Simulating Object Weight in Virtual Reality: The Role of Absolute Mass and Weight Distributions

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Figure 1: In the study, participants were presented with a series of differently configured virtual objects in VR. For each of the 54 object configurations tested, 13 identical instances were displayed at a time (left image), which were aligned with different physical weights (right image). Participants then indicated which weight sensation corresponded best to the virtual object.

ABSTRACT

Weight interfaces enable users of Virtual Reality (VR) to perceive the weight of virtual objects, significantly enhancing realism and enjoyment. While research on these systems primarily focused on their implementation, little attention has been given to determining the weight to be rendered by them: As the perceived weight of objects is influenced not only by their absolute mass, but also by their weight distribution and prior expectations, it is currently unknown which simulated mass provides the most realistic representation of a given object. We conducted a study, in which 30 participants chose the best fitting weight for a virtual object in 54 experimental trials. Across these trials, we systematically varied the virtual objects' visual mass (three levels), their weight distribution (six levels), and the position of the physical mass on the grip (three levels). Our Bayesian analysis suggests that the visual weight distribution of objects does not affect which absolute physical mass best represents them, whereas the position of the provided physical mass does. Additionally, participants overweighted virtual objects with lower visual mass while underweighting objects with higher visual mass. We discuss how these findings can be leveraged by designers of weight interfaces and VR experiences to optimize realism.

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CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Virtual reality**.

KEYWORDS

virtual reality, weight interfaces, weight perception, weight simulation, multisensory integration

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1 INTRODUCTION

The ability to sense the weight of objects is fundamental to our interaction with our environment, informing us about the properties of objects and providing vital input for coordinating and executing object manipulations and movements [60]. To realistically perceive objects in Virtual Reality (VR), it is therefore vital to make their weight perceptible. To address this, researchers have developed various haptic interfaces, which aim to replicate the sensation of weight in virtual environments, enhancing the users' realism and enjoyment [35]. Beyond pseudo-haptic techniques [27, 49, 52] and devices that adjust their weight distribution [51, 54, 66], presented approaches include controllers that change their weight through liquid mass transfer [9, 10, 32, 35, 43, 64], force feedback devices using propeller propulsion [23, 28] or motor-controlled strings [1], and electrical muscle stimulation pads targeting specific muscles [13, 29].

Despite the growing interest in weight interfaces, there remains a gap in understanding how to determine the weight to render for given virtual objects. The perceived weight of objects is influenced by both their absolute mass and their weight distribution [61]. However, current weight interfaces are limited in their ability to change weight distributions [31], making it difficult to decide on the appropriate absolute mass to be rendered, when there are discrepancies in weight distribution between a virtual object and the weight-changing device held in the real world. Rendering the accurate absolute weight in these cases might not increase the haptic realism, but instead increase the visuo-haptic mismatch through an amplified discrepancy in weight distribution. Hence, the goals of replicating an object's absolute weight and avoiding a visuo-haptic mismatch might conflict.

Additionally, visual cues are integral to the sensation of weight [38, 42]. Considering that VR allows for convincing visual cues, it is conceivable that rendering a lesser weight (compared to the accurate absolute mass) might suffice for realistic weight perception. For instance, prior work has simulated the weight of medieval war hammers using a physical mass of less than 500 g [35]. Simulating heavy weights presents challenges in the form of increased latency [31], bulk [39] and noise [23]. Thus, evidence that rendering weights less than a heavy object's true weight still produces realistic results may be useful to mitigate these issues.

Lastly, humans rely on internal models of an object's weight to plan their lifting effort. These prior expectations affect the object's perceived weight [8, 12, 47]. For instance, when a person lifts two equally weighted but different-sized objects, they perceive the bigger object as lighter. A common explanation of this illusion is that humans perceive an object's weight relative to their expectations [7, 17, 56].

