Determining Perception Thresholds for Real and Virtual Inclinations While Cycling in Virtual Reality

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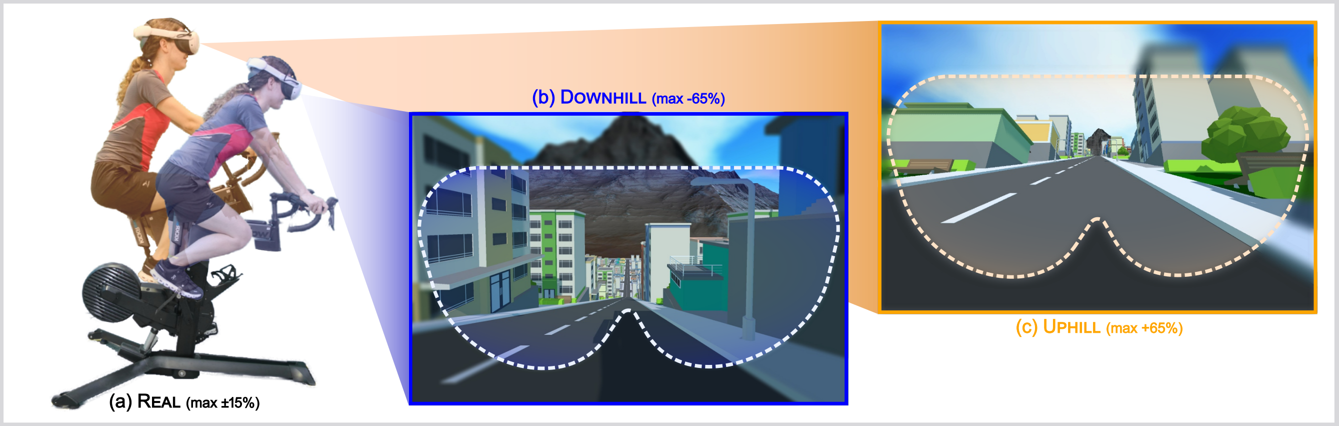

Figure 1: Measuring perceptual thresholds before mismatches between the real and the virtual inclination become noticeable to cyclists: (a) Participant on a stationary bike experiencing real inclinations of up to ±15%, (b) Virtual downhill inclinations perceived through the VR head-mounted display of up to −65%, (c) Virtual uphill inclinations in VR of up to +65%.

Abstract

In virtual reality (VR) experiences, mismatches between reality and virtuality are usually undesirable, as they can disrupt immersion and induce cybersickness. However, when carefully controlled, they may expand the design space of VR. This research investigates perceptual detection thresholds for mismatches between real and virtual inclinations during cycling in VR. Using a custom simulation, $N = 30$ participants cycled through a virtual city while physical and visual inclinations were independently manipulated. Real inclinations were implemented with a tilting indoor bike, providing vestibular and proprioceptive feedback, while virtual inclinations within the simulated environment were presented visually. A multiple staircase procedure derived estimates for perceptual thresholds that approximate which mismatches in visual and physical inclination were still perceived as congruent. These thresholds reveal a window of perceived congruence before mismatches become noticeable to users. These findings advance understanding of sensory integration in VR cycling and inform applications in immersive training, exergames, and rehabilitation systems.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**; **Virtual reality**; *Interaction techniques*; *Empirical studies in HCI*; • **Computing methodologies** → **Virtual reality**; • **General and reference** → *Measurement*; • **Software and its engineering** → Virtual worlds training simulations; • **Applied computing** → Computer games; Consumer health; Transportation.

Keywords

Virtual Reality, Indoor Cycling, Biking, Inclination, Perception, Thresholds, Sports, Exergames

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1 Introduction

Cycling is widely recognized as beneficial for health [32, 33, 113]. Indoor cycling, in particular, has become popular when combined with entertainment such as video games, VR [62], and exergames that increase enjoyment during exercise [81]. Building on this potential, immersive training systems and cycling-based exergames have been developed to further enhance motivation [11, 12, 17, 46, 57, 63, 80, 89, 94, 120], supported by evidence that game-based exercise interventions improve engagement and persistence [55, 77]. VR in particular provides high levels of immersion, making VR exergaming a growing research domain [79], while cycling simulators were also applied to areas such as transportation and safety [72]. Since most VR research strives to create congruent experiences between the virtual and physical world, mismatches are undesirable as they can disrupt immersion and induce cybersickness. Yet, when applied deliberately, they can extend the range of experiences beyond physical constraints [2, 10, 78].

Prior work has explored such deviations in various domains, but the question remains open for cycling in VR. While natural limits exist, such as the steepest road gradients encountered in reality while cycling, or hardware limitations of restricted tilt ranges on simulators and ergometers, these constraints do not bind virtual environments. Moreover, vision often dominates other senses, overriding vestibular and proprioceptive input without users' awareness [1, 44, 93]. These characteristics suggest that controlled mismatches between real and virtual inclinations could be leveraged to expand the design space of VR cycling. To leverage these opportunities, it is essential to determine the congruence window within which mismatches between real and virtual inclinations can be introduced without cyclists noticing.

In this paper, we investigate perceptual thresholds for VR cycling by independently manipulating visual and physical inclinations. Thirty participants cycled in a virtual environment on an indoor bike that tilted between ±15%, providing vestibular and proprioceptive feedback, such as changes in body posture and pressure distribution in the hands and seat. In parallel, virtual inclinations were extended up to ±50% beyond the real tilt, conveyed through visual cues such as houses, street lamps, trees, a mountain, and the visible slope of the street. We quantified perception thresholds using a multiple staircase procedure [59], revealing the extent to which visual inclinations can deviate from physical ones while still being perceived as congruent. Our findings show that virtual inclinations can be manipulated within a congruence window without users noticing. The most pronounced effect appeared for negative real inclinations: participants tolerated considerably steeper virtual downhill slopes, extending from -15% in reality to up to -50% virtually. A similar, slightly smaller effect was observed for positive inclinations, where real tilts of +15% could be paired with virtual inclinations of up to +31%. Analyses of correlations with demographics, prior cycling and VR experience, cyclists' posture, and subjective load did not reveal significant effects. With this work, we contribute an empirical evaluation of detection thresholds for real-to-virtual inclination mismatches in VR cycling experiences.

2 Related Work

Our work builds on two strands: Cycling in HCI, which examines cycling for mobility, health, and exergaming through sensors and simulators, and Illusions in VR, which demonstrate how controlled perceptual mismatches alter experience. Combining these, we investigate how visual-physical mismatches shape inclination perception in VR cycling.

2.1 Cycling in HCI

Cycling has been widely studied in HCI as a platform for safe, sustainable, and healthy mobility. A substantial body of work has focused on safety support, including systems for warnings, navigation, and traffic information [41]. Researchers have investigated visual [69], auditory [5], and vibro-tactile feedback [54, 69, 88, 104]. Cycling is also recognized as both sustainable transport [47, 52] and beneficial exercise for improving health [32, 33, 38, 112, 113]. Despite progress in designing CyclingHCI systems [56, 95], the field continues to face major challenges [71].

Beyond safety and mobility, research has leveraged sensor-based approaches to monitor physiology and behavior [34, 70, 99]. Bike trainers and simulators have been augmented with actuators and VR displays to simulate real-world cycling dynamics [61, 72, 73, 108, 117], address motion sickness [76], and study interactions with other cyclists and road users [109, 110]. Tandem-based simulators have even explored future experiences with self-driving bicycles [72, 74, 118], and AR has been integrated into cycling scenarios [75]. Physiological sensors further extend CyclingHCI, for instance by monitoring vital signs [18, 31], enhancing vision [8], or supporting posture [6]. Systems have also visualized heart rate [3, 110], measured stress [19, 107], and tracked fatigue [60, 105], with applications in adaptive training [35]. Novel fabric-based sensors have been developed to measure cycling posture and joint angles [119], though challenges remain regarding the reliability of physiological signals in outdoor contexts [16, 67, 98].

Parallel to these systems, cycling exergames have been widely studied [11, 12, 17, 42, 46, 48, 57, 63, 80, 89, 102, 120, 121], often relying on ergometers with custom sensors [4, 6, 7, 49, 96]. Beyond motivation, cycling exergames could also benefit from controlled perceptual manipulations, broadening training possibilities. Gamification and interactive training approaches employ real-time data from direct-drive or on-wheel trainers [14], or even smartphones [30]. Research on cycling simulators has addressed competition, feedback, realism, comfort, and emotional factors to enhance performance and engagement [71]. These simulators are generally designed to replicate real-world cycling and study safety [47, 72, 111, 117], rather than to intentionally manipulate perception.

