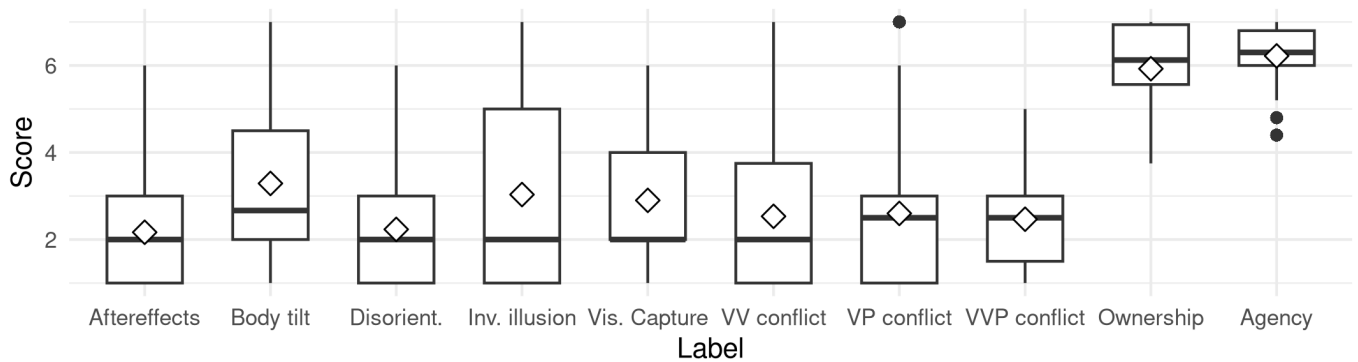


Fig. 9: Boxplot with answers to post-VR questions with whiskers extending to the $1.5 \times$ IQR and mean values denoted with diamond (*Aftereffects*: Postural aftereffects, *Body tilt*: Body tilt illusion, *Disorient.*: Spatial disorientation, *Inv. illusion*: Inverse illusion, *Vis. Capture*: Visual capture, *VV conflict*: Visuo-vestibular conflict, *VP conflict*: Visuo-proprioceptive conflict, *VVP conflict*: Visuo-vestibular-proprioceptive conflict (multisensory integration disruption), *Ownership*: Sense of ownership, *Agency*: Sense of agency).

even playful comparisons (e.g. feeling “like I was meant to be Spider-Man (so weirdly natural)”) reflect a positive emotional involvement, even when slight disorientation occurred. Several participants simply described their experience as “comfortable”, “just fine”, or reported that they “felt normally” during many tilt conditions. A few explicitly mentioned a sense of safety (e.g., “comfortable, safe”).

Some respondents noted brief discomfort at the beginning of the tilts (e.g., “slightly uncomfortable at the beginning of each tilt”) but reported rapid adaptation as they reoriented themselves. Others described a transition from initial calmness or neutrality to mild unease as the tilts became more pronounced. One participant described stronger physiological reactions under more extreme tilts, influenced by the organization of the virtual space: “Uncomfortable at some [tilts], aware of strong heart beat... At stronger tilts I felt uncomfortable, especially backward – as if I felt the weight of the object in front of me and blood rushing to my head”.

Overall, perceived comfort was often linked to how intuitively participants could orient themselves in virtual space. When spatial cues were clear (e.g., the “brown panel” as a fixed reference point), participants felt more at ease. In contrast, when objects were “upside-down” or immediately after a tilt change, brief discomfort was sometimes reported. Still, most participants indicated quick adaptation and a return to comfort, even after initial unease. This suggests that transient discomfort does not tend to persist throughout the session.

4.4.3 Cognitive load and adaptation

Many participants reported an initial period of conscious effort to understand or “get used to” the tilted environment, which later transitioned into more automatic or intuitive interaction. Several responses men-

tioned the need to “look around” or “move my head around” to regain orientation before feeling at ease. Early tilts often required deliberate focus, but with repetition, cognitive load diminished. Comments such as “it was easy to adapt” and “after a few rounds I felt comfortable” reflect this learning curve in spatial adaptation.

In some cases, extreme tilts increased perceived difficulty, both for VR tasks (e.g., aligning or placing objects) and while completing the questionnaire (one participant commented: “the environment and orientation influenced the way I believe that I executed each task”). At the same time, for many, the main focus remained on object manipulation and the tilt did not interfere with task execution (“It was easy to adjust, tasks seemed to have the same difficulty every time”, “The extreme tilts were interesting to look at but did not necessarily affect focus on the task”).

Overall, these findings suggest that while the novelty of the tilted environment can impose an initial cognitive burden, participants generally adapted quickly.