Hence, replicating an object's absolute mass does not necessarily produce the most realistic haptic representation. To understand which mass provides the most realistic representation of a given virtual object, we conducted a VR study with 30 participants who were tasked with selecting the most fitting weight for a series of virtual objects. In 54 experimental trials, we systematically varied the visual mass (three levels) and weight distribution (six levels) of the virtual object, as well as the position of the physical mass relative to the grip (three levels). We found effects of both physical mass position and visual mass on the participants' weight selections. Participants overweighted objects with lower visual mass and underweighted those with higher visual mass. Additionally, participants tended to choose lighter weights when the physical mass was positioned at the bottom compared to the top. We derive a predictive model to estimate the weight to render for a given visual mass and physical mass position and discuss how these insights can be leveraged to enhance realism in VR experiences.

2 RELATED WORK

We provide an overview of the various weight interfaces that have been developed to evoke weight sensations in VR. Thereafter, we discuss sensory and cognitive mechanisms underlying weight perception.

2.1 Weight Simulation in VR

The challenge of accurately simulating weight has led to the development of various techniques and devices, which we present in the following.

2.1.1 *Visuo-haptic Weight Illusions.*

Due to the physical challenges of creating gravitational forces, numerous prior works proposed methods to convey weight metaphorically. These approaches range from manipulating the air resistance [67] or the button resistance of a VR controller [57], to varying the cutaneous pressure on the finger skin [19] or the wrist [21, 46]. Pseudo-haptic weight rendering techniques convey weight through visual cues by applying hand tracking offsets depending on the weight of a virtual object [49, 52] or altering the displacement of a virtual object [27]. Some of these techniques can be combined to enhance the visuo-haptic weight illusion, as demonstrated by Stellmacher et al. [58], who combined the approach of adaptive button resistance of a VR controller with pseudo-haptic feedback through hand tracking offsets.

While these approaches are effective in indicating that objects differ in weight, they do not provide physical gravitational forces, which are crucial to realistically feeling an object's weight [39].

2.1.2 *Center of Gravity Simulation.*

One way of providing this feedback is through the use of proxy objects [24, 55]. Proxy objects are physical counterparts of virtual objects, with haptic properties that match the virtual object. By mapping the proxy object with a virtual object, users can perceive the proxy's weight as the weight of the virtual object [65]. However, it is highly impractical to provide a suitable proxy object for every object users interact with in the virtual world. To cover a broader range of objects with a single proxy object or VR controller, researchers have developed devices that shift internal masses to alter their center of mass. *SWISH* employs a mechanism to shift the center of gravity in a 3d printed vessel, to simulate fluid dynamics. The mechanical system uses a three-dimensional cylindrical coordinate setup with motors controlling the position of the mass inside the vessel along three axes. Zenner and Krüger [66] presented *Shifty*, a proxy, which changes its weight distribution through a pulley that enables a 127 g weight to be moved along an attached rod. Extending the range of perceived shapes, Shigeyama et al. [54] developed *Transcalibur*, which encompasses two rods, which can be rotated up to 90° along one axis. Each rod is affixed with a 72 g weight block that can move along the rod.

These internal weight-shifting mechanisms can also be employed to induce the illusion of an absolute weight change, as the shifted weight affects the force required by users to handle the controller when held at an angle [66]. However, the range of absolute weight sensations this approach can produce is inherently limited. For the illusion to be induced users need to hold the object at an angle, and swinging the device might reveal the true center of mass, disrupting the illusion of a different absolute weight. Additionally, the range of simulated weights is directly tied to the fixed mass of the movable weight block. If a heavier movable mass is incorporated, it increases the overall weight of the device, which in turn limits its ability to convincingly render lighter weights. Conversely, using a lighter movable weight constrains the maximum weight that can be simulated.