2.2 Illusions in Virtual Reality

Beyond cycling, VR research has long examined illusions that alter perception through visuo-haptic mismatches [1, 28, 40]. Such mismatches can induce VR sickness, but when kept within perceptual thresholds, they may also be harnessed positively to enable new possibilities. Examples include using physical props to enhance height perception in VR climbing [101], electrical muscle stimulation to modulate perceived weight [36] or slope walking [87], and wearable devices such as plateau shoes to simulate steps [97] or visual shifts and bumps to simulate stairs [82].

Unlike stairs or steps, continuous slopes lack distinct edges, leaving walkers or cyclists without haptic boundary cues to perceive inclination. Ishikawa et al. [51] tested treadmill-based walking on virtual slopes but were unable to collect sufficient data to confirm their hypotheses. They noted that uphill walking differs from walking on flat terrain in the direction of weight force, stepping energy, and foot angle–of which only the change in weight force is transferable to cycling, since the movement of pedaling is independent of inclination. Related findings [29, 87] support this view and highlight the dominance of vision over haptics in enabling slope illusions. Cano et al. [29] used a treadmill with an immersive 360-degree dome screen and showed that humans rely mainly on visual cues to perceive gravity-related forces, adapting locomotion in anticipation of corresponding feedback. This demonstrates that visual stimuli can override haptic input, particularly during the initial stage. Similarly, Ohashi et al. [85] used a slanted handrail to simulate walking on a slope, an effect which, in cycling, is instead mediated by the bike. Compared to walking, however, cycling differs fundamentally because the feet do not contact the ground directly, suggesting that findings from walking-based studies may not transfer.

Research on cycling illusions remains sparse. Speed has been manipulated using combined visual and haptic cues, deceiving riders by over 15% without detection [68]. For inclination, Wang et al.[111] investigated simulator sickness and immersion, showing that cyclists adapted their pedaling to virtual slopes, indicating strong plausibility illusions in which visual stimuli were compelling enough to influence physical actions, again highlighting the significant role of visual perception. More recently, Bruce et al.[25] tested virtual hill gradients and found that higher visual slopes increased exertion and blood pressure, even when resistance was held constant. Participants completed congruent and incongruent trials with either matched or fixed workloads across gradients. Their results demonstrate that VR can modulate perceived effort and cardiovascular responses. These studies underline the significant role of vision in modulating perception and action but have not yet established perception thresholds for inclination mismatches.

3 Design Rationale

To investigate perception thresholds for inclinations in VR cycling, we first explain our design rationale addressing both how inclinations are represented and how thresholds are measured. Throughout this work, we express inclination in percent (%), as this unit is commonly used for describing street gradients in real-world contexts. It is important to note that a 100% incline corresponds to a 45° angle, rather than a vertical wall, following the relation:

$$\textit{inclination in degree}\,(^\circ) = \arctan\left(\frac{\textit{inclination in percent}\,(\%)}{100}\right)$$

As a reference, the steepest street in the world is Baldwin Street in New Zealand, with an inclination of approximately 35%, which is a 19.29° gradient [115].

3.1 Perception of Inclination

To determine perception thresholds for inclinations in VR, we first considered how inclinations are perceived in both real and virtual environments, and what this implies for the simulation design.

Visual information is the primary cue for perceiving inclination, as it often dominates other senses when conflicts occur. Visuo-haptic illusions demonstrate this effect, showing that when sensory input diverges, vision typically prevails [1, 27, 37, 44, 93]. Even when slope angles are geometrically evident, slant perceptions are systematically overestimated [91], indicating that inclinations can be manipulated despite the presence of reference lines. Importantly, slope perception transfers well to VR: Lester et al. [64] found no significant differences between slope estimates made in reality, on an LCD, and in VR, suggesting that VR provides a faithful representation of slope magnitudes.

Prior work has modeled inclination in VR using diverse environmental cues such as houses, street borders, and road bends [51]. Li and Durgin [66] showed that perceived optical slant increases logarithmically with viewing distance, particularly for shallow slopes, while Hecht et al. [45] demonstrated that lower viewpoints amplify perceived slant. Cano et al. [29] further used a brick wall and greenery as references in comparison to the horizon, highlighting how visual context influences slope perception.

Based on these insights, our simulation combines multiple cues into a coherent city environment: (1) perspective and horizon line, where object height and alignment relative to the horizon create depth and slope; (2) contextual references, including houses, trees, and street lamps with vertical and horizontal lines at varying distances; (3) ground and distance cues, such as road textures and a bend that reveals or occludes city elements depending on uphill or downhill direction; (4) a fixed reference point, a mountain in the far background for consistent height comparison; and (5) lighting and shadows, cast by houses and roadside objects to reinforce depth and surface orientation.

In addition to vision, humans perceive inclination through kinaesthetic and vestibular feedback, such as balance, posture, and muscle strain. We modeled this with a stationary bike capable of tilting, allowing cyclists to experience "real" inclinations through their bodily senses alongside the virtual ones.

3.2 Threshold Measurement Method

We assume that cyclists in VR accept a congruence window in which virtual inclinations are perceived as matching the real inclination felt in the body. Outside this window, mismatches become noticeable. Accordingly, each real inclination should be associated with an upper and lower perceptual threshold defining the limits of this window. These thresholds may vary depending on the real inclination, as deviations may be easier to perceive around level ground (0%) but harder to distinguish at more extreme up- or downhills.

To measure these thresholds, we implement a One-Alternative Forced Choice (1AFC) design with a symmetric question: cyclists judge whether the virtual road appeared "too steep" or "too flat." We employ the interleaved multiple staircase procedure proposed by Zenner et al. [122]. Typically used to measure a single detection threshold, the staircase method here needs to capture both lower and upper bounds: mismatches are noticed below the window, not noticed within it, and noticed again above it. Thus, we split the procedure into two staircases, one for each boundary.

For each real inclination, we initiate two staircases: one manipulating virtual inclinations upward from reality, and one downward. Each staircase consists of two sequences: an outward sequence starting at the real inclination and moving away (e.g., -15% decreasing further), and an inward sequence starting from an extreme value (reality ±50%) and approaching reality. For example, at a real inclination of -15%, the lower staircase includes one sequence starting at a virtual inclination of -15% and another starting at virtual -65%.

We formulated the question as "In which direction does the virtual inclination need to change in order to match your perception of the real inlination?", or as short task: "Adjust the inclination of the (virtual) road." The binary response can be given via buttons on the handlebar (arrow up / arrow down), indicating whether the virtual slope would need to increase or decrease to match the felt real inclination. This phrasing avoids the need to explain thresholds or staircase directions. Based on the responses, the inward and outward sequences converge to each other; at this point, subjects can no longer decide consistently whether real and virtual inclinations match, leading to reversals that define the perception threshold.

We optimized the staircase parameters through pilot testing. Step sizes began at 15% until the first reversal, followed by 8% until the second, and 3% for the final two, resulting in four reversals per sequence. After a total of eight reversals per staircase (e.g., for "-15% lower"), the last two reversals are used to calculate the threshold. This design balanced precision against study duration and cyclist fatigue. Given the high number of repetitions in this procedure, using 3% steps in the final phase is sufficient, as the law of large numbers ensures reliable estimation of perception thresholds.

The method implicitly assumes that matched real and virtual inclinations lie within the congruence window. If this were not the case, staircases would fail to converge. To handle this, we define an additional stopping criterion: if cyclists consistently give the same response for a given real-virtual pair (five consecutive times) and the staircase reaches its boundary (the inner "reality" boundary or outer extreme boundary "real±50%"), the sequence terminates. In such cases, fewer than four reversals might occur; we then use the last stimulus values of the sequence to estimate the threshold. Allowing staircases to cross reality would confound upper and lower measurements, require impractically small step sizes, and necessitate prior knowledge of the congruence midpoint. Thus, this assumption was necessary to make the study feasible.

4 Evaluation

Our goal is to determine the upper and lower thresholds at which mismatches between real and virtual inclinations become perceptible for cyclists.

