Persistent Biases in Gravity Perception at Altered Scale in Virtual Reality Despite Interactive Priming

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Figure 1: Examples of the participant's perspective during various stages of the priming phase.

Abstract

According to multiple previous studies, perceiving "correct" rigid body dynamics in VR is difficult when the experience contains size cues that are inconsistent with users' prior experiences, such as when the user is virtually rescaled. In this study, we investigated whether demonstrating physically accurate behavior to users facilitates their ability to identify the correct physics model. We conducted a preregistered experiment with 44 participants, in which users first completed an introductory (priming) phase designed to illustrate correct object behavior both at normal and reduced scale (1/10) conditions, followed by an interactive task where they operated at a reduced scale and evaluated two competing physics models (named "True Physics" and "Movie Physics" similar to previous studies). Contrary to our hypotheses, participants consistently preferred the "Movie Physics" model where gravity is adjusted to preserve human-scale motion over physically accurate behavior. This preference persisted despite direct interaction with correctly simulated dynamics and closely replicated prior findings obtained without such priming. These findings indicate that internalized expectations of Earth gravity and human-scale interactions are highly resistant to change, even with interactive demonstration. The results highlight fundamental challenges in conveying physically accurate altered-scale phenomena in VR and suggest that more extensive approaches may be required to support user adaptation.

CCS Concepts

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

Keywords

Virtual Reality, Perception, Multiscale, Gravity Perception

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1 Introduction

One of the most interesting properties of immersive virtual reality (VR) is its capability to simulate experiences that would be impossible to achieve in real life. A particular example of this is the capability to simulate experiences in which the user is scaled into different sizes, similar to characters from popular movies such as *"Honey I Shrunk the Kids," "The Incredible Shrinking Man,"* or *"Ant-Man."* Various VR applications and interaction techniques utilize this paradigm. In Multiscale Collaborative Virtual Environments (MCVEs), multiple VR users can collaborate around various tasks so that the users coexist at different scales [Zhang and Furnas 2005]. MCVEs have been suggested, for example, as a collaboration and

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interaction mechanism for applications such as medical visualizations and architectural planning [Kopper et al. 2006; Zhang and Furnas 2005]. Besides MCVEs that exist purely in the VR domain, several collaborative multiscale Mixed Reality (MR) systems have been suggested as well [Billinghurst et al. 2001; Piumsomboon et al. 2018a,b]. Self-scaling has also been utilized for design tasks inside VR [Zhang et al. 2020a,b]. Furthermore, self-scaling has been suggested as a locomotion technique for VR; a VR user can temporarily virtually enlarge him/herself to cross larger distances in VR with natural walking [Abtahi et al. 2019; Krekhov et al. 2018]. In addition to VR and MR applications that utilize self-scaling, teleoperation of robots working at non-human scales is an emerging topic (e.g. [Hejrati 2025; Izumihara et al. 2019]). As a practical example, immersive teleoperation of construction machinery has been suggested for working in hazardous or otherwise challenging environments [Hu et al. 2025]. Humans have, however, not evolved to operate at multiple scales; the environment relevant to our ordinary day-to-day manual interactions is measured in centimeters and meters, which is only a fraction of the scale encompassing the physical reality [Gibson 2014]. This leads to interesting perceptual phenomena when we simulate human interaction at multiple scales while attempting to faithfully simulate the physical laws of that scale.

1.1 The relationship between scale and gravity

If the multiscale VR application simulates Newtonian physics, self-scaling elicits an interesting perceptual phenomenon; as the user's scale changes, the apparent gravity of physically simulated objects changes as well. For example, if an average-sized person extends his/her arm and drops an object from a height of 1.6m, it would take approximately 0.57s for this object to reach the ground. However, if this person were scaled ten times smaller or ten times bigger, the object would reach the ground in 0.16 seconds or 1.8 seconds, respectively. In the eyes of the VR user, this usually appears as unexpected or incorrect physical behavior of objects when the user or some other (scaled) entity interacts with these objects [Pouke et al. 2021, 2020, 2024a].

Humans appear to exhibit limited adaptability to altered gravity conditions. Prior research indicates that people rely on a strong internal model of Earth's gravity and rigid body dynamics observed within [Merfeld et al. 1999]. A survey by Jörges and López-Moliner [2017] suggests that this internal model constrains adaptation to non-Earth gravity, particularly when using visual stimulus only. While gradual adaptation may occur in real microgravity environments, such adaptation is considered unlikely in VR, where only audiovisual cues are available. However, tasks involving a strong motor component, such as point-to-point arm movements, and throwing, appear to facilitate faster adaptation to altered gravity than interception tasks [Crevecoeur et al. 2009; Jörges and López-Moliner 2017; La Scaleia et al. 2020; Pouke et al. 2024b]. It also appears that humans are capable of experiencing a visual reorientation illusion (VRI) and a false sense of acceleration caused by gravity when manipulating body orientation and visual field using VR [McManus and Harris 2021].

