Users rely on a body-centric model to assess gravity in virtual reality

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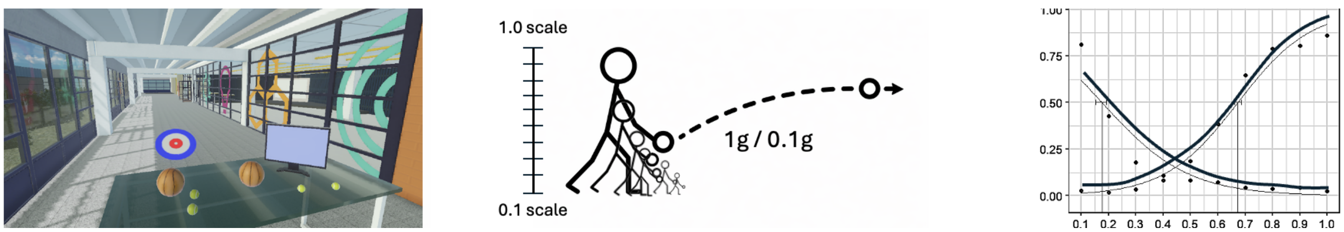

Figure 1: Left: Practice phase - 50 seconds of throwing under normal gravity and scale. Center: Trial phase - 200 throws in randomly permuted, exhaustive combinations of gravity and scale (10 scales, 2 gravity conditions, 10 trials per gravity). Participants assess gravity coherence in each trial. Right: Psychometric modeling - Two logistic curves were fitted to predict responses at each combination of scale and gravity. A point of subjective equality (PSE) estimated for each gravity condition.

Abstract

In virtual reality, altering the size of a user can lead to a mismatch between subjectively realistic and physically accurate simulations. This study investigates whether humans judge gravity based solely on its physical value, or whether it is also biased by their perceived body size. Participants were presented with a virtual environment of constant size and asked to throw a ball towards a target. On each trial they were subjected to one of ten scales and two gravity conditions. In the *normal physics* condition, objects behaved using Earth gravity. In the *movie physics* condition, gravity was set to one tenth of the Earth's gravity. Participants were asked to report after each throw whether they experienced *normal physics.* We fit two Bayesian logistic mixed-effects models to predict participants' responses. The first one used gravity as its sole predictor, consistent with the idea that humans judge gravity based only on its physical value. The second one used the interaction of gravity and size as predictors, consistent with the idea that humans use a combination of both variables when judging gravity. We used Bayes factors to quantify the likelihood of our observed data under each model. The latter model was overwhelmingly preferred by the data, supporting our prediction that participants use both gravity and perceived body size as guides when judging gravity. Participants considered the *normal physics* condition as realistic when their bodies were close to normal size and the *movie physics* condition to be more realistic when scaled down, consistent with a body-centric model of gravity perception.

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CCS Concepts

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

Keywords

Gravity perception, Virtual Reality, Psychophysics, Graviception

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1 Introduction

Virtual reality (VR) technology is often used to simulate environments with varying scales and kinematics, i.e. where spatial perception and kinematics might differ from the average human experience. One remarkable development in this area are the Multi-scale Collaborative Virtual Environments (mCVEs), where users can resize their virtual bodies to collaborate on complex structures, enabling forms of interaction that are otherwise restricted in real life [Kopper et al. 2006; Zhang 2002; Zhang and Furnas 2005]. Other use cases include architecture, where manipulating spatial scale perception can help identify risks from multiple viewpoints, such as those of children or people in wheelchairs [Zhang et al. 2020]. In education, VR has been used as a user interface device, allowing users without specialized training to directly manipulate microscopic structures, and interact with nanoscale phenomena [Millet et al. 2008; Stefani et al. 2018]. Overall, when dealing with environments with altered scales and kinematics, VR offers perspectives that would otherwise be physically impossible in the real world.

Research has shown that humans possess a strong internal expectation of gravity, created through years of experience in Earth's gravitational conditions [Jorges and Lopez-Moliner 2017]. Humans use this internal model of gravity as a reference when judging interactions with the physical world [Jorges and Lopez-Moliner 2017; La Scaleia et al. 2020]. It has also been shown that a user's perception of their virtual body acts as a reference when judging distances in virtual environments [Ogawa et al. 2019; van der Hoort et al. 2011]. A refined understanding of how changes in perceived body size affect gravity perception is, therefore, necessary to maintain physics plausibility and to guide design choices for VR experiences with altered gravity and/or scale. Adapting to altered gravity is challenging, especially when visual and other sensory cues are conflicting [Pouke et al. 2024b]. Humans tend to judge physical simulations subjectively, relying on their perspective and internal expectations. This phenomenon might lead to physically accurate simulations being labeled as unrealistic [Pouke et al. 2022, 2021].