4.1 Study Design

To avoid participant fatigue, the study is split into two parts: one measuring upper thresholds and the other measuring lower thresholds. The order is counterbalanced across participants, who either start with the upper or the lower measurements. Thresholds are determined for seven real inclinations (-15%, -10%, -5%, 0%, 5%, 10%, 15%). Within each part, the multiple staircase procedure is applied in an interleaved and fully randomized manner across all real inclinations [122]. After each run, participants complete questionnaires to assess perceived load, ensuring that physical or cognitive strain does not bias threshold estimates.

4.2 Apparatus

We use a Wahoo KickR Bike[1], which supports two-way communication via the Fitness Machine Service (FTMS) Bluetooth protocol[2]. This enables direct data exchange between the bike and our VR system. To decouple perception from physical effort, we fix the pedaling resistance to gears 1-4, ensuring that resistance does not act as an additional cue for inclination. From an application perspective for motivation and training, this setup also reflects the most relevant use case: manipulating the perception of slope while keeping resistance constant. To achieve this, we connect an ESP32 microcontroller to the bike. The VR system requests the current bike position via Bluetooth, and the ESP32 then sends "up" or "down" commands until the target inclination is reached. Figure 2 shows the setup with a participant at three real inclinations (+15%, 0%, and -15%).

To prevent participants from inferring real inclinations through motor movement, the bike briefly overshoots and readjusts between trials. During these transitions, the virtual scene fades to black and back in once the new inclination is set, minimizing both visual motion cues and simulator sickness. Because staircases are randomized across inclinations and sequences, participants cannot anticipate the condition and must rely purely on perception. Responses are given using thumb buttons integrated in the handlebars (Figure 3).

We use a Meta Quest 3 head-mounted display connected via Meta Quest Link to a PC running Unity, which hosts both the virtual city (designed according to our design rationale, cf. Figure 4) and the staircase procedure. Ambient sounds (wind, birds, tire noise) play continuously, masking the motor sounds of the bike setting the real inclination and preventing participants from inferring the magnitude of changes in real inclination.

4.3 Procedure, Data Collection and Asked Questions

The study procedure is illustrated in Figure 5. After welcoming participants and obtaining written informed consent, we collected demographic data and self-assessments of cycling and VR experience using Likert items: Never, Rarely (<1/month), Sometimes (1-3/month), Regularly (1-2/week), Frequently (3+/week). To tailor the bike setup, we measured participants' height, arm and leg length and adjusted the bike for a safe and consistent seating position.

The study began with a two-part demonstration phase. In the first part, participants experienced only real, physical inclination changes while placed in a generic VR loading room. In the second, they experienced only virtual inclination changes while cycling in the simulated city. Here, participants could press the handlebar

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[1] KickR Smart Bike: https://www.wahoofitness.com/devices/indoor-cycling/smart-bikes/kickr-bike-buy, last visited on 08/09/2025

[2] FTMS Bluetooth Protocol: https://www.bluetooth.com/specifications/specs/fitness-machine-service-1-0-1/, last visited on 08/09/2025

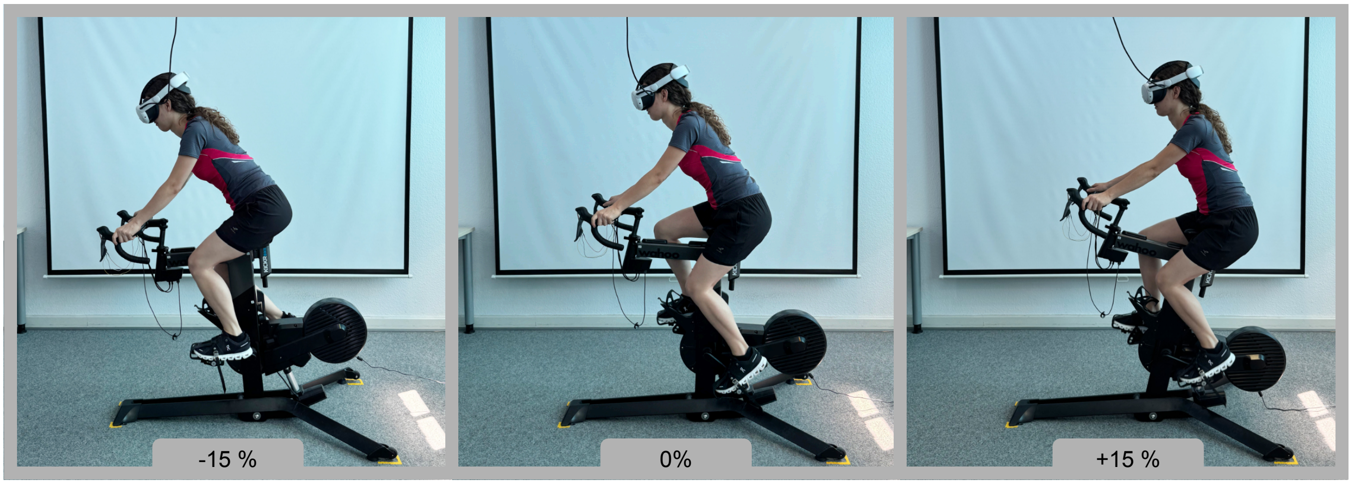

Figure 2: Participant wearing a VR headset experiences real inclinations ranging from -15% to +15% in increments of 5%.

Figure 3: Study setup and buttons. Left: Experimental setup with a participant on the Wahoo KickR Bike wearing a VR headset. Right: Close-up of the handlebar with participants' thumbs placed on the buttons for deciding the 1AFC with "up" or "down". Additionally, a box with an ESP32 microcontroller is attached to the handlebar.

buttons to adjust the virtual slope, allowing them to see the immediate effect of their input–an option not available during the actual staircase trials due to randomization. To verify comprehension, they were explained the question thoroughly: "In which direction does the virtual inclination need to change to match your perception of the real inclination?" which was simplified in VR to "Adjust the inclination of the virtual road" with binary "up" or "down" options as answers, ensuring participants understood the task.

After the demo phase, which also served as a warm-up, participants completed either the upper or the lower staircase procedure, counterbalanced across participants. Within each, staircases for all real inclinations were interleaved. In every trial, participants made a binary choice, whether the virtual road should be steeper or flatter to match their perception of the real inclination by pressing the corresponding handlebar button. Identical buttons were rendered on the virtual bike labeled with "up" and "down" symbols for clarity.

After each run, participants completed questionnaires to measure perceived exertion (Borg-RPE [20–22]), task load (NASA-TLX [43]), and VR-related well-being or discomfort (VRSQ [58]). A break followed, during which participants could rest, drink water, and have light refreshments. They then completed the second run (upper/lower, opposite to the first), again followed by Borg-RPE, NASA-TLX, and VRSQ.

At the end of the study, participants completed the Igroup Presence Questionnaire (IPQ [13, 15, 100]), including the subscales Spatial Presence (sense of being physically present), Involvement (attention and engagement), Experienced Realism (subjective realism), and General Presence. Finally, open-ended interview questions probed participants' perceptions of real and virtual inclinations, strategies for detecting mismatches, impressions of resistance, and additional reflections.

Figure 4: Virtual inclinations experienced during the study, which could occur during the staircase procedure based on the real inclination and previous answers of the participants. Examples of -65%, -15%, 0%, 15%, and 65% are depicted here.

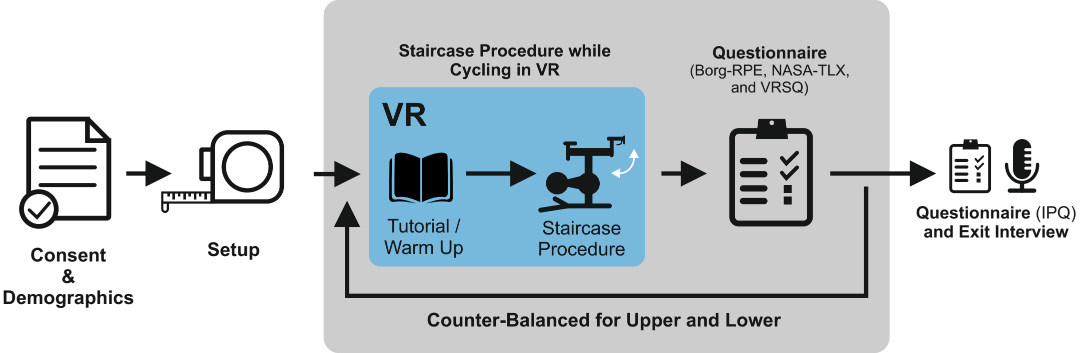

Figure 5: Overview of the study procedure with counter-balanced order for measuring upper and lower perceptual thresholds with a break in between for filling out questionnaires and resting.