McIntyre et al. [2001] examined astronauts intercepting vertically moving objects in microgravity and observed earlier initiation of catching movements compared to normal gravity, suggesting reliance on an internal gravity model in addition to perceptual cues. Adaptation effects emerged over approximately two weeks. Similarly, Gaveau et al. [2011] studied cosmonauts performing point-to-point arm movements before and after spaceflight, finding evidence of sensorimotor adaptation during exposure to reduced gravity. Upon returning to Earth, participants overestimated gravitational effects, as if their motor system had been recalibrated for a higher-gravity environment, potentially due to altered vestibular and proprioceptive inputs.

Zago et al. [2004] used a projection-based setup to study interception of vertically moving targets with varying motion profiles. Participants consistently assumed motion consistent with Earth gravity and showed strong resistance to adopting alternative gravity models, although training improved timing of motor responses. A subsequent study suggested that rather than forming new internal models, participants rely on the default Earth gravity model and compensate through adjustments in processing time [Zago and Lacquaniti 2005].

Using immersive stereoscopic VR, Senot et al. [2005] asked participants to intercept targets with varying motion characteristics. While performance was highest for constant-velocity motion, participants systematically initiated actions earlier for downward-moving targets, indicating an expectation of gravitational acceleration regardless of actual motion parameters.

Ye et al. [2017] investigated adaptation across multiple VR tasks under different simulated gravity conditions, including interception and prediction tasks. Although participants demonstrated a persistent bias toward Earth gravity, they were able to improve performance and accuracy across conditions. Gravano et al. [2021] further showed that mental imagery training alone can update internal gravity models, as astronauts improved simulated 0g performance without physical exposure to altered gravity.

Cano Porras et al. [2020] explored locomotion under simulated gravity in VR and found that visual cues initially dominated behavior, leading participants to adapt their gait to virtual inclines. Over time, however, body-based cues regained influence.

Despite strong performance in motor tasks involving object motion, humans often exhibit poor intuitive understanding of physical principles [Kozhevnikov and Hegarty 2001; La Scaleia et al. 2020]. Ullman et al. [2017] proposed that human physical reasoning resembles heuristic-based approximations rather than precise computations. In VR contexts, environmental cues such as object size can support gravity perception [La Scaleia et al. 2020], whereas inconsistent cues may impair it [Pouke et al. 2024a]. Addressing the relationship between perception and action, La Scaleia et al. [2020] investigated both perceptual judgments and interception performance under varying gravity conditions in VR. Their findings indicate that the internal gravity model influences both perceptual and motor processes.

Multiscale VR provides a relevant context for studying perception at altered scale, and the increasing use of robotic systems operating at non-human scales, especially in teleoperation of heavy machinery, further motivates the need to understand how users perceive physics in such conditions. Prior research has consistently shown that humans tend to perceive non-human-scale or otherwise abnormal gravity-driven dynamics as unnatural, reflecting a strong bias toward Earth-scale expectations. Building on this foundation, the present study investigates whether this bias can be mitigated through experiential priming. Specifically, we examine whether an interactive introductory task—designed to demonstrate physically accurate behavior at a reduced scale—can facilitate users' ability to recognize and accept the correct physics model. By directly following up on earlier findings (e.g. [Pouke et al. 2021]), this work aims to clarify the extent to which perceptual biases in gravity and scale can be influenced through interaction in immersive VR.

2 Related Research

Earlier experiments by Pouke et al. [2021, 2020] manipulated VR user's scale by changing their virtual viewpoint height, interpupillary distance (IPD), and mesh size of the user's virtual character. Furthermore, they found that, when interacting with physically simulated objects, approximately 3/4 of participants found the objects' behavior unrealistic both at 1/10 and 10x scale. Instead, the participants found it more realistic when the behavior of the objects was similar to as if the participants themselves remained at a regular scale, and the size of the environment was changed instead (i.e. an object would reach the ground in approximately 0.57s regardless wheter it is dropped at the height of 16cm or 16m). The authors dubbed the correct approximation of rigid body dynamics *True Physics*, and the incorrect one *Movie Physics*, and the subsequent follow-up studies followed the same convention.

The fact that the participants in Pouke et al. [2021, 2020] acted as if the world had changed in size instead of the participants is conceptually in line with the findings of van der Hoort et al., who used synchronized visuo-tactical stimuli (sometimes called body-scaling in related literature) to create an illusion of having either doll-sized or giant-sized body and found that their participants felt that the size of their surroundings changed under the illusion, whereas they themselves remained at a regular scale [Van Der Hoort et al. 2011]. The studies of Pouke et al. [2021, 2020], however, queried only the plausibility (coherence) of the physics models and did not specifically ask whether the participants felt as if the environment's size or their own size was changing.