In previous research, gravity perception in virtual environments has been investigated using two main methods: by manipulating the virtual scale of the user by changing his/her virtual interpupillary distance and viewpoint height, [Pouke et al. 2022, 2021, 2024a,b], and by manipulating body ownership illusion towards a virtual body of non-human size [Ogawa et al. 2019; Pouke et al. 2022; van der Hoort and Ehrsson 2014]. In this study, we revisit the former approach. We aimed to distinguish whether humans judge gravity based solely on its physical value, or whether gravity perception is also influenced by visual cues such as perceived body size. Similar to multiple studies described above, we used two gravity conditions. The *normal physics* condition uses a gravitational acceleration of 1 *g*, consistent with normal Earth gravity, whereas the *movie physics* condition uses an acceleration of 0.1 *g*. At a normal scale, objects will be perceived as behaving normally under the *normal physics* condition, and objects will behave as if they were on the moon under the *movie physics* condition. We also modified the virtual scale of the VR user using ten different scales, ranging from 0.1x to 1x, in increments of 0.1x. Participants experienced all combinations of ten scales and two gravity conditions ten times each for a total of 200 trials. Trials were presented in a randomly permuted order. During each trial, participants were asked to throw a ball and judge whether it behaved according to normal gravity (see Figure 1).

The study thus investigates how virtual scaling influences perceived physics plausibility (defined as perceived realism of an event; not to be confused with Plausibility Illusion in presence research). We predict that participants, when subjected to smaller-than-human scales, will rely on a body-centric internal model, perceiving the environment as changing scale rather than their body. Consequently, they are expected to more likely identify the *normal* gravity as correct when virtually larger, and *movie* gravity as correct when virtually smaller, contrasting with a body-independent model where judgments would remain consistent across scales.

2 Related Work

Gravity perception in virtual reality is driven by factors such as body ownership, presence and spatial perception. This section reviews previous relevant research. We will examine how altered virtual body sizes and scaled environments affect gravity perception, and we will discuss how humans judge gravity based on internalized models, which are robust yet still subject to various illusions.

2.1 Spatial Perception

Visual and other sensory cues inconsistent with reality can significantly alter the perception of our own body and the environment. Inducing the illusion of body ownership towards a scaled virtual body can lead to the user perceiving the whole environment as resized [van der Hoort and Ehrsson 2014], with a smaller virtual body making objects feel bigger and more distant, and vice versa [van der Hoort et al. 2011]. Similar studies also suggest that virtual hands serve as a reference when interacting with scaled objects [Linkenauger et al. 2013], with this effect being more evident when the hand is highly realistic [Ogawa et al. 2019].

The perception of a virtual environment is susceptible to altered visual cues, either deliberately, or as a result of the inherent spatial distortions associated with a VR system. Due to display limitations or rendering techniques, distances in virtual environments are often perceived as shorter than intended [Creem-Regehr et al. 2023; Renner et al. 2013]. This misrepresentation of distances can lead to poor depth perception [Creem-Regehr et al. 2023; Renner et al. 2013]. Similarly, deliberate alteration of spatial cues, such as virtual interpupillary distance, familiar size cues, or body cues, can alter perceived distances and perceived size of objects [Banakou et al. 2013; Kim and Interrante 2017; Linkenauger et al. 2013; Ogawa et al. 2019; van der Hoort and Ehrsson 2014; van der Hoort et al. 2011].

2.2 Gravity Perception in VR

Humans judge gravity using a combination of internalized expectations and multisensory stimuli [Jorges and Lopez-Moliner 2017; Lacquaniti et al. 2015; Merfeld et al. 1999]. Jorges and Lopez-Moliner [2017] found that humans tend to use their own expectation of gravity as a "strong prior," using it to resolve ambiguities in kinematics, and prioritizing it over other visual cues. This internal model is the result of years of experience in Earth's gravitational environment, serving as a reference, which can also guide motor control. This phenomenon is reflected in cases where mere visual cues can trigger changes in posture consistent with the expected inertial forces associated with such cues, even when other sensory input might be conflicting [Cano Porras et al. 2020].

Although internal models are typically tuned to Earth's gravity, adaptation has been shown to be possible in Earth-discrepant gravitational conditions. McIntyre et al. [2001] studied adaptation to 0g conditions during a 17-day space shuttle mission, with astronauts being asked to catch balls thrown in their direction. Participants' movements to intercept the ball consistently began too early to catch the object correctly. The final velocity of hand movements decreased, which allowed for a smoother catch. However, even after 15 days, the movements were not comparable to those performed under Earth's gravitational conditions. Jorges and Lopez-Moliner [2017] have argued that adaptation to altered gravity cannot happen unless visual and bodily sensory input indicate the same earth-discrepant gravity value. However, recent studies have found that adaptation is possible in VR when utilizing repetitive motor tasks, despite only visual cues being provided by the head mounted display (HMD) [Pouke et al. 2024b]. Overall, humans use gravity as a persistent, reliable anchor when interacting with the environment.