4.4.4 Stable vs challenging tilt conditions

Several participants found that $\pm 90^\circ$ and $\pm 180^\circ$ tilts provided natural, stabilizing reference points. Comments such as “rotations close to 90, 180, 270 degrees felt completely natural” and feeling “stable and upright” suggest that these orientations disrupted internal spatial models less than the tilts nonaligned with the virtual walls. As one participant put it: “I noticed a difference between tilts that were perpendicular or parallel to the ground and tilts that were not. The ones with right angles felt much more natural/without conflict with my feeling”.

However, not all participants perceived wall-aligned tilts as easier. One noted increased cognitive load during “the surrounding rotation

at 90 degrees”, while another remarked: “It took me a while before I regained orientation in the 90 degree forward tilt, otherwise it was fine.” These responses suggest that while right-angle tilts often serve as spatial anchors, the 90° forward condition may be more challenging in some contexts, possibly due to its specific relation to the user’s viewpoint or the layout of environmental cues.

5 DISCUSSION

We investigated the performance and subjective experiences of seated VR interaction across 12 distinct tilt conditions, ranging from mild to extreme orientations. Our findings highlight weak to moderate perceptual disturbances, slight reductions in comfort, minor increases in disorientation at extreme tilts, and, notably, no meaningful increase in nausea.

Performance results were less consistent; positive tilts generally led to performance improvements compared to baseline, while negative tilts resulted in similar or slightly degraded performance. In the case of the docking task, a clear trade-off between speed and accuracy was observed.

Although the extent of perceptual disturbances and, in turn, changes to task performance varied significantly in the sample, the persistent theme was rapid adaptation to the tilted environment in cases of initial discomfort or disorientation. Furthermore, some users reported a different perception of $\pm 90^\circ$ and $\pm 180^\circ$ tilts.

5.1 Subjective Responses

5.1.1 Simulator Sickness

Equivalence tests (TOSTs) demonstrated that nausea did not significantly exceed our predefined SESOI (1 point on the 7-point Likert scale) in any tilt conditions, with Holm corrected $p < 0.001$ for all conditions tested. Differential SSQ scores confirmed negligible nausea symptoms, exceeding our initial expectations, as moderate nausea levels were anticipated given the unconventional user orientations. Only one participant reported a notable, but still relatively mild, nausea score above 20 on the SSQ (Figure 4).

Other simulator sickness dimensions, oculomotor disturbances and disorientation, were similarly low overall. Although disorientation was classified as “significant” according to the strict standards of SSQ, the overall symptoms remained in the “minimal” range. It is important to emphasize that SSQ norms, originally derived from military pilot populations [24], may represent an overly stringent benchmark. Previous VR studies frequently report higher SSQ scores [9], exceeding thresholds classified as problematic, emphasizing the mildness of simulator sickness symptoms experienced here.

In-VR questionnaires further corroborated mild disorientation effects, with angles exceeding $\pm 150^\circ$ causing an average increase of only about 0.5-1.12 points from baseline (approximately 1 on average). Even though some confidence intervals slightly exceeded our 1-point SESOI, these were minimal increases.

5.1.2 Comfort and Spatial Perception

Equivalency tests showed closely aligned reductions in comfort and spatial perception, particularly beyond $\pm 90^\circ$ tilts, corresponding closely to increases in disorientation. Despite these minor declines, comfort and spatial perception ratings consistently remained within the favorable range (5-7 on a 7-point Likert scale), indicating only a slight compromise in subjective experiences relative to significantly expanded interaction possibilities. This underscores the robust adaptability of the human perceptual system.

The qualitative analysis revealed a mixed acceptance of the “right angle” tilts ($\pm 90^\circ$ and $\pm 180^\circ$). While some participants found them “natural” or “stable”, others found some of them (especially the $+90^\circ$ tilt) demanding. This helps to explain irregularities in the 90° condition (seen in Figure 3 and Figure 8), where the extent of the illusory physical body tilt decoupled from the distorted gravity pull and spatial perception became slightly lower than perceived comfort.

5.2 Perceptual Effects of Tilted Body Orientations

Perceptual illusions, although moderate, were observed primarily in a subset of participants. Fine-grained analysis via in-VR questionnaires revealed that perceptual disturbances peaked around $\pm 150^\circ$, with weaker effects at perpendicular angles ($\pm 90^\circ$ and $\pm 180^\circ$). Qualitative data support the hypothesis that most participants found perpendicular conditions somewhat less disorienting, likely due to alignment with spatial reference cues (e.g., walls). At the same time, the 90° tilt had mixed reception, with some users finding this specific tilt orientation problematic.