A follow-up study by Pouke et al. [2022] investigated whether the perceptual effect found in Pouke et al. [2021, 2020] can be achieved when the user is scaled by using the body-scaling technique [Van der Hoort and Ehrsson 2014; Van Der Hoort and Ehrsson 2016; Van Der Hoort et al. 2011] instead of viewpoint height and IPD manipulation. In this study, the participants did not interact with the physically simulated objects themselves but instead watched an animated humanoid virtual character on a 0.2 scale to perform similar interactions. Surprisingly, the body scaling appeared to have no effect on physics plausibility, but the participants still considered the *Movie Physics* as the more realistic physics model regardless of condition. The authors hypothesized that the probable reason for this surprising finding was that the participants interpreted the plausible trajectories of the physically simulated objects according to the scale of the virtual character instead of their own scale, or the environments scale. This hypothesis was partially confirmed in a later study where it was found that when observing virtual characters interacting with physically simulated objects at multiple scales (the participants were scaled using viewpoint height and IPD manipulation similar to the original studies [Pouke et al. 2021, 2020],) the identity of virtual characters (a regular-sized housecat vs. a humanoid robot as in [Pouke et al. 2024a]) could predict the preference between *True Physics* and *Movie Physics* whereas the self-scaling could not. This finding is in line with the results of Langbehn et al. [2016], who found participant used the scale of virtual characters as the guiding metric when faced with multiple conflicting scale cues in VR.

Pouke et al. [2024b] investigated whether humans can adapt to simulated hypergravity of 5g (corresponding to a reduction in perceived scale to one fifth of the original size) using the so-called "prism adaptation" methodology [Redding et al. 2005]. In this paradigm, the relationship between participants' physical actions and visual feedback is systematically altered (e.g., moving one's hand to the right appears as movement to the left). After an extended exposure period, the transformation is removed and participants' performance is evaluated. Using this approach, Pouke et al. [2024b] reported evidence that participants can temporarily adapt to a visually simulated hypergravity model. Similar to Pouke et al. [2024b] Porco et al. [2024] focused on throwing in MR environments for the purpose of adaptation under different gravity models (Earth, Mars, and Moon), however, the main focus in this study was on the validation of the accuracy of the virtual ball's simulated trajectory instead of human adaptation itself.

The present study focuses on the role of priming rather than adaptation. Similar to the original studies of Pouke et al. (e.g. [Pouke et al. 2021, 2020]), the emphasis is on participants' perception of subjective plausibility between competing physics models (i.e., physics coherence [Skarbez et al. 2017]), rather than performance in motor tasks such as throwing [Porco et al. 2024; Pouke et al. 2024b]. The priming approach employed here involved interactively demonstrating rigid body dynamics of physically simulated virtual objects at both human scale and at 0.1× scale. Following this priming phase, participants' judgments of physics coherence were assessed using a methodology similar to Pouke et al. [2021, 2020]. In the past, tasks involving more pronounced motor interaction have appeared to be effective in producing gravity adaptation [Jörges and López-Moliner 2017; Pouke et al. 2024b]. It appears reasonable, therefore, that interacting with physically simulated objects (instead of merely observing them), would be effective in demonstrating correct behavior of physically simulated objects.

Contrary to expectations, however, the priming appeared to be ineffective: participants again preferred *Movie Physics*, replicating earlier findings reported in Pouke et al. [2021, 2020]. Specifically, participants judged *Movie Physics* to be both more realistic and more consistent with their expectations. Furthermore, no evidence was found that participants in the present study selected *True Physics* more frequently than participants in the original study reported in Pouke et al. [2020].

3 Methods

A within-participants study was conducted to investigate the effect of cognitive priming on physics coherence. Our preregistered [1] hypotheses are described below.

- H1: For a scaled-down participant, after priming, *True Physics* is more likely to feel realistic than *Movie Physics*

[1] https://osf.io/8ynhm/

- H2: For a scaled-down participant, after priming, *True Physics* is more likely to match the participant's expectations than *Movie Physics*.
- H3: Participants experiencing a priming phase are more likely to consider *True Physics* to feel realistic than participants who did not experience a priming phase.
- H4: Participants experiencing a priming phase are more likely to consider *True Physics* to match their expectations better than participants who did not experience a priming phase.

Following the convention from earlier research, *True Physics* refers to physically accurate simulation in which object dynamics follow real-world scaling laws (e.g., gravitational acceleration remains constant regardless of the participant's apparent size), resulting in motion that may appear unfamiliar at reduced scale. In contrast, *Movie Physics* refers to a perceptually adjusted model in which gravity is implicitly scaled with the participant's size to preserve motion patterns consistent with human-scale expectations. The experiment was conducted under the existing IRB statements by Oulu University institute for human sciences and the European Research Council.