The perception of gravity in VR is therefore also driven by the user's internal models and contextual cues provided in the virtual environment. As Cano Porras et al. [2020] showed, visual cues can override other sensory input, which can lead to a mismatch between a physically accurate simulation and a subjectively realistic one, at least from the user's perspective. Pouke et al. [2022, 2021, 2024a] explored gravity plausibility with self-scaling in normal-sized virtual environments. They found users to prefer gravity that matches their scaled dimensions, where the perceived physics coincide with their normal behavior under a normal scale, even if the simulation is therefore not physically accurate. This phenomenon is evident across different interaction methods, from simple observation to active tasks. This pattern suggests that internal gravity models are resistant to recalibration, up to a certain extent. For example, temporary recalibration was achieved in the study of Pouke et al. [2024b] in which participants performed repeated motor tasks in visually simulated hypergravity. Furthermore, familiar size cues, especially when related to other virtual characters in the scene, appear to make it possible to perceive correct gravity even when the user is at abnormal scale [Pouke et al. 2024a].

Three previous studies investigating gravity perception in VR stand out as relevant to this study due to the experimental manipulation they utilized. The first study [Pouke et al. 2021] comprised two experiments, with the first experiment scaling down participants' perceived body sizes by a factor of ten, and the second experiment scaling them up by a similar factor. In both experiments, participants were subjected to two gravitational conditions in which one was physically accurate (i.e. *True Physics*), simulating earth gravity, whereas the other altered kinematics to behave in what would be the approximation of the environment being scaled instead of the VR user (i.e. *Movie Physics* [Pouke et al. 2021]. In both experiments, participants grabbed and dropped objects and were later asked which gravity condition appeared more realistic. It was found that participants considered the physically accurate gravity to be less realistic in both experiments, with only 27% and 30% of the participants favoring the physically accurate gravity, respectively. The second study [Pouke et al. 2022] shifted the methodology to passive observation. This study investigated whether the Body Ownership Illusion utilized in a manner similar to previous research by van der Hoort et al. [2011] and van der Hoort and Ehrsson [2014] can alter participants' judgments of physics plausibility while virtual IPD and viewpoint height remained unaltered [Pouke et al. 2022]. The participants' task was to observe a humanoid robot grabbing and dropping objects under two gravity conditions, similar to the previous study. It was found that the body ownership illusion did not have an effect on participants' judgments of gravity. Surprisingly, however, most of the participants (70% during the embodied condition and 75% in the control condition) again considered *Movie Physics* more plausible, even though their IPD was unaltered. In a third study [Pouke et al. 2024a], participants passively observed a 0.2x scale humanoid robot and a realistic, average-sized housecat to perform a similar interaction task using two gravity conditions while the participants were either standing at normal scale, or scaled down (with IPD and viewpoint height manipulation) to 0.2x scale. Again, participants generally considered *Movie Physics* as the plausible model when the scaled-down humanoid robot was performing the interactions (regardless of their own scale). However, the judgments were split more evenly when the virtual cat was performing the interaction task [Pouke et al. 2024a].

This study uses a procedure similar to that of the previously mentioned experiments. We used two different gravity conditions, 1 g and 0.1 g, or "*normal*" and "*movie*" gravity, respectively. However, to investigate gravity perception in a more granular manner using, we used 10 different scale conditions, ranging from 0.1x to 1x, in increments of 0.1. Moreover, we specifically weighed evidence against two competing explanations of human perception using Bayes factors (for a primer, see [Wagenmakers et al. 2018]). This study employs a within-subjects design to examine how participants perceive gravity under varying scale conditions. Each participant experienced all combinations of gravity and scale conditions, allowing for a direct comparison of responses within individuals.

3 Methodology

Anonymized experimental data, including experimental conditions and presence questionnaires (with demographic information removed for privacy), the Unity project source code, and the analysis scripts are available on GitHub.

3.1 Conditions

During the experiment, participants' virtual bodies were scaled (by manipulating IPD and viewpoint height), while the virtual environment around them remained of constant size. The participants threw a virtual ball under each scale (0.1x-1.0x) under both *normal gravity* (1 g) and *movie gravity* (0.1 g) conditions. Our manipulation of gravity changes the actual rigid body dynamics of objects in relation to scene coordinates, whereas the manipulation of scale changes the participant's visual field in terms of viewpoint height and IPD, which in turn affect the *perceived* sizes and distances of objects as well as object free fall time independently of the simulated gravity. Each combination of gravity and scale was repeated 10 times, resulting in 200 throwing tasks in a randomly permuted order. After each throw, participants judged whether gravity felt natural. Responses and experimental conditions were recorded. Additionally, we computed points of subjective equality (PSE) for each gravity condition to understand at which scales 1 g and 0.1 g are equally likely to be selected as the correct gravity model.

3.2 Hypothesis

Our hypothesis, sample size, methods, and confirmatory analyses were preregistered at osf.io (see preregistration at: OSF). We hypothesized that participants perceive scale and gravity changes in VR through a body-centric instead of a body-independent model, defined as the following:

- Body-independent model: Individuals maintain a stable external reference, correctly identifying the physically accurate gravity, regardless of their size.
- Body-centric model: Participants judge physics using their virtual bodies as reference. They will perceive the gravity as realistic only when it is scaled proportionally to their size.