In general, the average values of in-VR perceptual disturbance metrics did not exceed the mid-scale ratings, and similar moderate levels emerged in post-experimental multisensory conflict assessments (disruptions in the integration of visual, vestibular, and proprioceptive signals). However, a qualitative analysis and closer inspection of post-experimental body tilt illusion ratings reveal substantial inter-individual variability. Approximately a quarter of participants notably experienced body tilt illusions, whereas a significant proportion did not or reported minimal illusions. While the perceptual disturbances were generally mild and did not significantly disrupt most users’ VR experiences, the variability in responses (likely influenced by differences in prior VR exposure, as most participants were not seasoned users) warrants further investigation. Nonetheless, the qualitative data and prior literature align in suggesting that such perceptual illusions may diminish with prolonged adaptation and repeated exposure.

5.3 Performance, Influence of Training, and Tilt Direction

Interpreting the performance results is complicated by apparent effects of adaptation (to the tilted conditions, as well as to the tasks). The results must be interpreted with the specific study design (incorporating progressive tilting) taken into account.

In the case of the shooting task, negative tilts showed smaller deviations from baseline performance, compared to positive tilts (where performance tended to improve). This strongly suggests a distinct effect depending on the tilt direction.

Performance in the docking task showed more complex behavior. The temporal metric revealed no clear equivalency, as well as no significant difference in performance. Nevertheless, a direction-specific effect trend was observed; mean trial times mirrored the baseline in negative tilts but showed lengthened durations in positive tilts. Although seemingly contradictory to shooting task trends, positional accuracy data show the opposite trend. Combined, it seems that participants performed docking tasks slightly faster but with worsened accuracy in negative tilts compared to positive tilts. In positive tilts, participants improved slightly in positional accuracy but slowed task execution, suggesting the willingness to spend more time with the detailed positioning of the target under these conditions.

This tendency suggests greater comfort during forward tilts. The docking task’s orientation-specific trade-offs between speed and accuracy align with shooting task performance, implying that negative tilts impair interaction.

Localized performance drops appeared at 15° (docking times), -15° (docking accuracy, shooting times), and to a lesser extent at -30° (docking times) and 30° (shooting times). This may reflect visuo-vestibular cue-weighting instability near the upright condition, where dominant environmental verticals subtly conflicted with vestibular signals, producing intermittent reference-frame ambiguity and excess corrections. At larger tilts the conflict is clearer, enabling commitment to a tilted frame and more stable motor strategies. Such visuo-vestibular mismatch via gravity alignment degrading hand-eye coordination would suggest a “sensory mismatch uncanny valley” where small deviations are most disruptive.

5.4 Implications

Our data demonstrate that virtual user orientation can be flexibly manipulated without compromising immersion or comfort in VR experiences. Tilt-induced discomfort and spatial confusion were generally minor and transient, with rapid adaptation, and the performance was not systematically degraded, as suggested by prior research [16].

These results support the feasibility of VR environments where virtual body orientation diverges from the physical one. Building on prior studies showing successful interaction in supine positions with upright virtual bodies [30, 41], this work extends those findings by demonstrating effective interaction across a broad range of pitch tilts. Our findings further parallel those of Medeiros et al. [32], but instead of rotating planar interaction surface relative to an upright passenger, we introduced a vestibular component. Our work generalizes Medeiros' conclusions from visuo-proprioceptive redirection to full visuo-vestibular redirection, expanding the safe design space for perception manipulation.

5.4.1 Actionable implications for VR design

The outcomes of this work suggest that pitch tilts up to $\pm 45^\circ$ can be confidently deployed without compromising comfort, spatial orientation, or inducing simulator sickness. Forward tilts were more consistently tolerated than backward tilts and should be preferred when designing pitch-based interactions. In room-like environments, the $\pm 90^\circ$ and $\pm 180^\circ$ tilts may be accepted as exceptionally natural, though care should be taken with the $+90^\circ$ orientation due to occasional disorientation. Designers should anticipate substantial inter-individual variability: while some users may experience vivid bodily illusions of tilt, others may not. Rapid adaptation across conditions indicates that minimal onboarding is sufficient, enabling practical deployment of tilted interaction paradigms with little user training.

These findings offer practical opportunities across domains. Artists, designers, and architects can exploit tilted perspectives with sculpting or painting tools, enabling workflows such as leaning forward for detail work or reclining for broader views. Filmmakers and VR storytellers may use tilt as a narrative tool to shift perspective or emotional tone. In virtual workspaces, pitch tilt can optimize screen layout; for example, by revealing additional virtual panels or controls without requiring physical head or body rotations. Game designers can integrate tilt as a core gameplay mechanic, encouraging spatial reasoning and perspective shifts. In collaborative 3D visualization and content creation, tilt allows users to access alternate views without rotating shared objects for other participants.