4.4 Ethics

For conducting this study, we adhered to the ethical guidelines of our institution and obtained approval from our ethics committee. Before participation, we provided each participant with a comprehensive explanation of the study procedure and obtained their written and informed consent. All questions regarding the procedure were thoroughly addressed before its commencement. Participants were required to pedal and exert physical effort; but in case of increased discomfort, participants could quit the study at any time. To mitigate the risk of injury, a brief warm-up during a demo was conducted. All interviews were manually transcribed, pseudonymized, and subsequently deleted upon the conclusion of the project.

4.5 Participants

We recruited 30 participants[3] through university mailing lists and advertisement via the university sports club. Of these, 7 identify as women, 22 as men, and 1 preferred not to answer. Ages ranged from 21 to 56 years ($M = 29.8$, $SD = 7.5$). Participants' height ranged from 163 to 196 cm ($M = 179.6$, $SD = 8.9$), their arm length ranged from 44 to 65 cm ($M = 56.0$, $SD = 4.1$), and their leg length ranged from 70 to 98 cm ($M = 85.1$, $SD = 6.1$). None of the participants had physical restrictions for riding a bike. Participants rated their experience with VR: 7 answered "Never", 15 "Rarely" (<1/month), 6 "Sometimes" (1-3/month), and 2 "Regularly" (1-2/week). Participants self-reported their experience in cycling: 4 answered "Never", 4 "Rarely", 7 "Sometimes", 10 "Regularly", and 5 "Frequently" (3+/week). A detailed overview of the demographic data is provided in Table 2 in the appendix A. Grouped coarsely into "never/rarely/sometimes" versus "regularly/frequently", this yields 15 less experienced and 15 more experienced cyclists; however, this binning does not fully capture nuances in cycling experience. On average, participants cycled 29:22 minutes ($SD = 5{:}31$) per run (upper/lower), and the entire study including setup, explanations, demo, questionnaires, and interview, lasted between 90 and 120 minutes. Each participant received 10€ as compensation.

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[3] We conducted an a priori power analysis using G*Power for two-sided pearson-correlation ($\rho = .5$, $\alpha = .05$, $1 - \beta = .8$) based on finding correlations of thresholds to demographics or load, yielding critical $r = \pm 0.367$, actual power 0.814, suggesting a minimum sample size of 29.

5 Results

We first report objective measures, followed by quantitative and qualitative subjective results. For the objective analysis, we compute each participant's threshold deviation as the absolute difference between the determined perceptual threshold and the real inclination (i.e., deviation from the reality line). We then use this deviation as the dependent variable in correlational analyses, applying Pearson's r or Spearman's ρ as appropriate based on data type and normality.

5.1 Objective Measures

Table 1 and Figure 6 summarize the final estimates for perceptual thresholds that approximate which mismatches in visual and physical inclination were still perceived as congruent.

Table 1: Determined Perception Thresholds for Real and Virtual Inclinations While Cycling in VR

Real Inclinations	Virtual Thresholds			
	Lower		*Upper*	
	Mean	**SD**	**Mean**	**SD**
-15%	-49.7%	15.2%	-12.9%	4.9%
-10%	-41.6%	14.5%	-7.9%	5.9%
-5%	-29.8%	15.2%	-2.9%	5.2%
±0%	-16.9%	11.8%	2.3%	3.7%
+5%	-3.1%	7.7%	13.4%	10.2%
+10%	2.7%	6.1%	21.5%	11.6%
+15%	8.8%	7.0%	31.0%	12.3%

We further analyzed whether demographic factors correlated with threshold deviations. No statistically significant correlations were found for age (Pearson's $r(28) = .12$, $p = .540$, 95% CI $[-0.25, 0.46]$), height (Pearson's $r(28) = -.35$, $p = .057$, 95% CI $[-0.63, 0.01]$), arm length (Pearson's $r(28) = -.22$, $p = .242$, 95% CI $[-0.54, 0.15]$), or leg length (Pearson's $r(28) = -.13$, $p = .483$, 95% CI $[-0.47, 0.24]$).

In addition to demographics, we examined the cyclists' posture on the bike. For this analysis, we used side-view video recordings collected during the study, with participants' consent. For each decision in the staircase procedure, we extracted a single video frame and estimated 2D body keypoints (ear, shoulder, hip, and wrist) using MediaPipe[4]. From these keypoints, we derived three angles that characterize the rider's posture on the bike: a *hip angle* β between upper body and the line connecting hip and wrist, a *neck angle* δ between upper body and head, and a *shoulder angle* φ between upper body and arm (cf. Figure 7). We do not use the elbow angle directly, as lateral elbow flexion cannot be measured reliably from 2D side-view images. Instead, given that the pelvis and hands are constrained by the saddle and handlebars, the three angles (hip, neck, and shoulder) capture the relevant degrees of freedom in posture, which are mainly realized through elbow flexion and head orientation. Frames in which participants temporarily left their normal riding posture for unrelated reasons (e.g., scratching or shaking out the arms) were removed.

We computed the hip, neck, and shoulder angles across all valid decisions and correlated these angles with the respective threshold deviations. We could not find statistically significant correlations for hip angle β (Pearson's $r(28) = -.15$, $p = .254$, 95% CI $[-0.39, 0.11]$), neck angle δ (Pearson's $r(28) = -.05$, $p = .684$, 95% CI $[-0.30, 0.20]$), or shoulder angle φ (Pearson's $r(28) = .18$, $p = .176$, 95% CI $[-0.08, 0.41]$). Further, we correlated the angles with the real inclinations, where we found statistically significant correlations for hip angle β (Pearson's $r(28) = .06$, $p < .001$, 95% CI $[0.04, 0.08]$), neck angle δ (Pearson's $r(28) = -.18$, $p < .001$, 95% CI $[-0.20, -0.16]$), and shoulder angle φ (Pearson's $r(28) = -.04$, $p < .001$, 95% CI $[-0.07, -0.02]$). And lastly, we correlated the angles with the virtual inclinations, where we also found statistically significant correlations for hip angle β (Pearson's $r(28) = .05$, $p < .001$, 95% CI $[0.03, 0.07]$), neck angle δ (Pearson's $r(28) = -.10$, $p < .001$, 95% CI $[-0.13, -0.08]$), and shoulder angle φ (Pearson's $r(28) = -.03$, $p = .004$, 95% CI $[-0.05, -0.01]$). Effect sizes for neck angles are small, whereas those for hip and shoulder angles are negligible ($|r| < .10$). Taken together with the above statistics, the higher variability in neck angles compared to hip or shoulder angles (Table 3 in the appendix A) suggests that participants primarily adapted their gaze by adjusting head posture while maintaining a largely stable torso position on the bike.

5.2 Subjective Measures - Quantitative Data

Similarly for our ordinal data, we examined whether prior experience influenced threshold deviations. Because VR and cycling experience were measured on ordinal scales and were not normally distributed (cf. Table 2 in the appendix A), we used Spearman's rank correlation. No statistically significant correlations were observed for VR experience (Spearman's $\rho(28) = .12$, $p = .521$) or cycling experience (Spearman's $\rho(28) = -.15$, $p = .422$).

Next, we analyzed participants' load measures. Perceived exertion (Borg-RPE), task load (NASA-TLX), and VR sickness (VRSQ) show no significant correlations with threshold deviations: Borg-RPE (Pearson's $r(28) = .11$, $p = .405$, 95% CI $[-0.15, 0.35]$), NASA-TLX (Pearson's $r(28) = .09$, $p = .487$, 95% CI $[-0.17, 0.34]$), and VRSQ (Pearson's $r(28) = .01$, $p = .922$, 95% CI $[-0.22, 0.27]$).