Participants were explicitly told that their body is being scaled, and the room dimensions stay the same throughout the experiment. We expected however, that participants would behave in a way consistent with the room changing scale, and their bodies staying the same size, i.e., more likely to identify the *real physics* (1 g) as realistic when the scale is closer to 1x, and the *movie physics* (0.1 g) when the scale is closer to 0.1x, supporting a body-centric model. This opposes the body-independent model, where participants would correctly identify the realistic gravity (1 g) regardless of the scale.

3.3 VR Experience

The VR experience was developed using Unity 2022.3.9f1 and Open XR for compatibility with Quest 2 headsets. The Virtual Environment (VE) where all interaction tasks take place is a wide and modern hallway with large windows to the sides (see Figure 2), providing a wide area for participants to complete the tasks. The VE itself is a virtual model of the local university campus, which maintains realistic dimensions and materials, allows users to be in a familiar environment, provides accurate size cues, and mitigates the distance compression effect [Creem-Regehr et al. 2023].

The experiment begins with a short 50s practice session, which introduces participants to the grabbing and throwing mechanics needed in the main part of the experiment. During the practice session, the VE contained a desk with four small and two large balls, each weighing 70 grams, and 1.1 kilograms, respectively (See Figure 1). The main experiment phase took place in the same virtual location, but the previously mentioned desk and balls were removed. During each trial, balls weighing 70 grams where spawned directly in front of participants' heads in their gaze direction.

The experiment lacked any tactile feedback, but participants were able to discriminate different objects based on their perceived accelerations by observing their trajectories, providing participants with visual information about the gravitational conditions of the scene [Lacquaniti et al. 2015]. We did not aim to achieve a high level of body ownership [Slater et al. 2022], therefore we used the virtual hands provided by Unity's XR Hands 1.1.0 package (see Figure 2).

3.4 Participants

Participants were recruited from the local university community through a university-managed research participation platform. We aimed for a total of 40 participants, based on sample sizes from other similar scale-changing experiments that investigated gravity perception [Pouke et al. 2022].

Participants were then screened for any pre-existing conditions such as headaches or nausea, and recommended to reschedule or cancel their participation if necessary. Ten participants were excluded based on predefined criteria as noted in the preregistration, namely: participants who had previously completed any previous scale-changing experiments or failed to complete the entire study protocol (due to e.g. early withdrawal or technological malfunction) were excluded, and, participants who failed to select the correct gravity model for at least 16 out of 20 trials at 1x scale (when the correct selection should have been extremely obvious, as in the 1 g condition the ball flies normally and in the 0.1 g condition it floats away as if the participant is on the moon) were excluded on the grounds that they were either responding indiscriminately or did not exhibit a typical internal model of Earth gravity. Excluded participants were replaced prior to all analyses.

Our final sample consisted of 40 participants (70% male and 30% female), with an average age of 27.2 years (range: 18-40). All participants reported having corrected-to-normal vision and depth perception. The median educational level was a bachelor's or polytechnic degree. Median VR experience was reported as "once or just a couple of times ever", and median video game experience as "once or twice a month".

3.5 Experimental Protocol

All protocols used were consistent with the Declaration of Helsinki and approved by the local ethical review board. All participants gave written informed consent to participate. They were informed of the possibility of VR sickness and their right to withdraw at any time. Participants completed a background questionnaire (see Supplementary Files). Once complete, the participant's interpupillary distance was measured to ensure the correct settings were used in the Meta Quest 2 headset [Meta Quest Help Centre 2024].

Participants were introduced to the task using verbal and written instructions (see Supplementary Files). During the practice session, several balls of different appearances and sizes were provided to participants in the VE, they were instructed to grab and throw the balls towards the target using an underhand throwing motion. The target was located four meters away from the participants' location. The target's diameter was a 1m circle, and resembled a brightly colored curling target with a clearly defined center.

Once the practice session ended, the main section of the experiment followed. During this section, the size of participant's virtual bodies changed multiple times, and the size of the curling target, balls and distances were adjusted accordingly, so that they always appeared to be the same from the participant's perspective. This section consisted of 200 trials in total, with each scale level (ranging from 0.1 to 1 in intervals of 0.1) being tested ten times under each gravity condition, totaling 200 trials in a random order. Participants were again instructed to grab and throw balls towards the target using an underhand throwing motion (see Figure 2). After each throw, participants were asked: "Did the ball use normal gravity?" They responded by selecting "Yes" or "No", using the left and right trigger buttons in their controllers, respectively.

Figure 2: First person perspective of the throwing task.

After the completion of the main task, participants were instructed to complete a 5-item version of the Slater-Usoh-Steed presence questionnaire as implemented by Pan et al. [2016] (see Supplementary Files) on a traditional computer display. Participants received either a €10 gift card or similarly valued university-branded merchandise as compensation. Finally, the VR equipment was sanitized using a Cleanbox CX1 UVC LED disinfection system [Cleanbox Technology 2023].