2.1.3 Absolute Weight Interfaces.

Researchers designed various haptic weight interfaces that actuate adaptive force feedback or change their overall weight to simulate absolute weight in VR. Heo et al. [23] presented *Thor's Hammer*, a hammer-shaped handheld device, which uses six propellers, one on each side of the hammer head, to generate intense air thrusts in an arbitrary direction. This force feedback is capable of rendering up to 400 g of weight in VR. Similarly, Je et al. [28] employed two propellers facing downwards on a VR controller to create downward forces of up to 14 N (1400 g). By targeting the two propellers individually, they were able to mimic horizontal weight shifts. Another method to imitate gravitational pulls is through strings. Achberger et al. [1] employed a brushless DC motor to pull a string attached to a VR controller. The other end of the string led through a moveable pulley and was, together with the electronics, attached at the user's shoe. By creating a constant torque the researchers simulated weights from 180 g to 730 g. Other systems explore using electric muscle stimulation to induce weight sensations [13, 26, 41]. For instance, the wearable device by Lopes et al. [41] comprised 16 electrodes and a backpack containing a muscle stimulator. The system applied an electrical stimulus to the user's shoulder muscles and triceps to convey weight when lifting a virtual cube. However, a key limitation of electric muscle stimulation is that it inherently creates unintended "tingling" sensations, leading to discomfort [59] and reduced acceptance, in particular for applications that manipulate perception [14].

A method for weight interfaces to provide gravity forces unintrusively and without a constantly running motor consists in devices that adjust their own mass [34]. Cheng et al. [10] presented *GravityCup*, a handheld VR controller containing a 330 ml water bag, which has a tubing connection to a waist-worn water bag. Both units integrated a water pump to transfer water between them. By filling or draining the handheld unit, the system can alter its weight and thus adjust the absolute weight perceived on the user's hand. Likewise, Monteiro et al. [43] introduced *Fluidweight*, a device that employs a container with three water balloons, each of which with a tubing connection to a water reservoir in a backpack. As the balloon in the back of the container was targeted by a different actuator than the two frontal balloons, different weight distributions could be achieved along one axis. Nevertheless, as the container with the balloons was attached to the bottom of a commercial handheld VR controller, the center of weight was always at the bottom. A similar controller extension was presented with *VibroWeight* [64], which combined *FluidWeight*'s mechanism with vibrational feedback. Kalus et al. [35] developed *PumpVR*, a system comprising bottle-shaped controllers, held at their bottleneck, whose absolute weight can be altered by a high-capacity pump drawing water from an external reservoir. The system can change the controllers' weight simultaneously or separately at a rate of 150.9 g/s, with weight ranges of 500 g per hand. Chen et al. [9] employed liquid mass transfer in a wearable VR system involving four sleeves and a stationary water supply. This enabled users to perceive weight changes of up to 1360 g distributed over four body parts. Most recently, Kalus et al. [32, 33] introduced *MobileGravity*, which utilizes quick disconnect couplings to decouple the weight-changing object from the liquid supply after the weight adjustment. This enabled the system to render a weight range of up to 1 kg while maintaining mobility. The weight-changing object could be grabbed at an additional handle, perpendicular to its main handle, to perceive a shifted center of mass for specific virtual objects.

2.2 Weight Perception

Weight is primarily sensed through kinesthetic cues, detected through the muscles and tendons that exert force to hold an object against gravity [30]. These cues provide information about the force required to lift and maintain the position of an object, directly contributing to our perception of its weight. Additionally, tactile cues contribute to weight perception, sensed through cutaneous pressure exerted on the skin by the object being held [30].

Furthermore, the distribution of an object's weight substantially affects its perceived heaviness: When humans wield objects, they sense their rotational dynamics, which makes objects feel heavier or lighter depending on how the mass is distributed relative to the axis of rotation [2, 61, 66]. While it was initially assumed, that the inertia tensor alone governs the perception of length and heaviness in handheld objects, Kingma et al. [36] showed that length perception during rod wielding is influenced by both the object's resistance to rotational acceleration (as governed by the inertia tensor), but also by its static moment. Further findings by Kingma et al. [37] suggested that static moment is the dominant factor in heaviness perception during rod wielding, with the inertia tensor playing a less significant role.