We also compared participants' load between the first and second run. Normality was tested using Shapiro–Wilk, and paired t-tests or Wilcoxon tests were applied as appropriate. For perceived exertion (Borg-RPE), no significant difference is observed between the first run ($M = 120.4$, $SD = 19.7$) and the second run ($M = 124.0$, $SD = 21.2$), $t(29) = -1.66$, $p = .108$. Task load (NASA-TLX) likewise shows no significant difference ($M_1 = 47.2$, $SD_1 = 15.4$; $M_2 = 48.4$, $SD_2 = 15.2$), $t(29) = -1.37$, $p = .183$. VR sickness (VRSQ) also remains stable across runs ($M_1 = 25.2$, $SD_1 = 16.6$; $M_2 = 26.9$, $SD_2 = 18.1$), $W = 140.5$, $Z = -0.89$, $p = .374$, $r = 0.17$. Analysis of VRSQ subscores also shows no significant changes: Oculomotor ($M_1 = 32.2$, $SD_1 = 18.9$; $M_2 = 35.6$, $SD_2 = 23.5$), $W = 88$, $Z = -1.25$, $p = .211$, $r = 0.26$; Disorientation ($M_1 = 18.2$, $SD_1 = 20.2$; $M_2 = 18.2$, $SD_2 = 17.2$), $W = 75.5$, $Z = -0.05$, $p = .962$, $r = 0.01$. In sum, no significant differences in exertion, task load, or VR sickness are found between the two runs, indicating that repeated measurement did not systematically increase participant load and influence the measurement of perceptual thresholds.

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[4] MediaPipe: https://ai.google.dev/edge/mediapipe/solutions/vision/pose_landmarker, last visited on 01/12/2025

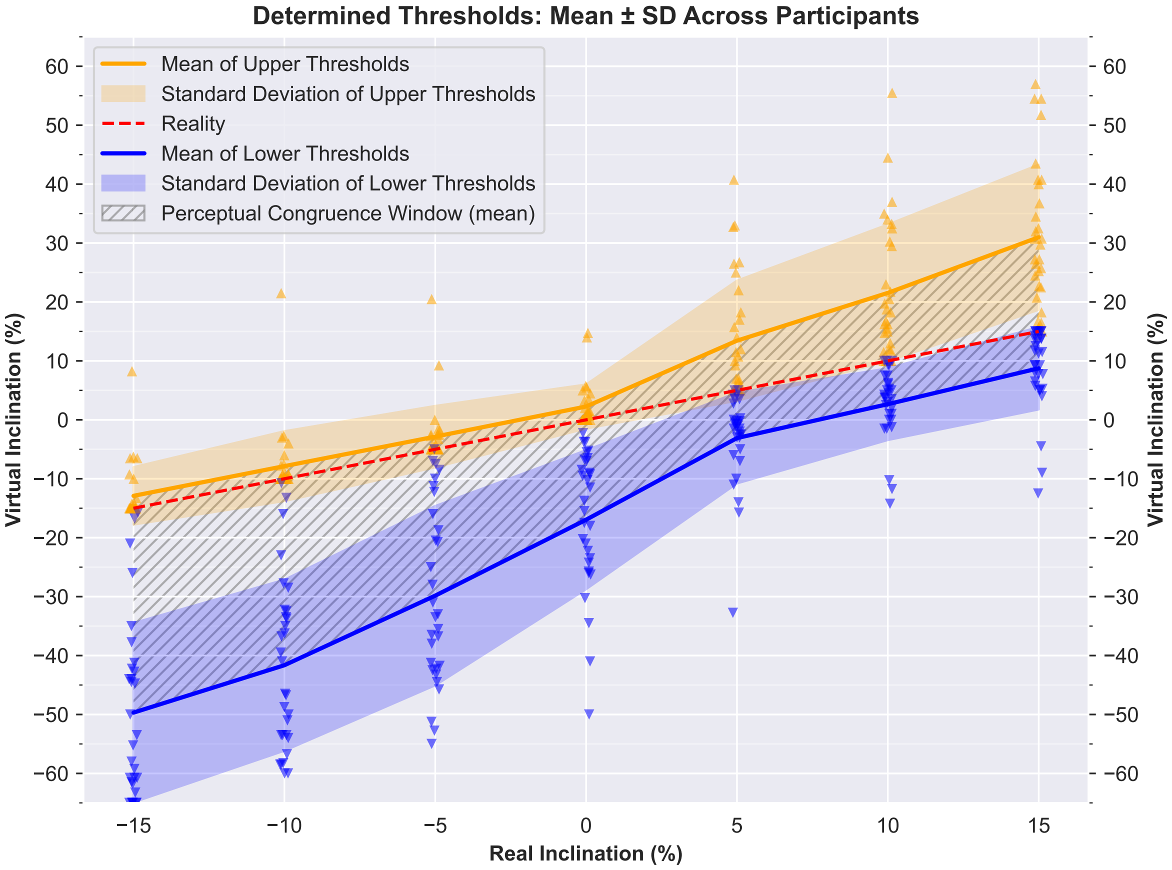

Figure 6: Mean and standard deviation of upper and lower perception thresholds across all 30 participants, indicating the ranges within which real and virtual inclinations are still perceived as congruent. A red diagonal line represents the reality where real and virtual inclination exactly match, while orange and red triagles depict individual measurements of perceptual thresholds.

Finally, we assessed presence using the IPQ. In addition to the overall score, the IPQ includes the subscales Spatial Presence (sense of being physically present in the virtual environment), Involvement (attention devoted to and engagement with the environment), Experienced Realism (subjective realism of the environment), and General Presence.

Participants reported an IPQ Overall Score of $M = 0.005$, $SD = 0.73$. Subscale scores are: Spatial Presence ($M = 0.93$, $SD = 0.78$), Involvement ($M = -0.15$, $SD = 1.16$), Experienced Realism ($M = -1.17$, $SD = 0.90$), and General Presence ($M = 0.70$, $SD = 1.51$). An overview of the quantitative data can be found in Table 4 in the appendix A.

When compared to normative values reported by Tran et al. [106], our results align closely with the mean values of previous systems (Overall Score $M = -0.08$, Spatial Presence $M = 0.80$, Involvement $M = 0.30$, Experienced Realism $M = -0.30$, General Presence $M = 0.90$). Thus, presence in our study is average, indicating that our perceptual threshold measurements are obtained under typical levels of immersion, without requiring exceptionally high or low presence.

5.3 Subjective Measures - Qualitative Data

After completing both parts of the study, participants were asked about their perception of real and virtual inclinations, how they detected mismatches, whether their strategies changed during the study, the influence of pedaling resistance, and any further impressions. All interviews were transcribed verbatim and analyzed using Reflexive Thematic Analysis [23, 24]. This approach supports inductive coding and theme development. The first and second authors conducted open coding, then discussed and refined the codes into three themes capturing key findings. We report these themes below, illustrated with excerpts from participant interviews (IDs shown). Quotes originally given in languages other than English were translated by the authors with an emphasis on preserving meaning.

5.3.1 *Theme 1: Perception of Inclinations.*

Real inclinations: Most participants reported relying on bodily pressure points, particularly in the hands and seat, and in some cases also in the neck, shoulders, or arms. As one participant explained: "The feeling in the saddle and at the handlebar, where the

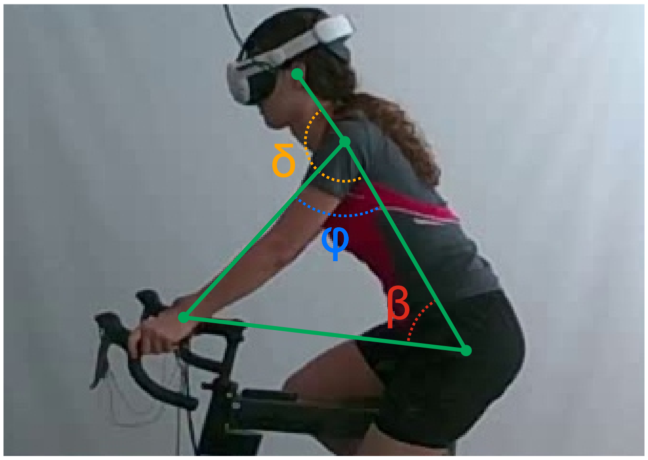

Figure 7: Visualization of the body angles used to characterize cyclists' posture on the bike. A side-view camera, placed perpendicular to the participant, recorded the entire study. From these images, we derive the hip angle β, the neck angle δ, and the shoulder angle φ.

weight rests" (P03), or "the force acting on the hands and the seat" (P04). Others referred to changes in balance and body alignment, describing a "shift of the body's center of gravity" (P09) and their "general sense of balance" (P11, P26). Some participants also highlighted proprioceptive cues, such as the relation between head and trunk position: "The tilt of my head to look straight compared to my hips/spine" (P14).