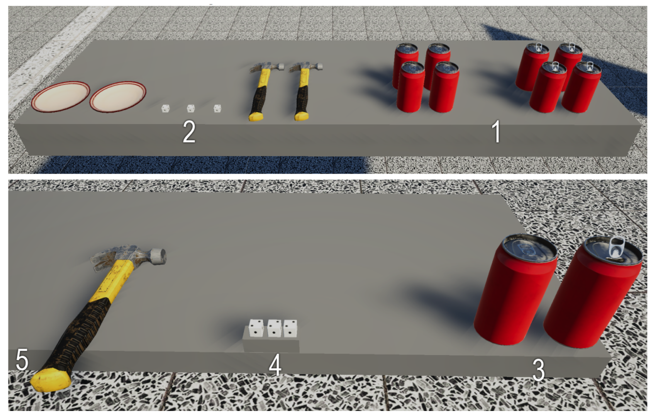

Figure 2: The upper figure displays the priming locations for normal-scale interaction and the lower one for reduced scale interaction (the perspectives are not in scale with the participants' viewpoint). Numbers 1-5 display different teleporting locations during the priming phase. Figure adapted from the MSc thesis of Sierilä [2023].

3.1 Participants

Participants were recruited using an online research participation system and consisted mostly of students and employees from the university community. A preregistered sample of 44 participants was used in order to compare the results to a similar earlier study, in which no priming took place [Pouke et al. 2021, 2020]. From these participants, 34 were male and 10 female. 26 and 18 participants had normal or corrected-to-normal vision, respectively. The participants' median videogame experience was reported as "Once or twice per week" whereas median experience in VR systems was reported as "Have used once or twice."

3.2 Experimental Apparatus

The application was developed using the Unity game engine (editor version 2020.3.26f1) for the Valve Index headset and motion controllers. The virtual environment where the experiment took place was modeled to resemble a familiar real-world location (i.e. the local university campus) to account for the distance compression effect in VR [Creem-Regehr et al. 2023]. The application utilized a priming phase with multiple locations and a test phase. The purpose of the priming phase was to demonstrate how gravity functions at normal human scale and in 1/10 scale. The purpose of the test phase was to test the participants' perception of physics coherence using the procedure used in earlier studies [Pouke et al. 2021, 2020]. Furthermore, the priming phase was divided into two parts. In the first part of the priming phase, the participants interacted with various physically simulated household objects at a normal scale using the motion controllers. More specifically, these objects included two sets of four soda cans, two hammers, three dice, and two plastic plates (Fig. 2, upper). The participants were instructed to knock down the soda cans, and try dropping and throwing the dice, hammers, and plates. In the second part of the priming phase, the participants were shrunk down to 1/10 scale, and continued to interact with objects. Similar to earlier studies [Pouke et al. 2021, 2020], the scaling took place by altering the participant's virtual viewpoint, IPD, tracking properties, and hand mesh size. At this stage, the participants could interact with two soda cans, a set of three dice, and a single hammer (see Fig 2, lower). Here they could, again, knock down the cans and throw the dice, but they could only lift and let fall the side of the hammer that was facing them (see Fig. 1, right). The participants were standing and were able to move short distances using natural walking. To cover longer distances, the researcher teleported the participant across predefined waypoints, moving from one waypoint to the next as soon as the participant had interacted with all objects (see Fig 2, areas numbered 1-5). After the participants had interacted with all objects at each location (taking approximately 1-3 minutes per participant), they entered a testing phase (similar to Pouke et al. [2020]) located in the same virtual environment, in which they were instructed to drop and throw five poptabs under two physics models (*Movie Physics* and *True Physics*) in a counterbalanced order and to evaluate their physics coherence (see Fig. 3 and questions FC1 and FC2 below). Examples of the priming phase depicted from the participants' perspective at both scales can be seen in Fig. 1.

3.3 Confirmatory metrics

Our hypotheses (H1-H4) were addressed by the following two forced-choice questions:

- FC1 Thinking back how the pull tabs were behaving in the experiment, which felt more realistic (like what would happen in the real world if you had been shrunk down), the first or the second time?
- FC2 Thinking back how the pull tabs were behaving in the experiment, which matched your expectations (similar to what would happen in the real world if you had been shrunk down), the first or the second time?

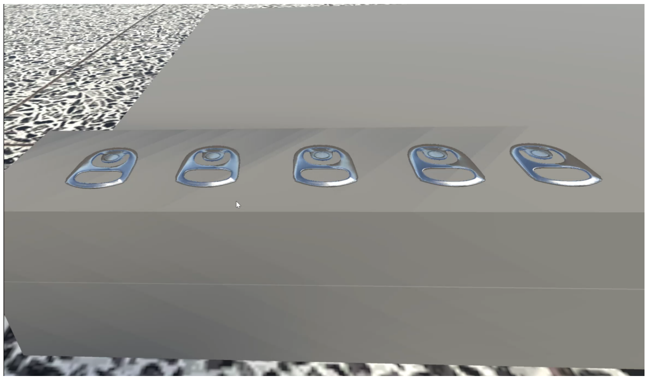

Figure 3: The participants manipulated physically simulated poptabs under two physics models and estimated the subjective realism of their behavior as well as whether it matched their expectations similar to [Pouke et al. 2020].

3.4 Exploratory metrics

We collected exploratory data in the form of qualitative open-ended questions and questionnaires concerning perceived object trajectories, perceived helpfulness of the priming phase, perceived relationship between one's own size and the environment's size, and presence. In addition, we collected basic demographic information (as reported earlier).