Besides an object's mass properties, internal models about an object's weight also affect the perceived weight of an object. For instance, a study involving golfers and non-golfers lifting real and practice golf balls demonstrated that golfers perceived practice balls as heavier than real ones, despite them having equal weight. This was attributed to golfers' prior knowledge that practice balls are usually lighter than real golf balls. Non-golfers, lacking this specific expectation, perceived the weights as equal [12]. Related work demonstrated that humans use such expectations of an object's weight to predict its weight and plan the lifting effort accordingly [62]. Visual cues can inform these expectations based on learned relationships between weight and visual properties of objects [38, 42, 50]. For instance, when comparing the weight of equally weighted but different-sized objects, a size-weight illusion

(SWI) is induced and humans estimate the larger object as lighter and the smaller object as heavier. Similar perceptual biases, where the heavier looking object feels lighter, can also occur with material-weight [45] and brightness-weight relationships [63]. Heineken and Schulte [22] recreated the SWI in VR, indicating that such perceptual biases persist in virtual environments and may be applied to virtual objects. Hence, it seems plausible that the visual weight distribution of virtual objects involve perceptual biases as well, especially when they conflict with the physical weight distribution of the handheld controller.

While the aforementioned studies by Kingma et al. [36, 37] explored how humans perceive the length and heaviness of handheld rods without visual input, they left the interplay between physical and virtual object properties unexplored. Park et al. [44] aimed to resolve the sensory mismatch between the visual and haptic perceptions of handheld objects in VR by developing a length perception model that accounts for the moment of inertia and diameter of the controllers. They proposed to adjust the controller's internal weights and handle diameter based on the model's output for its haptic perceptions to match the virtual object. Similarly, Fujinawa et al. [18] created a model to predict the perceived shape of planar controllers based on the mass properties. These models do not consider scenarios where the physical or virtual weight is at the bottom of the grip, such as when holding a virtual sack, or with controller designs that specifically position the mass at the bottom of the controller handle [43, 64]. Most importantly, they rely on the ability to adjust the shape of the controller, which is however limited in absolute weight interfaces. Consequently, while the models can optimize the use of shape-shifting devices, they cannot be applied to determining the optimal absolute mass to render.

2.3 Summary

Overall, related work presented numerous weight interfaces, that enable VR users to perceive weight forces at the top [23, 28, 32, 35], center [13, 41] or bottom [1, 43, 64] of their grip. Insights from cognitive science show that our perception of weight is influenced not only by the absolute mass of an object [30] but also by our expectations [12, 38, 42, 50] and the object's weight distribution [2, 61, 66], making it difficult to decide which weight to render for a given virtual object. This difficulty is exacerbated as, unlike center of gravity simulation devices, absolute weight interfaces are limited in their capability to change their shape, hindering the application of models that counteract visual-haptic mismatches through shape-shifting [18, 44].

3 METHOD

We conducted an experiment to understand which rendered mass provides the most realistic representation of a given virtual object. In the study, participants could determine the most realistic weight for a series of virtual objects with different visual absolute masses, different visual centers of mass, and different positions at which the physical weight was provided.

3.1 Study Design

To test a comprehensive range of weight distributions the virtual objects had a visual mass positioned at either the center, the bottom, or the top of the grip, or at a 45°, 90° or a 135° frontal angle. The visual mass was either 360 g, 720 g, or 1080 g.

This resulted in the independent variables VISUAL MASS (with the levels *light*, *medium*, and *heavy*), and VISUAL CENTER OF MASS (with the levels *central*, *bottom*, *45°*, *90°*, *135°* and *top*). As most weight interfaces alter the weight at the top or bottom of the grip instead of at its center, we also varied the position at which the physical weight was perceived. Hence, a further independent variable was the PHYSICAL MASS POSITION (with the levels *bottom*, *central* and *top*).

We used a within-subjects design. The 18 different virtual object configurations (3 levels of VISUAL MASS × 6 levels of VISUAL CENTER OF MASS) were tested once per PHYSICAL MASS POSITION condition, resulting in 3 blocks of 18 trials each, a total of 54 trials. To avoid sequence effects, the order of the 3 PHYSICAL MASS POSITION conditions was counterbalanced using a balanced Latin square design, while the order of the 18 trials within a single block was randomized for each participant.