Virtual inclinations: Visual references were dominant to perceive virtual inclinations. Participants often compared the inclination to architectural features, such as "the slope of the road compared to the floor levels of surrounding houses" (P10), or noted that "the more one could see of the underside of the roof, the steeper the slope" (P07). Several relied on the curb line: "I looked at the curb next to me to judge whether real and virtual inclinations matched" (P09, P28). Others emphasized the horizon: "The horizon gave the first indication of the slope" (P11), or "the houses at the edge and the bend in the horizon" (P03, P30). As P04 summarized: "I compared the slope of the street with the base of the houses. In many scenarios, I also compared the slope of the street ahead with that of the street in the distance." A few also mentioned the mountain as a stable reference point (P18, P19).

Differences uphill vs. downhill: Participants noted asymmetries in their perception of uphill and downhill slopes. Physical downhill inclinations were often easier to detect due to pressure on the hands: "I paid attention to whether there was pressure on my wrists. If yes, it meant downhill. Estimating uphill was more difficult" (P18). Several confirmed that the absence of hand pressure when leaning backward made uphill perception less distinct compared to downhill. Additionally, some participants reported experiencing a brief moment of fear, "comparable to the sensation felt just before a rollercoaster descent" (P17), when confronted with very steep virtual downhills.

5.3.2 *Theme 2: Strategy Changes.*

Participants reported adapting their strategies over the course of the study. Some initially experimented with deliberate methods to identify inclinations. For example, one participant let their arm hang loosely "to sense the vertical" (P20), while another described starting with a "thinking aloud method, negotiating with myself" before later deciding more intuitively (P18). As the study progressed, strategies shifted from conscious reasoning to more intuitive judgments. Several participants emphasized that they initially relied on visual cues but gradually focused more on bodily sensations. As P02 noted: "At the beginning it was difficult because there were many impressions. At first I paid more attention to the road, but over time I focused more on body feeling."

5.3.3 *Theme 3: Pedaling Resistance.*

Most participants reported that pedaling resistance did not influence their perception of inclination. Several only realized at the end of the study that the resistance had remained constant, or stated explicitly that it had no effect on their judgments. A few participants, however, found the lack of resistance change distracting. As P17 explained: "It sometimes bothered me that it did not match what I saw. But when the difference was not too big, I didn't notice it as much." Others even perceived resistance changes that were not present: "The resistance felt harder when going upwards" (P19), or "It made me more aware of uphill slopes, but I didn't notice much difference for downhill" (P25).

6 Discussion

In the following, we interpret our findings, relate them to rotational gain literature, formulate design implications for HCI practitioners, highlight limitations, and outline directions for future work.

6.1 Manipulating Perception of Inclinations

Our results show that manipulating perceived inclination in VR cycling is feasible within congruence windows defined by the measured thresholds. Notably, these windows are asymmetric: participants accept substantially steeper virtual downhills than the corresponding real downhills, and a similar (though smaller) effect appears for uphills. At the extremes, a real -15% downhill can be paired with virtual inclinations near -50% without cyclists noticing, and a real +15% uphill with virtual inclinations around +31% remains acceptable. We also observe a bend between 0% and +5%, with downward manipulations generally more permissive than upward ones. A plausible explanation is that hand and seat pressure provide salient cues to "down" even when the real bike is at 0% only by leaning onto the handlebar; seeing a virtual downhill may thus align with subtle pressure cues, easing the illusion. This also aligns with prior work suggesting steeper apparent slants from the top of hills [90].

These patterns can be interpreted through multisensory theories of locomotion on slopes. Cano et al. [29] demonstrate that visual inclines alone induce systematic "braking" and "exertion" effects in walking that anticipate gravitational forces and are initially dominated by vision, before body-based cues gradually gain weight through sensory reweighting. Our congruence windows complement this account by identifying the parameter range within which such visually driven predictions of gravity remain perceptually coherent during cycling: as long as virtual and real inclines fall within the window, the internal estimate of gravity can accommodate the mismatch without triggering a conscious detection of conflict. Beyond these bounds, sensory discrepancies between vision, vestibular input, and pressure cues become large enough that cyclists reliably notice the incongruence.

Cycling also changes the cue combination problem compared to walking. Unlike walking, cycling lacks foot-ground angle cues [51], so participants cannot rely on step geometry. In walking, Cano et al. [29] show that gait kinematics and effort can gradually signal a mismatch between visual and physical slopes, but in cycling pedal kinematics remain largely similar across inclinations; thus, even with unlimited decision time in our task, the manipulation remains effective because pedal motion does not convey inclination mismatch over time. In line with other perceptual-manipulation studies, we also observe substantial between-participant variability. For instance, Auda et al. report that a visually expanded box remains undetected until, on average, 11.5 boxes (resulting in around 50% larger boxes), with large variability between participants [9]. Motivated by this variability, we also probed potential influencing factors (demographics, experience, and load).

6.2 Robustness of Perceptual Thresholds Across Demographics, Experience, and Load

Across all correlation analyses, we find no statistically significant effects of demographics, prior experience, or subjective load on perceptual thresholds. Given our a priori power analysis, medium to large effects should have been detectable. Their absence therefore suggests that if such influences exist, they are likely small. Specifically, thresholds do not vary systematically with demographics (age, height, arm length, leg length), with prior VR or cycling experience, with sitting posture, or with subjective measures of exertion (Borg-RPE), task load (NASA-TLX), or VR sickness (VRSQ). Interestingly, this contrasts with prior work suggesting that hills appear steeper as people become fatigued, based on increased visual slant estimates after exhausting exercise [90]. In our setting, however, we measured mismatches between visual and physical inclinations during VR cycling under moderate exertion on an incline, a task that likely taps sensitivity to sensory mismatches rather than explicit judgments of hill steepness from a distance. Within the bounds of our a priori power analysis and our predominantly younger sample, this suggests that the observed thresholds did not show systematic associations with these variables; that is, perceptual congruence windows were similar across the measured variables in this group. However, these findings should not be overgeneralized to populations with substantially different age profiles, VR familiarity, or cycling backgrounds.

6.3 Influence of Seating Position

We observe a slight bend in the thresholds between real inclinations of 0% and 5%. One possible explanation is the sportive seating position of the Wahoo KickR Bike in combination with above mentioned consistent pressure cues. For participants unfamiliar with race-bike ergonomics, this posture may shift the perceived neutral position slightly, making 0% feel closer to a mild negative inclination. In our own testing, sitting even higher relative to the handlebars enhances this effect: the cyclist gets the impression of a stronger sensation of downhill riding in VR, which could shift thresholds slightly down. As a result, negative real inclinations can feel even steeper, while positive real inclinations could appear less pronounced.

This observation led us to hypothesize that riders who lean further forward by flexing the elbows and reducing the hip angle, potentially combined with an altered neck posture, would have a more nuanced sense of the offset to gravity and thus be more sensitive to mismatches between visual and physical slopes. We tested this by quantifying posture using angles of the hip, neck, and shoulder. No statistically significant relationships between angles and thresholds emerged, and together with the absence of correlations with height, arm, and leg length, this suggests that if seating position does influence thresholds, the effect size is likely small in our setting.

At the same time, the significant correlations between posture angles and real and virtual inclinations, together with the interview data, indicate that participants did engage in subtle postural adjustments, primarily through head and neck movements. Several participants reported relying on gaze direction and visual references (e.g., horizon and building geometry) when judging inclinations. According to our neck angle analysis, participants tend to perform slight compensatory neck movements as real and virtual inclinations change. This pattern fits with sensory conflict accounts of VR perception, where the brain integrates partially conflicting visual, vestibular, and proprioceptive cues and may privilege vision when resolving discrepancies, as typically observed in motion sickness [86, 114], e.g., for yaw rotations [84], where compensatory movements might occur as a consequence. Similar mechanisms are evident in body-ownership illusions such as the rubber hand illusion [39], where visual input overrides haptic and proprioceptive signals. Overall, while visual information in our setting appears to override other senses, cyclists still subconsciously adjust their posture to maintain comfort, without fundamentally changing the perception thresholds.