3.4.1 Reasoning behind FC1 and FC2. The open-ended responses O1 and O2 qualitatively addressed the reasoning behind participants' responses concerning physics realism and expectations (questions FC1 and FC2). This data was collected by coupling both FC1 and FC2 with an open-ended questions labeled *"Why?"* and provided additional validation that the participants' responses were caused by physics-perception related aspects of the experience, as intended.

3.4.2 Object trajectories. Questions L1-L3 were 7-point Likert scale items addressing the participants' perception of object trajectories. The questions were asked for both conditions.

- L1 How did you perceive the speed at which the pull tabs fell? *Too fast - Too slow*
- L2 How did you perceive the distance at which the pull tabs flew when thrown? *Too far - Too near*
- L3 How did you perceive gravity when interacting with the tabs? *Too weak - Too strong*

3.4.3 Perceived helpfulness of the priming phase. The forced-choice question FC3 addressed the perceived helpfulness of the priming phase.

- FC3 Did you feel that being able to interact with objects at normal size (before being shrunk down), was helpful in choosing which time felt more real? *Yes / No*

Furthermore, the reasoning behind this choice was addressed with an additional open-ended question O3 labeled *"Why?"*

3.4.4 The relationship between one's own size and the environment's size. Many of the earlier findings concerning self-scaling indirectly indicate that VR users tend to perceive distances and rigid body dynamics as if the environment was changing in size instead of themselves. Therefore, we addressed the phenomenological sensation concerning the relationship between one's one size and the environment's size with the forced-choice question FC4.

- FC4 After being shrunk, which of the following sensations better matched your experience?" *(I felt normal-sized and the environment looked enlarged - I felt scaled down and the environment looked normal-sized.)*

3.4.5 Presence. Finally, the extended Slater-Usoh-Steed (SUS) questionnaire [Slater et al. 1994; Usoh et al. 2000] was utilized to evaluate presence (specifically Place Illusion [Slater 2009]).

4 Results

The responses to questions FC1 and FC2 were analyzed to assess hypotheses H1-H4.

Contrary to our predictions, more participants considered *Movie Physics* as the realistic physics model instead of *True Physics* (31 vs 13 participants, respectively). Furthermore, almost all participants considered Movie Physics to match their expectations better than *True Physics* (37 vs 7 participants, respectively). As per our preregistration, we conducted one-tailed binomial tests to investigate whether *True Physics* is more likely to feel realistic compared to *Movie Physics* (H1) or whether *True Physics* matches the participants expectations better (H2). The results of the binomial tests did not support either hypothesis ($ps > .99$). Bayes factors were computed using the 'proportionBF' function from the BayesFactor package in R [Morey and Rouder 2026], which indicated strong support for the null hypothesis with respect to both H1 ($BF_{10} = 0.11$) and H2 ($BF_{10} = 1.67 \times 10^4$).

Hypotheses H3 and H4 concerned the comparison of the physics model preferences of primed vs unprimed participants by comparing the results of this study to the results reported in [Pouke et al. 2021, 2020]. As per our preregistration, we performed a two-proportions Z-test to investigate whether *True Physics* was considered as more realistic more often by the primed participants of this study (13 of 44) than the unprimed participants of the previous study (12 of 44). A similar test was carried out for expectations, (7 of 44 and 4 of 44, respectively). Additionally, Bayes factors were computed using the 'contingencytableBF' function from the BayesFactor package [Morey and Rouder 2026]. According to the results of the Z tests, there was no evidence of primed participants considering *True Physics* either being more realistic ($\chi^2(1) < 0.01$, $p > .99$, $BF_{10} = 0.24$) or matching their expectations better ($\chi^2(1) = .42$, $p = .52$, $BF_{10} = 0.27$) than unprimed participants. Based on these results, we fail to support all hypotheses H1-H4.

4.1 Exploratory results

As an exploratory analysis, we performed additional two-tailed binomial tests to investigate whether the participants in this study considered *Movie Physics* as the more realistic model or matching their expectations better. According to these tests, *Movie Physics* was indeed considered the more likely choice in both cases (two-tailed; $p = .004$ and $p < .001$, respectively)

4.1.1 Object trajectories. Investigating the perception of expected object trajectories using Likert-7 questions L1-L3, we also found

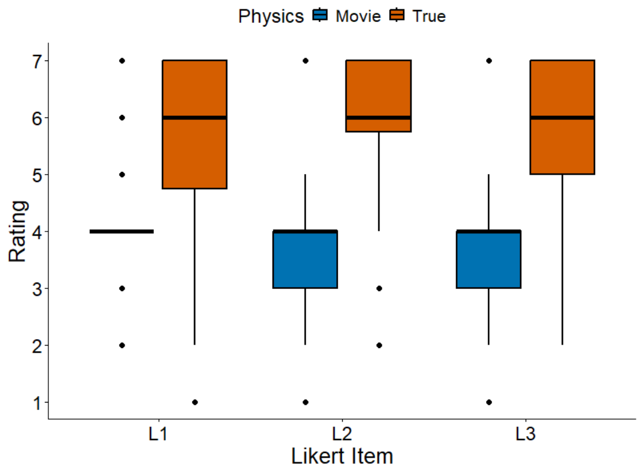

Figure 4: Boxplots for Likert questions 1-3, where thick lines are medians and boxes are interquartile ranges. Note that responses to L1 have been reflected to so as to be consistent with the direction of responses to L2 and L3, i.e., the descriptors at the scale extremes were reversed such that the feature at the higher end of the scale now matches the phenomenology typically associated with the *True Physics* condition (too fast), as is the case in L2 (too near) and L3 (too strong).