3.2 Task & Measures

In each of the 54 trials, participants were presented with a rack of 13 virtual objects that looked identical, but had different physical weights. Participants were informed that these objects were arranged linearly from left to right in ascending order of weight. Their task was to determine the object that felt the most realistic to them. They were instructed to use their dominant hand to freely pick up, wield, heft and return the different objects and were reminded of these instructions if they attempted to only briefly lift the objects. They were permitted to try any object until they felt that the haptic sensation of the object in their hand most closely aligned with the virtual object in the virtual environment. They could submit their decision via a thumbs-up gesture, which initiated the next trial, replacing the 13 virtual objects with those from the new trial.

By choosing the weight that best matched the virtual object, participants provided the object's expected weight. In line with previous weight estimation tasks, we used weight estimation error as dependent variable [6, 15, 20], defined as the difference between selected and actual weights: $WeightEstimationError = visual\ mass - selected\ weight$. As the weight assignment alone provides no insight on whether a particular PHYSICAL MASS POSITION produces superior results in terms of realism, participants were additionally asked to rate their perceived object realism using the questionnaire item "How real did the virtual objects seem to you?" adapted from the Presence & Reality Judgment Questionnaire [4]. The item is scored on an 11-point Likert scale ranging from 0 (not at all) to 10 (absolutely). To ensure that participants only take their chosen object-weight combinations into account for their rating, the term "virtual objects" was replaced by "virtual objects you chose as the most realistic".

3.3 Apparatus

We developed a VR application using the game engine Unity. Participants wore a Meta Quest 2 head-mounted display (HMD), which was connected to a desktop PC running the VR application (Windows 10, Intel i7-9750H, 16GB RAM, NVIDIA GeForce RTX 2060).

Figure 2: The haptic stimuli in the *center* (left image), *bottom* (middle image) and *top* (right image) Physical Mass Position.

We used the HMD's native hand tracking with Meta's default hand models to enable the participants to interact with the virtual world.

3.3.1 Environment. In our laboratory, 13 haptic stimuli were placed on a table and arranged linearly from left to right, in order of their weight. The spacing between them was 11 cm. The virtual world was a replica of the laboratory, but the haptic stimuli were hidden. Instead, a rack holding 13 identical instances of the current trial's virtual object was displayed. The positions of these 13 virtual objects were aligned with the positions of the 13 haptic stimuli in the physical space. As a result, there were 13 identical-looking virtual objects with different physical weight on the virtual rack.

To enable the users to grasp the virtual objects, the virtual objects were programmed to snap to the virtual hand when the corresponding haptic prop was grabbed and return to their initial position when the haptic prop was released. The detection of these events was facilitated by tracking the positions of the hands and their finger joints using Unity's Physics module and Meta's Interaction SDK. For locating the haptic props, they had pre-defined positions on the table, and the virtual and physical spaces were precisely aligned. This alignment was calibrated using the Meta Quest Touch Controller as the reference point. The experimental setup and its alignment with the virtual environment is shown in Figure 1.

3.3.2 Visual Stimuli. The visual stimuli consisted of virtual objects varying in absolute mass and weight distribution. Each object consisted of a cylinder, at which the object was grabbed, and a visual weight load attached to it. The cylindrical grip was translucent, to clarify that it was empty and did not carry additional weight. The visual weight load was either positioned at the bottom of the cylinder, at a 45° frontal angle, at a 90° frontal angle, at a 135° frontal angle, at the top of the cylinder or within the cylinder. Standard 330 ml canned beverages were used to represent visual mass, to ensure that the participants were familiar with the weight of the visual weight load and had a mental association with it. Either one (360 g = *light* level of visual mass), two (720 g = *medium*) or three (1080 g = *heavy*) cans sticking together on their sides, comprised the visual weight load, ensuring that participants could quantify the differences between these three levels while maintaining consistent prior expectations based on size and material. The cans were modeled to follow the size specifications of 330 ml standard cans [48], with a prominent label additionally indicating the 330 ml volume.

For the *central* visual center of mass, where the visual mass was within the cylindrical grip, the cans were on top of each other to not affect the grip width, maintaining consistent grasp types in line with Blaga et al. [5]. The resulting virtual objects are depicted in Figure 3.