3.6 Analyses

3.6.1 Points of Subjective Equality. We estimated the PSE by fitting a logistic function for both gravity conditions using the `logistic_fun` function from the `quickpsy` package in R [Linares and López-Moliner 2019]. The PSE represents the point at which participants are most uncertain about whether they are experiencing *movie physics* or *normal physics*.

3.6.2 Bayesian Model Comparison. We employed Bayesian logistic mixed-effects models implemented using the *brms* package in R [Bürkner 2017]. Since our output variable is a simple binary response, we chose the *bernoulli* family combined with a *logit link*. Brms starts with a neutral assumption for all other variables, using a flat prior. To account for individual differences and tendencies within participants, we used the participant number as a random effect. Brms models this effect as coming from a normal distribution centered around zero. We compared the three following models:

- The **null model** (intercepts only) serves as a baseline and as a way of determining whether the addition of other predictors in subsequent models increases explanatory power.

$$Y_{ij} \sim \text{Bernoulli}(p_{ij}),$$
$$\text{logit}(p_{ij}) = \beta_0 + u_j, \quad (1)$$
$$u_j \sim \mathcal{N}(0, \sigma^2)$$

- The **gravity-only model** uses `gravity` as predictor variable. It supports the idea of a body-independent model, where physics plausibility is solely determined by external cues and not on internal expectations.

$$Y_{ij} \sim \text{Bernoulli}(p_{ij}),$$
$$\text{logit}(p_{ij}) = \beta_0 + \beta_1\ \text{G}_{ij} + u_j, \quad (2)$$
$$u_j \sim \mathcal{N}(0, \sigma^2)$$

- The **full model**, using the interaction between `gravity` and `size` as predictor variables. This supports a *body-centric* perspective, aligning with prior work suggesting that humans possess internal models of gravity [Jorges and Lopez-Moliner 2017; Lacquaniti et al. 2015; Merfeld et al. 1999; Pouke et al. 2022, 2021] and that these internal models act as strong priors developed through lifelong experience in Earth's gravity relative to our own body proportions.

$$Y_{ij} \sim \text{Bernoulli}(p_{ij}),$$
$$\text{logit}(p_{ij}) = \beta_0 + \beta_1\ \text{G}_{ij} + \beta_2\ \text{S}_{ij} + \beta_3\ (\text{S}_{ij} * \text{G}_{ij}) + u_j, \quad (3)$$
$$u_j \sim \mathcal{N}(0, \sigma^2)$$

Where:

- Y_{ij}: The binary outcome for trial i of participant j, with $Y_{ij} \in \{0, 1\}$.
- $p_{ij} = P(Y_{ij} = 1)$. Probability of a "success" on that trial.
- $\text{logit}(p) = \ln(p/(1-p))$: The log-odds link function.
- β_0: The fixed (population) intercept.
- β_1, β_2: Fixed-effect coefficients for gravity and size, respectively.
- β_3: Coefficient for the interaction between object size and gravity condition.
- u_j: Random intercept for participant j, capturing deviation from β_0.
- $u_j \sim \mathcal{N}(0, \sigma^2)$, where σ^2 is the variance of the participant-level random intercepts.
- Gij, Sij: The gravity condition and size for trial i of participant j, respectively.

Bayesian regression models were compared using Bayes Factors (BFs) to quantify how much more likely the data is to be observed under one model compared to another [Gelman et al. 2021; Ly et al. 2015; Makowski et al. 2019]. We consider a Bayes factor of 3 or more (or 1/3 or less) to indicate moderate support (or opposition) for a comparison model, and 10 or more (or 1/10 or less) to indicate strong support (or opposition).

4 Results

We fitted logistic curves showing the probability that a participant identified gravity as realistic as a function of the virtual body size for each gravity condition (see Figure 3). The estimated PSEs correspond to the size ratios of 0.673x and 0.176x for the normal and movie gravity conditions, respectively, with corresponding slopes of 7.52 and -6.39.

The computed Bayes factors support the more complex models over the null one. The gravity-only model was 4.91×10^{89} times more likely than the null model, and the full model was "infinitely" more likely than both the null and gravity-only models. The infinity values are not errors, but rather reflect an overwhelming evidence

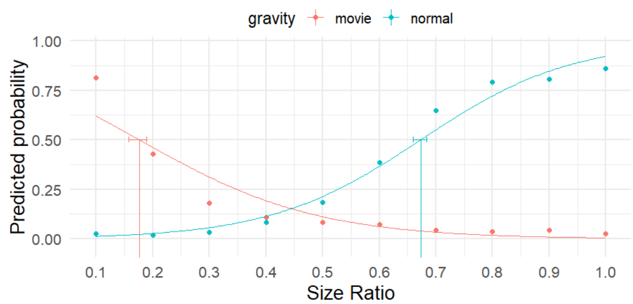

Figure 3: Psychometric curves fitted separately for each gravity condition with PSEs marked.

Table 1: Posterior means, variances and 95% CIs for each model parameter.