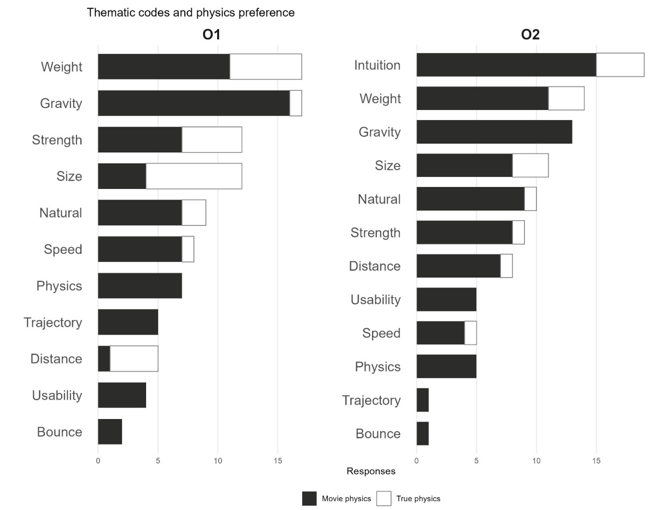

Figure 5: Thematic codes for questions O1 and O2.

that *Movie Physics* was considered more realistic across all questions (see Fig 4). We carried out Wilcoxon signed-rank tests with continuity correction and found that the differences were statistically significant (L1: $W = 730$, $p < .001$, $r = .53$; L2: $W = 13$, $p < .001$, $r = .83$; L3: $W = 35.5$, $p < .001$, $r = .80$).

4.2 Open-ended responses O1 and O2

Two researchers coded the qualitative data independently using thematic analysis and inductive approach [Patton 2005]. The analysis revealed that the almost all responses addressed physics-related aspects of poptab behavior, e.g. *"The first ones fell slower and rotated while falling down which is in my eyes a more realistic behavior. The second ones seem to hit the ground immediately which I think is not that realistic,"* and *"The first ones fell slower and rotated while falling down which is in my eyes a more realistic behavior. The second ones seem to hit the ground immediately which I think is not that realistic."* The participants who considered *True Physics* more realistic in O1 often considered relative strength, e.g. *"I assume that my strength would be shrunken with my size so I would not be able to throw them as far,"* or poptab behavior in general, e.g. *"when i throw those in the first time, it did not went that far. since i am shrunk down, it felt more realistic for me"*. The participants who chose *True Physics* for O1 and *Movie Physics* for O2 often described that *Movie Physics* felt intuitively more real but through reasoning they considered *True Physics* to be the correct model, e.g. *"Before thinking about what is more realistic I didn't expect them to behave differently, so the first time felt more like I was expecting it to be."* There were also five participants who described aspects that could be considered usability-related, e.g. *"I had better feel of the system"* and *"The response of the first experiment was more accurate and faster than the second. It felt like I was really throwing or dropping the objects with my hands."* However, these descriptions could also refer to poptab behavior indirectly. Summaries for the the qualitative coding for O1 and O2 can be seen in Fig. 5.

4.2.1 Perceived helpfulness of the priming phase. According to the results of FC3, 29 participants considered the priming phase helpful, whereas 15 participants considered it unhelpful. We used Fisher's exact test to measure whether there was any association between perceived helpfulness of the priming phase and the physics experience chosen as more realistic or expected. We were neither able to detect a statistically significant association between priming and realism ($p = .16$) nor expectations ($p = .077$) outcomes.

O3 addressed the reasoning behind whether or not the priming phase was considered helpful. Similar to O1 and O2, these responses were coded by two researchers independently utilizing thematic analysis and the inductive approach [Patton 2005]. The most common response was that the priming phase gave a useful point of comparison, e.g. *"It gave a better comparison how the gravity, distance and speed would feel at normal size and made it easier to see what was changed when shrunken down,"* and *"because as you start the experiment, you don't have much expectations for how things feel and how close is the experiment to real life. When you interact with them at normal size, it assures you that it is a real life simulation not just some virtual experiment and this sets the tone of your expectations well."* The participants who did not consider the priming phase helpful sometimes reported that the experience of being scale-down was too overwhelming, e.g. *"as the 'shrunk state' was surreal in itself, it did not matter when thinking in gravities and falling objects"* and *"I did not consider it in that way during the test. I was just thinking it's interesting and funny to be that size and try it out."* There was also one participant who reported that the behavior of the hammer during the scaled-down priming phase was unrealistic: *"hammer was unrealistic. dices were fine with both sizes. smaller ones were also*