6.4 Rejecting Reality

For negative real inclinations, and frequently also at 0%, the upper thresholds reached the "inner" boundary of reality. This suggests a systematic offset between physical and virtual perception. Cyclists in VR may not perceive physical reality as "veridical" when presented within the headset. A similar, though less frequent, effect occurs for positive real inclinations, where lower thresholds sometimes converge at the reality boundary. This bias resonates with earlier findings that steep hills appear harder to descend than to ascend, and thus are judged as steeper when viewed from above [90]. It also aligns with research showing that distances in VR are often underestimated compared to the physical world [50]. Together, these observations point to a general perceptual bias in VR, where physical reality is systematically distorted toward exaggeration.

6.5 Relating Inclination to Rotational Gain

The inclination mismatches we study can be understood as a form of pitch gain, analogous to yaw rotation gains used in redirected walking [65, 83]. In both cases, the virtual camera is rotated more or less than the physical body, with the goal that users do not consciously detect the manipulation. Early work by Razzaque [92] showed that small rotational changes in yaw are less likely to be detected, especially when injected while the user is already turning the head. This aligns with our finding that larger virtual deviations are acceptable at more extreme real inclinations: when cyclists already experience a clear sense of "downhill" or "uphill", additional visual pitch may be easier to hide within the ongoing sensation of tilt. Jerald et al. [53] further report that users are less sensitive to gains applied in the same direction as head rotation than to those applied against it. Similarly, our thresholds are lower around the flat 0% real inclination region than at steeper slopes. Together with our seating-position analysis, this suggests that many cyclists implicitly recalibrate "flat" to a slightly tilted real inclination between 0% and 5%, likely due to gravity acting on a race-bike-like posture to which most people are not accustomed, which in turn narrows the admissible gain range around this subjective neutral.

Steinicke et al. [103] quantified detection thresholds for redirected walking and found that participants tended to underestimate virtual rotations. In contrast, our participants often accepted virtual slopes that were much steeper than the corresponding physical inclines, i.e., a strong overestimation of pitch. This difference possibly reflects the change of rotation axis (yaw vs. pitch) and the different task context. Related work on VR cycling and vehicle simulators has explored small roll tilts as an additional cue. Wintersberger et al. [117] found that roll tilts in a narrow range of about −2.28° to +2.28° improved experience, whereas stronger tilts degraded performance and increased simulator sickness, suggesting a "sweet spot" for roll gain that is much smaller than the pitch gains tolerated in our study. Finally, Brument et al. [26] report that concurrent translational motion reduces users' sensitivity to rotation gains. In our experiment, cyclists were always moving forward through the virtual city, which may similarly elevate detection thresholds and help explain why relatively large pitch gains remain imperceptible within the measured congruence windows.

6.6 Design Implications

Our findings translate into several concrete implications for designing VR cycling systems that manipulate inclination.

DI 1: Use congruence windows as lookup budgets for slope manipulation. The measured perceptual congruence windows specify how far virtual inclinations can deviate from real inclinations without cyclists reliably noticing a mismatch. Designers can treat these ranges as design budgets: for a given physical inclination (or hardware limit), Table 1 and Figure 6 indicate the range of virtual slopes that will usually be perceived as congruent. For example, if a simulator can provide only a physical −5% decline, our data suggest that visual slopes of −30% to −3% can be paired without being detected as incongruent, effectively increasing the bandwidth of slopes that can be simulated with limited hardware. Conversely, when a target virtual slope is desired (e.g., a visually +20% uphill), the thresholds indicate which physical inclinations are required (+10% to +15%).

DI 2: Exploit asymmetry to emphasize downhills and subtly shape motivation. Because the congruence windows are asymmetric, designers have more freedom to manipulate downhills than uphills. Within moderate to steep real downhill inclinations, virtual downhills can be exaggerated substantially, (up to about −50% for a real −15% decline). This can be used to emphasize rewarding descents at the end of effortful segments or to present slight visual downhills while the user is physically riding on flat ground to support motivation in exergaming and training scenarios. Uphills afford a smaller, but still usable, range of amplification (up to about +31% for a real +15% incline). Particularly around the region between 0% and +5%, designers should be more careful, as our thresholds indicate smaller admissible deviations. Overall, our results suggest that VR systems can safely exaggerate many downhill segments, while uphill segments should be manipulated more cautiously.

DI 3: Provide stable visual references but allow compensatory head movements. Qualitative reports and our posture analysis indicate that cyclists rely on a combination of visual references (e.g., horizon, building edges, road markings) and coarse body cues such as hand pressure and head orientation. Scene design should therefore include clear horizontal and vertical structures and distant, relatively flat regions in the background that can serve as visual references for slope perception. Presence measured by the IPQ in our study was in an average range, suggesting that effective inclination manipulations do not require exceptionally high presence. At the same time, keeping the body posture largely constrained by saddle and handlebar appears unproblematic: participants mainly used small head and neck adjustments as compensatory movements. Designers can therefore allow natural head motion while keeping the torso posture relatively fixed by the simulator.

DI 4: Apply inclination manipulations in physically demanding scenarios. Perceived exertion (Borg-RPE), task load (NASA-TLX), and VR sickness (VRSQ) scores did not show systematic associations with perceptual congruence windows in our sample. This suggests that, within the ranges tested, inclination manipulations can be applied in physically demanding contexts (such as sports, training, or rehabilitation) without strongly modulating the detection thresholds themselves. Designers can therefore focus on using the congruence windows to shape motivational elements (e.g., inserted downhill "rewards").

Taken together, these implications provide actionable guidance for using inclination manipulations in VR cycling systems: designers can look up feasible virtual-physical slope combinations, exploit asymmetries between up- and downhill segments, craft scenes with appropriate visual references, and apply these techniques even in exercise-oriented applications, as long as they stay within the empirically derived congruence windows.

6.7 Limitations

We acknowledge several limitations of our study. First, although our sample included participants with diverse levels of cycling and VR experience, recruitment through university mailing lists and the sports club biased the group toward younger individuals. Our sample size ($N = 30$) is adequate for detecting medium effects in correlational analyses but not for reliably identifying small effects. While cycling experience is roughly balanced when grouped into "never/rarely/sometimes" versus "regularly/frequently", this binning is only one possible categorization, and some combinations of age and expertise are underrepresented (Table 2 in appendix A). Together, these factors may limit the generalizability of our findings to broader or older populations.

Second, we observed cases where thresholds converged at the boundary of reality, particularly for upper thresholds of negative real inclinations and, less frequently, for lower thresholds of positive inclinations. This suggests that the congruence window might be narrower than our estimates. While this does not affect most practical applications, where extending beyond reality is of primary interest, it indicates that future work should more precisely characterize the "inner boundaries" of the congruence window. Relatedly, we measured P_{50} detection thresholds based on symmetric step sizes, which characterize when mismatches become reliably noticeable, but not how far such mismatches can be pushed before causing discomfort, loss of presence, or simulator sickness. In other words, we did not measure tolerance thresholds in the sense of how much incongruence can be sustained before users start to reject the experience, as explored for yaw gains in recent work [116]. Follow-up studies should therefore determine higher detection levels (e.g., P_{75}) and explicit tolerance limits to provide a fuller picture of experiential boundaries.

Third, the procedure was physically demanding. Fatigue occasionally led to inconsistent answers, slowing staircase convergence. While counterbalancing and randomization help distribute such effects across participants, fatigue may nonetheless have influenced accuracy. Finally, our analysis of cyclists' posture is based on 2D pose estimation from side-view video frames. This constrains measurements to the sagittal plane, may miss subtle out-of-plane movements, and is subject to tracking noise. Although manual cleaning and aggregation across many frames help mitigate these issues, future work could employ dedicated 3D motion-capture systems to obtain more fine-grained postural measures. While we hypothesize that sportive seating posture may bias thresholds slightly toward negative inclinations, this requires further systematic validation before strong conclusions can be drawn.

6.8 Implications and Future Work

Our findings establish a perceptual congruence window within which mismatches between real and virtual inclinations remain unnoticed. These thresholds provide a foundation for applications across immersive training, transportation, and rehabilitation. For training systems [46, 57], inclination manipulations can be used to sustain motivation–for example, presenting a downhill at the end of a demanding session to encourage continued effort without altering real resistance. Within such windows, stronger virtual downhills could increase cadence and power output at constant resistance, enhancing training effectiveness. When combined with other manipulations such as speed adaptation [68], these effects may further amplify engagement. Prior work suggests that perceptual manipulations influence exertion and physiological responses [25], but our study adds the critical contribution of quantifying the ranges within which these manipulations remain imperceptible. Beyond performance, such effects may also impact emotions [89] and motivation [63]. In transportation research, the thresholds allow broader simulations of urban environments even with limited hardware. Similarly, rehabilitation scenarios may benefit from carefully designed manipulations that extend therapeutic possibilities.