Model	Coefficient	Mean	Variance	95% CI
Gravity-Only	Gravity	1.061	0.003	[0.957, 1.167]
Full Model	Gravity	-6.877	0.039	[-7.264, -6.484]
Full Model	Size	-7.1	0.077	[-7.655, -6.559]
Full Model	Gravity:Size	15.456	0.149	[14.697, 16.225]

for one model over the other, and can arise from exceeding the limits of the computer's 64-bit float memory. This result strongly indicates that the full model possesses the most explanatory power relative to the alternatives.

Instead of using simple scalar values, Bayesian regression models use probability distributions to represent the coefficients. Given enough training data, they can be approximated using a normal distribution, where the mean represents the estimated value of the coefficient, and the variance the uncertainty about it. Table 1 illustrates both values for the Gravity-only and Full models.

All of the posteriors' credible intervals excluded zero, indicating strong evidence for all variables in both models. The gravity-only model possessed a small positive effect for gravity, whereas in the Full model, the gravity:size interaction term was the strongest effect, dominating both simple main effects.

Our results indicate that under the *normal gravity* condition, participants correctly identify gravity more often when their virtual bodies are bigger. Under the *movie gravity* condition, participants tend to perceive this gravity as plausible when their virtual bodies are smaller in size. This pattern aligns with findings in previous studies [Pouke et al. 2022, 2021, 2024a].

4.1 Exploratory results

We collected demographic information from each participant using a background questionnaire (see Supplementary Files). Once the main experiment phase ended, participants filled out a 5-item version of the Slater-Usoh-Steed (SUS) presence questionnaire as implemented by Pan et al. [2016] (see Supplementary Files). The SUS score was calculated as the average score across participants, resulting in 5.29, with a standard deviation of 1.15. We aimed to explore if any demographic variabls would improve model fit. We employed `glmer` mixed-effects logistic models from the `lme4` package in R [Bates et al. 2025]. We used this approach over the brms models in our main analysis, as it minimizes the computational resources needed, while maintaining the mixed-effects structures of our previous models. Before model selection, we excluded the variable Education, as it showed moderate multicollinearity with Age (r=0.53), while Age provided more granularity as it is a continuous variable.

Table 2: Coefficients from the logistic regression model sorted by $|z|$ value,

Predictor	Estimate	Std. Error	z value	p value
gravity:size	4.23993	0.10507	40.355	$< 2e{-16}$
size	-2.00401	0.08023	-24.979	$< 2e{-16}$
Gender	-1.29373	0.11209	-11.542	$< 2e{-16}$
(Intercept)	-1.31366	0.13565	-9.685	$< 2e{-16}$
gravity:gender	1.45880	0.15264	9.557	$< 2e{-16}$
Age	0.21843	0.03472	6.291	3.15e-10
gravity	1.13575	0.18216	6.235	4.52e-10
Videogames	-0.09099	0.02953	-3.082	0.00206
gravity:Videogames	-0.12303	0.04025	-3.057	0.00224

We started with a maximal model which included all previous experiment variables in addition to the SUS score and demographic variables from each participant. Only our independent variables, gravity and size, were allowed to interact with other variables. Demographic variables were not allowed to interact with each other due to the sample size and limited number of values per cell. We included participant ID as a random effect.

We used the `buildmer` package [Voeten 2025] for model selection. It was tasked to start with the maximal model described previously and optimize for the nested model with the lowest Bayesian Information Criterion (BIC) value. The final model contained the variables described in Table 2. In the final model, the algorithm opted to drop the random effect (participant ID), which could reflect low inter-subject variability or sufficiently high variance accounted for by the fixed effects such that they could meaningfully describe individual participants without need for a random term. The main effect of each demographic variable indicates an increased general bias for that type of participant to perceive gravity as realistic. Interactions with gravity capture how these biases change as a function of whether *normal* or *movie* physics were actually used on that trial. All models were trained to predict participants responses to the question presented to them after each trial.

Consistent with our main hypothesis, the interaction term between *gravity* and *size* produced the highest z value, reflecting its importance as predictor of participants' judgments of gravity realism. Figure 3 illustrates the interaction between gravity and body size. It displays the percentage of positive responses, across different body sizes, along with fitted logistic functions as described in Section 3.6.1. Note that a gravity-only model would predict two mostly flat, non-intersecting lines separated by a mean shift across size ratios. Instead, it clearly shows the effect of size is variable, being affected by the gravity condition, with participants more likely to perceive *normal gravity* as realistic as their virtual body size approaches their real size and *movie gravity* as their size decreases.

The interaction of Gender with Gravity reflects how differently males and females adapt to each gravity condition. Both genders perform similarly in the *normal gravity* condition, although in the movie condition their performance diverged significantly. Our

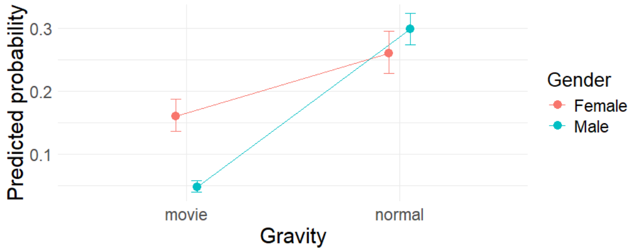

Figure 4: Probability of affirmative responses by gender and gravity condition derived from the logistic model after feature selection, with 95% confidence intervals.