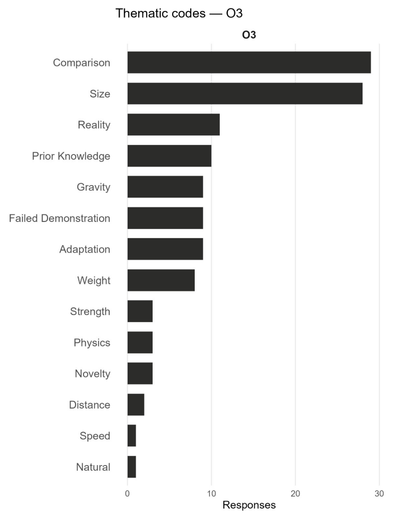

Figure 6: Thematic codes for question O3

easy to grab and so were the big ones. generally speaking, small items seemed more natural and realistic as they more relate to real world objects."

4.2.2 The relationship between one's own size and the environment's size. Question FC4 addressed the question whether participants experience self-scaling as changing one's own size relative to the environment, or vice versa. In the *True Physics* condition, the participants were split even, 22 choosing *"I felt normal-sized and the environment looked enlarged"* and the other 22 *"I felt scaled down and the environment looked normal-sized"*. As for the *Movie Physics* condition, the split was 32 to 12. Fisher's exact tests showed no association between which element participants perceived as scaling in either condition, and their choices regarding which physics model felt more realistic or better matched their expectations (all $ps > .41$).

4.2.3 Modeling Multiple Factors. We used logistic models to explore whether any of the previously mentioned single-measurement variables or demographic information could predict choices regarding physics realism and expectations. Models were fit to predict realism and expectations responses separately. The maximal two-way interaction model did not converge in either case, so the maximal additive model using age, gender, VR experience, video game experience, their response of whether they thought priming helped, and SUS mean was used. VR experience and video game experience are probably best thought of as ordinal variables, but because ordinal variables are fit as one through n-levels minus one polynomials under R's glm function, and we do not have enough data to meaningfully interpret higher order relationships, these variables were instead transformed to integers from 0 to 6, which must be taken into account in the model interpretation. Significant predictors are reported as odds ratios with profile likelihood 95% CIs, and nested models were compared using likelihood ratio tests.

For predicting responses related to realism, the maximal additive model indicated statistically significant effects for subjective priming assessment (those who indicated priming was helpful were more likely to indicate *True Physics* as more realistic; $OR = 11.17$, $CI = [1.52, 179.90]$) and VR experience (more experienced VR users were more likely to indicate *True Physics* as more realistic; $OR = 2.26$, $CI = [1.20, 5.15]$). Other factors in the model did not reach statistical significance ($ps > .13$). However, the model fell short of statistical significance in terms of improvement over the null (intercept-only) model, $\chi^2(6) = 12.34$, $p = .054$. Meanwhile, no variables significantly predicted the choice of which physics model was chosen as better matching expectations in its full additive model ($ps > .15$), and this model did not outperform its null counterpart, $\chi^2(6) = 9.02$, $p = .17$.

5 Discussion

The present findings reinforce a well-established view that humans rely strongly on an internalized model of Earth gravity and human-scale interactions, which is difficult to override even under altered perceptual conditions. Prior work has shown that while limited adaptation may occur in microgravity or in tasks with a strong motor component, such adaptation is typically slow, partial, and context-dependent (e.g. [Jörges and López-Moliner 2017; McIntyre et al. 2001; Pouke et al. 2024b]). In addition, previous research suggests that physics coherence in virtual environments tends to be anchored to the participant's own perceived body scale: motion that is consistent with one's embodied size is more likely to be judged as plausible. However, there are notable exceptions where external visual cues can dominate this interpretation; for example, the presence of virtual characters whose scale is inconsistent with the surrounding environment has been shown to bias gravity and scale judgments, effectively overriding the participant's own scale as the reference frame [Langbehn et al. 2016; Pouke et al. 2022, 2024a]. Our results extend this line of work by examining how these constraints manifest when both gravity and participant scale are manipulated in immersive VR together with interactive priming.

In this study, participants interacted with physically simulated objects both at normal human scale and at a reduced scale (1/10), with the goal of conveying the phenomenology of being physically shrunk. The introductory (priming) phase was designed to familiarize participants with the expected behavior of objects under correct physical scaling. However, the main task—where participants performed throwing and gravity judgment tasks while virtually shrunk—revealed a persistent bias toward *Movie Physics* in which gravity is implicitly rescaled to preserve familiar motion patterns.

Contrary to our preregistered hypotheses, the priming phase did not produce a significant shift toward selecting physically accurate *True Physics* behavior as more realistic. Instead, participants overwhelmingly favored the perceptually familiar model, even after direct interaction with correctly simulated, explicitly labeled, physics. Notably, these results closely replicate those reported by Pouke et al. [2021], despite the absence of a comparable priming phase in their study. This suggests that brief experiential exposure—even when interactive and motor-based—may be insufficient to override entrenched expectations about gravity and scale.