5.5 Limitations

The modest sample size limits generalizability and provokes further investigation into individual variability in responses to tilted VR environments. Several design choices may also have influenced participant reactions and should inform interpretation and future designs.

One such factor is the working wheel panel, perceived by some as a spatial anchor. It served two roles: (1) simulating realistic interaction with nearby objects during tilted orientations, and (2) reducing simulator sickness via spatial referencing. This anchoring was most evident during initial exposure and the docking task, while the shooting task required engagement beyond the panel.

Simple, relatively static tasks were chosen for this investigation. Dynamic, motion-intensive tasks that require continuous reference-frame updating (e.g., moving-target tracking, rapid head-hand reorientation, or locomotion) may amplify tilt-related effects on performance or discomfort. Thus, the present results support feasibility of pitch-tilted interaction for static/near-static tasks. The task set also prevented varied strategies and isolated performance effects to whole-body rotational mismatch rather than higher-level planning, while most higher-order demands remained untested. Future work should investigate tasks requiring increasing level of dynamic interaction, as well as tasks taxing spatial updating (e.g., locating remembered objects [6]) or mental rotation [26], to better assess the cognitive cost of extreme virtual tilts.

A self-avatar was not rendered. In applications with a visible body, the body axis could help users interpret orientation under pitch tilt and may reduce perceptual bias or improve interaction performance, particularly at extreme tilts. Thus, our results represent performance and subjective responses to tilted interaction in the absence of an avatar; future work should treat avatar presence (or minimal body cues) as a controlled factor.

The progressive tilt sequence may have introduced carryover or latent effects, which a Latin Square or full randomization could have

mitigated. The design was chosen to prioritize safety and reduce abrupt transitions – a fully counterbalanced design was avoided due to the severity of the manipulations. We partially mitigated order effects by counterbalancing tilt direction (forward-first vs. backward-first) and placing the baseline centrally. These conservative design choices were made to reduce adverse reactions and cognitive overload, given the already demanding nature of extreme virtual body rotations. We acknowledge that a possible consequence of the progressive design could be reductions to cybersickness, especially in the more extreme user rotations, due to adaptation. However, the encouraging results suggest that future studies could safely employ stronger manipulations, such as reduced anchoring and randomized tilt exposure.

6 CONCLUSIONS AND FUTURE WORK

This study examined user performance and subjective responses while performing simple tasks in a seated, bounded-space VR setting under a range of virtual body pitch tilts, including extreme orientations up to $\pm 180^\circ$. The findings demonstrate that substantial manipulations of virtual orientation can be achieved without significant compromise to user comfort, perceptual stability, or task performance. While some participants experienced moderate disorientation or altered spatial perception, nausea in our experimental conditions remained negligible, and adaptation occurred rapidly and reliably.

Subjective responses to tilts up to $\pm 45^\circ$ were largely comparable to baseline conditions. In more extreme manipulations, forward tilts were better tolerated than backward tilts and associated with improved positional accuracy and task completion times. The individual variability in perceptual effects (e.g., the illusion of physical body tilting during the virtual tilts) was high, and evidence of adaptation appeared both in participant feedback and in performance improvements across progressively more extreme tilt conditions.

Building on these findings, future research should investigate long-term adaptation effects and repeated exposure to spatially incongruent orientations, with a focus on the sustained feasibility of working under tilted viewport conditions. Potential changes in perceptual illusions, user comfort, and performance variability over time warrant systematic assessment. The role of spatial anchors and how their characteristics influence disorientation and adaptation should be further explored. The generally mild impact on cybersickness and comfort suggests that studies incorporating weaker or no spatial anchoring, as well as randomized exposure to tilt conditions, are both viable directions for further study. Assessment of cybersickness levels without adaptation-allowing progressive study design would be a logical next step, extending the validity of the results particularly for the more extreme tilt angles. Future work should also examine intuitive and well-tolerated methods for user-controlled orientation changes, and ultimately assess the feasibility of tilted virtual orientations under non-seated conditions.

Overall, our findings provide a foundation for future VR applications and research involving rotated user orientations. The results demonstrate that such manipulations can be incorporated without necessarily increasing simulator sickness or reducing user comfort. The experimental environment was well tolerated, with no significant impact on comfort across participants. These outcomes help guide practical implementations that broaden the potential of immersive technologies, with implications across a range of use cases including collaborative design, large-scale data visualization, artistic workflows, VR storytelling experiences, and gaming.

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