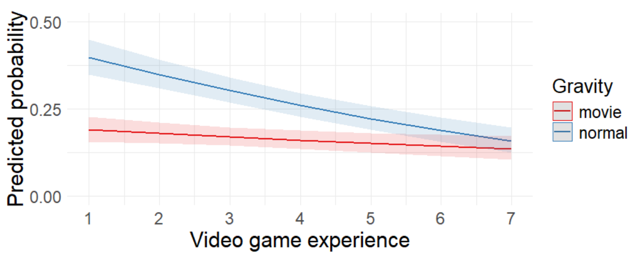

Figure 5: Probability of affirmative responses by video game experience and gravity condition derived from the logistic model after feature selection, with 95% confidence intervals.

participant pool consisted of 70% males and 30% females, thus a confirmatory experiment with a larger sample of female participants would be needed to draw any strong conclusions. Still, in this limited sample, males tended to be less likely to believe gravity was realistic in the *movie gravity* condition, while having a similar performance in the *normal gravity* condition. (See Figure 4).

Video game experience was also assessed in the background questionnaire. Participants selected one of seven response options: *Never, Once or just a couple of times ever, Once or twice a year, Once or twice a month, Once or twice a week, Several times a week, or Every day.* This variable was initially coded as ordinal, but as its linear trend proved to be much stronger than any higher order trends, responses were recoded on a 1–7 integer scale to simplify models, with 1 = *Never* and 7 = *Every day.* The main effect of this variable reflects a bias of participants with more video games experience to be less likely to believe that gravity was realistic. The interaction term between video game experience and gravity reflects an effect, where the influence of video game experience in participants' responses was more pronounced under the *normal gravity* condition (See Figure 5).

5 Discussion

Our results reveal a clear pattern in which gravity plausibility is determined not only by empirical physics, but also in large part by our perceptual priors in reference to our own bodies. The results align with previous research suggesting humans tend to prefer subjectively realistic simulations of gravity over physically accurate ones [Cano Porras et al. 2020; Pouke et al. 2022, 2021]. Humans possess internalized expectations of gravity, which, along with sensory stimuli, serve as a reliable basis when judging gravity [Jorges and Lopez-Moliner 2017; Lacquaniti et al. 2015; Merfeld et al. 1999]. However, this internal gravity model is not perfect [Ullman et al. 2017], and appears to be tightly calibrated according to the perceived size of our own bodies [Pouke et al. 2022, 2021].

Furthermore, we advanced previous research by investigating gravity perception more granularly: When scaling VR users in discrete steps, when does the VR user's gravity perception "flip" from a physically accurate model into "movie physics"? We calculated the Points of Subjective Equality for both gravity conditions. These represent the scale at which participants were the most unsure about whether they were experiencing *normal* or *movie* gravity. The PSE under the *movie gravity* condition was 0.176, and 0.673 under the *normal gravity* condition. This means that participants were more likely to consider "normal physics" as plausible when closer to the normal human scale, whereas "movie physics" was most plausible when closer to 0.1x scale. In other words, on average, when perceiving *normal physics*, the physics model starts to appear unrealistic below the scale of 0.67x, whereas *movie physics* starts to appear more unrealistic when above the scale of 0.18x. At 0.1 scale, approximately 3/4 of the participants considered "movie physics" more realistic, which roughly corresponds to the findings from Pouke et al. Pouke et al. [2021]. This pattern shows the difficulty in overcoming our perceptual priors; when the ratio of body scale and object physics matches our expectations, cues from the environment can do little to overcome these biases. When interacting with physically simulated objects, participants' physics judgments were more aligned with a scenario in which the virtual room was changing scale and their bodies were staying the same size, despite being explicitly told their bodies were being scaled. These findings align with numerous existing gravity and size perception studies (e.g. [Pouke et al. 2022, 2021, 2024a; van der Hoort and Ehrsson 2014; van der Hoort et al. 2011]).

In this study, we built upon VR perception studies such as those above, sought further evidence by systematically comparing a range of scales, and specifically compared evidence on whether humans' internal gravity models are body-centric or body-independent. We tested our hypothesis by comparing three different Bayesian mixed-effects models, which allowed us to account for differences across individuals and weigh evidence for two competing models of gravity perception [Brown 2021; Winter 2013]. The first model served as a reference and only included the random intercepts for each participant. The second model used gravity as a sole predictor variable, capturing the idea of a body-independent gravitational model. The third model used the interaction between gravity and size as predictor variables, capturing the idea of body-dependent gravitational models, where scale affects physics plausibility.