The exploratory analysis provides some nuance to this interpretation. In the logistic multiple regression model, participants who reported the priming phase as helpful were more likely to select true physics compared to those who did not, with an odds ratio estimate of about eleven to one once other factors taken into consideration. The apparent contradiction between the Fisher's exact test result and the logistic model could be explained by the power of multiple regression; in the former case, the effect of priming is tasked with accounting for all of the variance in the outcome variable, whereas latter case, priming must only account for the variance left over after other factors (critically, VR experience) have been accounted for. The result could indicate that there were individual differences regarding which participants were able to internalize the information from the priming phase, and that there is some level of meta-awareness among participants regarding priming efficacy. More experienced VR users were also found to have increased odds of correctly identifying *True Physics* as the proper model. It is possible that those who have spent more time in virtual environments have had more experiences that challenge the perceptual priors they have built in the real-world, and these experiences gave them greater flexibility to adapt to physics at the smaller scale. However, these results should be treated with a healthy dose of skepticism given that these analyses are exploratory, and the model including these variables ultimately fell short of outperforming the null model statistically.

Taken together, these findings highlight a fundamental challenge for VR and telepresence applications that aim to depict physically accurate phenomena at altered scales. Even when users are provided with interactive experience and motor engagement, and even when the phenomenology of scale is partially conveyed, their judgments remain anchored to Earth-scale intuitions. This has implications for the design of educational simulations, training systems, entertainment applications, and robotic telepresence: designers may need to carefully balance physical accuracy with perceptual plausibility, or provide more prolonged and multimodal training to facilitate deeper adaptation.

Future work should investigate whether longer exposure, better priming strategies, richer multisensory feedback, or alternative task designs could more effectively shift users' internal models. Combining motor interaction with consistent vestibular or proprioceptive cues may be necessary to achieve more robust adaptation to non-Earth gravity and scale, however, this is very difficult, if not impossible, to achieve using contemporary systems.

5.1 Limitations

This study has several limitations that should be considered when interpreting the results. First, the experimental design was intentionally aligned with prior work to enable direct comparison, with the primary addition being the priming phase. As a result, the study focused exclusively on physics coherence—i.e., subjective judgments of plausibility—and did not examine task performance under altered gravity. Consequently, the findings do not address whether priming might influence action-based adaptation even if perceptual judgments remain unchanged. Also, the statistical comparison with the prior study concerning hypotheses H3 and H4 is limited in the sense that the the current and prior studies were not conducted using the same experimental apparatus and we did not control confounding factors within the participant pool, such as experience with VR or videogames. This experiment focused only on a single scale (1/10), however, it appears that as scales become less extreme perceptual biases decrease [Garcia et al. 2026], potentially making adaptation easier.

The priming phase itself was designed heuristically and may not have been sufficient to effectively convey physically accurate object behavior. It is possible that in order to overcome lifelong habituation, and even evolutionary disposition, to perceive objects at human scale [Gibson 2014], simple interactive priming is simply not enough. Although many participants reported the priming phase as helpful, some still chose *Movie Physics* as the correct model even after reportedly considering the demonstrations given in the priming phase. In addition, occasional technical artifacts may have affected the experience; for example, at least one participant reported that an object (a hammer) appeared unrealistic in the small-scale condition, possibly due to visible instability during interaction. Such factors may have reduced the clarity or credibility of the intended demonstration. In the future, it could be beneficial to investigate more ecologically valid interaction tasks, such as actual multi-user collaboration in MSCVEs, or tasks simulating real-world robotics or teleoperation at abnormal scales. Furthermore, either more extensive priming strategies (such as repetitive motor exposure utilized in Pouke et al. [2024b]), or ones involving more cognitive strategies (i.e. trying to get more participants to reason themselves into favoring the correct gravity model) could be more effective in overriding the strong prior of earth gravity at human scale [Gibson 2014; Jörges and López-Moliner 2017].

Finally, the exploratory analyses—suggesting that perceived helpfulness of the priming phase and prior VR experience may relate to the selection of true physics—should be interpreted with caution. These analyses were not preregistered and were not powered for confirmatory inference, and therefore require validation in future studies.

5.2 Conclusion

This study investigated whether a brief priming phase could help participants adapt to physically accurate gravity when interacting at a diminished (1/10) scale in VR. Despite providing both perceptual and motor experience with correctly simulated physics, participants consistently favored a perceptually familiar *Movie Physics* model over physically accurate behavior. These findings suggest that internalized expectations of Earth gravity and human-scale interactions are highly resistant to change, even in immersive and interactive settings. While subjective reports indicate that priming may have some limited influence, its overall effect appears insufficient to produce a measurable shift in gravity perception. Together, the results highlight the difficulty of conveying physically accurate altered-scale phenomena in VR and underscore the need for more effective methods—such as extended exposure or richer multisensory feedback—to support adaptation to non-Earth physics.

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