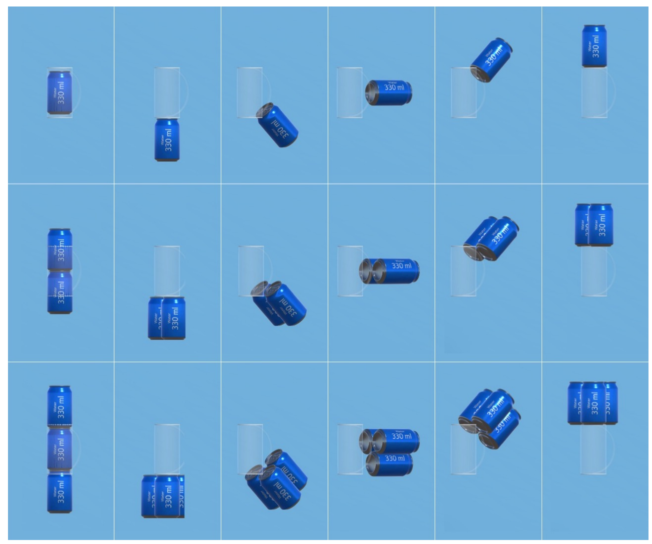

Figure 3: The virtual objects for the *light* (top row), *medium* (middle row) and *heavy* level of visual mass. The columns show the different levels of Visual Center of Mass (from left to right: *central*, *bottom*, *45°*, *90°*, *135°* and *top*)).

3.3.3 Haptic Stimuli. The haptic stimuli were 13 3D-printed cylinders ranging from 100g to 1300g (in 100g intervals). To achieve each weight, a tube filled with steel granules and foam material was embedded in the center of each cylinder. The circumferences of the individual inner tubes were sized to prevent the granules from moving and causing an inertial force. The cylinders had an external diameter of 6.5 cm and a height of 11.5 cm, matching the dimensions of a 330 ml beverage can. In the *bottom* and *top* Physical Mass Position conditions the cylinders were - unbeknownst to the participants - lengthened with a hollow extension, at which the prop was grabbed to perceive the shifted center of mass. In these conditions, the y-position of the virtual rack was adjusted to align the extension with the virtual grip, ensuring that participants grabbed the haptic prop at the extension. The resulting lengthened cylinder had an overall height of 20.6 cm. As a result, the center of mass was concentrated 10.3 cm below the center of the grip in the *bottom* Physical Mass Position condition and 10.3 cm above the center of the grip for the *top* Physical Mass Position. Figure 4 shows the structure of a haptic stimulus. The arrangement of the haptic stimuli for each Physical Mass Position condition is depicted in Figure 2.

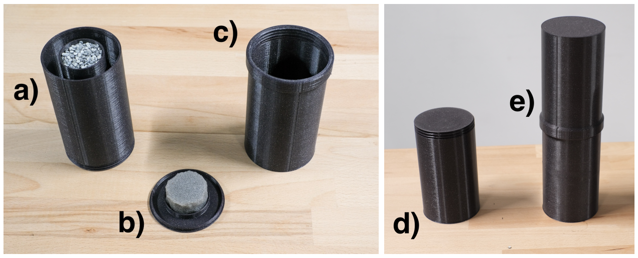

Figure 4: A haptic stimulus consists of (a) a weighted cylinder, that can be closed using (b) a lid with foam material. It can be lengthened with (c) an extension to create the *bottom* and *top* Physical Mass Position. The right image depicts the closed haptic stimulus (d) without and (e) with the extension.

3.4 Participants

The study involved 30 participants (14 identified as female, 16 identified as male), ranging in age from 18 to 34 years (M = 23.93, SD = 3.9). Participants were recruited through institutional mailing lists and were compensated with credit points for their study program. 25 participants were right-handed, 5 were left-handed. Regarding VR usage, 14 participants reported using VR applications a few times per year, 12 never using VR, two using VR a few times per week and two a few times per month. Using the Self-Perception of Fitness questionnaire's strength scale [11], which ranges from 1 (absolutely no strength) to 13 (exceptional strength), participants reported on average normal strength (M = 7.17, SD = 1.98). All participants finished the experiment.