Future studies should broaden this approach to other aspects of cycling. Systematically determining congruence windows for variables such as pedaling resistance or perceived speed [68] would help chart the wider design space of perceptual manipulations in VR cycling. Moreover, investigating long-term effects on motivation, training outcomes, and well-being are key to understand how such manipulations can be applied responsibly and effectively. Our staircase procedure frequently produced incongruent pairings in which participants could see a virtual uphill while physically experiencing a downhill, and vice versa. Especially for small positive, real inclinations, these pairings were still often perceived as congruent (cf. Figure 6). However, such situations occurred only at isolated decision points separated by a dark screen, not as sustained segments along a continuous route. An important next step is therefore to investigate how inclination manipulations behave under continuous, repeated changes in slope, and to what extent prolonged incongruence in pitch (analogous to incongruent yaw rotations utilized by Wilson et al. [116]) affects presence, comfort, and overall experience. A further promising direction is to investigate if and how similar congruence windows transfer to related domains beyond cycling (such as virtual car driving, roller coaster experiences, or skateboarding simulations), where visual and physical slopes can also diverge, and to examine to what extent domain-specific body postures and motion cues modify these thresholds.

7 Conclusion

This work determines the first empirical estimations for perceptual detection thresholds of real-to-virtual inclination mismatches during cycling in VR. Our results show that cyclists can easily be led to perceive steeper uphill or downhill inclinations than they physically experience without reliably noticing the mismatch, revealing a congruence window within which visual inclinations can deviate from real inclinations without users noticing. Interestingly, we also observed systematic perceptual offsets: when cycling at a physical tilt of -15% or +15% and viewing the same inclination in VR, many participants judged the slope as insufficiently steep, suggesting that in VR, reality itself is often rejected. While this is a noteworthy finding in its own right, it also highlights the need for further research to refine the "inner boundaries" of our congruence window (upper threshold for negative real inclinations and lower thresholds for positive real inclinations), which are partly constrained by the model assumption that reality is perceived in VR as veridical. The thresholds identified in this study enable researchers and practitioners to design immersive VR cycling experiences that expand the boundaries of reality without cyclists noticing. Practical applications include immersive training systems and exergames, where manipulated visual inclinations could motivate users, for example, by simulating a downhill section toward the end of a demanding session without altering the real inclination or pedaling resistance. Beyond training and entertainment, the findings may also inform rehabilitation scenarios or therapeutic interventions, such as exposure therapy for fear of heights. Overall, our results open up new opportunities to deliberately and systematically leverage perceptual mismatches in VR cycling.

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A Appendix

Table 2: Overview of participants' demographic data, including age, gender, height, arm and leg length (in cm), and self-reported VR and cycling usage frequencies.

ID	Age	Gender	Height	Arm Length	Leg Length	VR Usage	Bike Usage
01	39	m	181	57	93	Rarely (<1/month)	Sometimes (1-3/month)
02	26	f	169	52	82	Never	Regularly (1-2/week)
03	26	m	186	54	90	Sometimes (1-3/month)	Regularly (1-2/week)
04	24	m	183	57	90	Regularly (1-2/week)	Sometimes (1-3/month)
05	24	m	193	60	88	Rarely (<1/month)	Frequently (3+/week)
06	56	m	175	57	70	Never	Regularly (1-2/week)
07	43	m	180	55	85	Never	Never
08	24	m	188	58	88	Rarely (<1/month)	Rarely (<1/month)
09	26	m	190	65	91	Sometimes (1-3/month)	Regularly (1-2/week)
10	39	m	196	61	96	Rarely (<1/month)	Sometimes (1-3/month)
11	26	m	186	57	86	Never	Rarely (<1/month)
12	26	m	179	58	80	Never	Never
13	27	m	183	57	87	Sometimes (1-3/month)	Regularly (1-2/week)
14	25	m	185	57	81	Rarely (<1/month)	Sometimes (1-3/month)
15	26	f	172	53	80	Regularly (1-2/week)	Rarely (<1/month)
16	21	f	169	44	79	Rarely (<1/month)	Never
17	32	f	164	51	77	Rarely (<1/month)	Frequently (3+/week)
18	29	m	178	60	87	Rarely (<1/month)	Regularly (1-2/week)
19	38	f	163	49	80	Sometimes (1-3/month)	Never
20	35	m	178	57	98	Sometimes (1-3/month)	Sometimes (1-3/month)
21	35	m	194	57	83	Rarely (<1/month)	Sometimes (1-3/month)
22	22	m	180	54	87	Rarely (<1/month)	Regularly (1-2/week)
23	35	m	189	55	84	Rarely (<1/month)	Regularly (1-2/week)
24	28	f	171	57	86	Rarely (<1/month)	Regularly (1-2/week)
25	30	f	168	54	77	Sometimes (1-3/month)	Frequently (3+/week)
26	27	m	180	58	91	Rarely (<1/month)	Sometimes (1-3/month)
27	24	m	170	54	82	Never	Frequently (3+/week)
28	29	-	173	51	78	Never	Regularly (1-2/week)
29	29	m	178	59	88	Rarely (<1/month)	Rarely (<1/month)
30	24	m	188	61	89	Rarely (<1/month)	Frequently (3+/week)

Table 3: Mean and standard deviation (SD) of hip, neck, and shoulder angles in degrees for all participants, calculated over all decisions during the study.

	Hip Angle β		***Neck Angle*** δ		***Shoulder Angle*** φ	
ID	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
01	61.7	5.5	165.6	8.0	68.6	6.6
02	58.9	2.4	168.3	6.2	72.7	2.8
03	59.2	7.2	167.0	6.6	71.1	7.2
04	65.7	2.7	173.6	5.5	61.7	3.2
05	62.5	1.5	162.9	4.8	65.3	1.6
06	56.6	1.8	173.9	4.7	76.0	2.9
07	62.9	1.9	176.4	2.8	65.7	2.5
08	62.8	7.4	169.0	7.0	66.7	8.6
09	56.0	3.3	159.7	7.8	82.4	5.0
10	60.4	2.5	169.4	4.8	68.8	3.4
11	60.4	1.8	168.1	7.2	70.6	2.6
12	59.1	2.5	161.9	6.9	75.7	4.3
13	61.0	1.5	169.7	5.4	73.5	2.3
14	57.9	3.3	169.6	6.2	73.6	3.4
15	53.7	4.4	169.6	6.5	79.4	6.7
16	54.4	3.6	166.0	8.2	79.4	4.6
17	55.6	3.7	164.9	6.5	72.5	4.4
18	61.5	2.0	163.5	6.0	69.5	2.4
19	56.1	2.4	162.0	7.0	79.4	3.9
20	58.6	5.0	158.0	7.8	75.0	6.7
21	68.3	5.4	167.7	7.1	58.1	4.8
22	58.2	3.9	169.0	6.2	74.1	5.8
23	64.5	2.9	166.8	6.6	65.7	4.7
24	56.4	4.0	172.8	5.7	75.5	5.9
25	52.3	2.9	175.0	3.6	83.8	4.8
26	63.1	5.8	163.9	6.3	70.7	6.7
27	56.0	3.7	161.2	6.4	80.6	6.9
28	53.3	4.7	171.3	5.7	79.5	6.8
29	61.2	4.8	161.6	8.9	71.4	4.0
30	62.8	3.4	157.2	8.8	62.8	3.3
∅	59.4	3.6	166.9	6.4	72.3	4.6

Table 4: Overview of the quantitative data of the standardized questionnaires (mean and standard deviation).

	Post 1^{st} ***run***		***Post*** 2^{nd} ***run***	
Questionnaire	**Mean**	**SD**	**Mean**	**SD**
Borg-RPE	120.4	19.7	124.0	21.2
NASA-TLX	47.2	15.4	48.4	15.2
VRSQ Total Score	25.2	16.6	26.9	18.1
VRSQ Oculomotor	32.2	18.9	35.6	23.5
VRSQ Disorientation	18.2	20.2	18.2	17.2
IPQ Total Score			0.005	0.73
IPQ Spatial Presence			0.93	0.78
IPQ Involvement			-0.15	1.16
IPQ Experienced Realism			-1.17	0.90
IPQ General Presence			0.70	1.51