We used Bayes Factors to compare our models and found strong evidence favoring the body-dependent model, with a Bayes factor of ∞ over the two alternatives. This means that gravity as a sole factor cannot explain the participants' responses, and the model using both gravity and scale as predictors is much more likely given the observed pattern of data [Makowski et al. 2019], supporting our hypothesis. Our findings serve as further evidence that humans possess body-dependent expectations when judging gravity at different scales [Pouke et al. 2021]. This is also in alignment with previous studies according to which virtual self-scaling affects the perception of sizes and distances, as if the participant's own body stays the same while the environment is scaling (e.g. [Ogawa et al. 2019; van der Hoort and Ehrsson 2014; van der Hoort et al. 2011]). This so-called body-scaling effect suggests a body-centric model in estimating sizes and distances, while our results suggest that this body-centric model extends to the perception of gravity as well.

Our findings suggest interesting implications in several domains. Firstly, mCVEs rely on collaborative activities between VR users operating at different scales (e.g. [Kopper et al. 2006; Zhang and Furnas 2005]). It is not straightforward to enable meaningful collaboration between multiple users at various scales in scenarios in which realistic rigid-body dynamics are necessary. Perhaps even more interestingly, immersive robotic telepresence, i.e., teleoperation of machinery using HMDs or CAVE-like systems, has gained traction in recent research (e.g., [Botev and Rodríguez Lera 2021; Chi et al. 2025; Laukka et al. 2024]. Some application areas target construction machines, such as cranes [Duz et al. 2025; Hu et al. 2025], whereas some recent telepresence systems are even directly targeting humanoid robots at non-human scales [Hejrati et al. 2025; Izumihara et al. 2019]. Even in older work, it has been pointed out that microscale robotics operations exhibit difficulties for human operators because of physics-related peculiarities that arise when operating at micro-scales [Sitti 2007; Zhou et al. 2000]. Similar difficulties could potentially arise in robotic teleoperation as well, compelling the need for design considerations and special training when working at scales that exceed the limits of our daily lives.

All of the above said, however, it should be noted that our results do not completely align with previous studies in which there are *other* virtual characters in the scene besides the user, which may have additional implications to multi-user applications such as mCVEs. For example, a Langbehn et al. [2016] study concerning relative importance of inconsistent scale cues in VR found that the scale of other characters in the scene could be perceived as the dominant one, even when the participants' own scale otherwise served this purpose. Concerning gravity perception, specifically, the studies of Pouke et al. [2022, 2024a] found that when participants passively observed a humanoid robot of 0.2 scale throwing physically simulated objects, the participants tended to judge gravity plausibility according to the virtual character's scale instead of their own. As pointed out by, for example, DeLucia [2013], it appears likely that human visual systems consider multiple sources of information when judging object trajectories. It could therefore be that the body-centric model does not necessarily default to the VR user's *own* body, but to the dominant acting body in that scene.

5.1 Limitations

Human gravity perception relies on multiple sensory inputs, including the vestibular system, proprioception, and visual cues, which are integrated to form a sense of the gravity vector [Jorges and Lopez-Moliner 2017]. Because our VR simulation relied solely on visual stimuli, conflicts between vestibular, proprioceptive, and visual input could easily arise during the movie condition, limiting our ability to fully simulate altered gravity. However, it could be argued that despite simulating altered gravity only visually, our experimental paradigm was nevertheless similar to many potential "real-world" situations in which abnormal gravity could be perceived, such as immersive teleoperation of non-human-scale robots (e.g. [Hejrati et al. 2025]).

Our experimental design was also limited in the sense that we only considered the separated gravity extremes of 0.1g and 1g (10 trials per each gravity-scale combination) which does not allow granular inferences across the intermediate values. This was a deliberate tradeoff; adding the intermediate gravity steps while keeping the current count of 200 trials would have prevented us from quantifying measurement error at gravity-scale level within participants, whereas conducting a similar analysis with the intermediate steps would have lengthened the experiment significantly. Also, our design did not allow us to collect detailed experiences concerning each scale-gravity pair, for example, whether the participant's experience of scaling appeared phenomenologically more as if the world or they themselves changed in size (mixed results were collected in e.g. [Pouke et al. 2026]), or how participants perceived the visual trajectories of the thrown object in terms of speed, time-of-flight, or otherwise, and whether these estimates align with their gravity coherence judgments. However, this information has been collected in multiple similar studies and the results do align with this work [Pouke et al. 2021, 2026]. Findings from previous research involving multiple characters suggest that additional research is needed to understand how human gravity perception functions in more complex multiscale scenarios involving multiple agents. Finally, the study included both preregistered confirmatory analyses and additional exploratory analyses. We wish to remind readers to exercise appropriate caution when interpreting the latter.

6 Conclusion

This experiment demonstrated strong support for a body-centric internal model of gravity perception, as Bayes factors among our models overwhelmingly favored the model that uses both gravity and scale as predictors, supporting the body-dependent theory. We also showed that it is the interaction between gravity and scale that serves as a reference when judging gravity, and not simply their additive effects. Points of Subjective Equality further revealed that participants tend to identify the *movie physics* as realistic under smaller scales, even if this is not physically accurate. This strongly aligns with the previous findings in scale-changing experiments [Pouke et al. 2022, 2021]. We complemented them by showing that the transition from preferring *movie* to *normal physics* is gradual across a continuum of scales, rather than a binary switch.

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