3.5 Procedure

Before starting the experiment, participants gave informed consent and were provided with a brief introduction. This took place in a separate room in our laboratory to prevent the participants from seeing the physical apparatus. Participants were informed that they can use their dominant hand to pick up and return the objects. They were also informed that a thumbs-up gesture will be used as confirmation. Participants were asked to remove their jackets or jumpers to avoid interference with hand tracking. They were handed out single, double, and triple packs of 330ml canned beverages, which they could lift and move to re-familiarize themselves with their weight, ensuring consistent knowledge of weight properties. Concurrently, the experimenter started the Unity scene and re-calibrated the virtual and physical space. The participants then returned the beverages, donned the HMD and were guided to the main room, where the experiment took place. They were not informed of the physical weight levels of the haptic stimuli or the weight levels of the visual stimuli.

Subsequently, the first of the three blocks of 18 trials started. After each block, participants sat down on a virtual chair, co-aligned with a chair in the physical space. There they used their tracked hands to complete the object realism questionnaire, while the experimenter prepared the haptic props for the next condition. In line with Schwind et al. [53], the questionnaire was administered in the virtual environment, without interrupting the VR experience. Thereafter, the participants proceeded with the next block. Once completing all three blocks and subsequent object realism questionnaires, participants removed the HMD and filled out the demographic questionnaire.

4 RESULTS

We conducted a 3 (Visual Mass: *light* vs. *medium* vs. *heavy*) x 3 (Physical Mass Position: *top* vs. *center* vs. *bottom*) x 6 (Visual Center of Mass: *center* vs *bottom* vs. *45°* vs. *90°* vs *135°* vs *top*) Bayesian RM ANOVA on the weight estimation error. Furthermore, we conducted a one-way Bayesian RM ANOVA to investigate effects of Physical Mass Position on object realism. To derive the strength of evidence from the Bayes factors, we followed the categorization by Andraszewicz et al. [3]. Finally, we derive a regression formula for the selected weight using linear regression analysis.

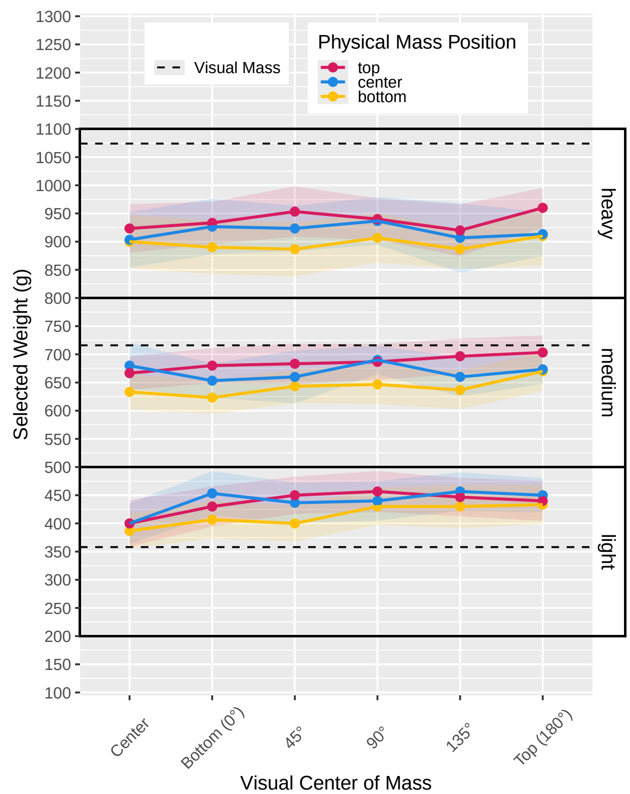

Figure 5: Mean weight selected for the different levels of Visual Mass, Visual Center of Mass and Physical Mass Position. The shaded areas indicate the within-subject 95% confidence intervals.

4.1 Weight Estimation Error

An overview of the selected weights by Visual Mass, Physical Mass Position and Visual Center of Mass is presented in Figure 5.

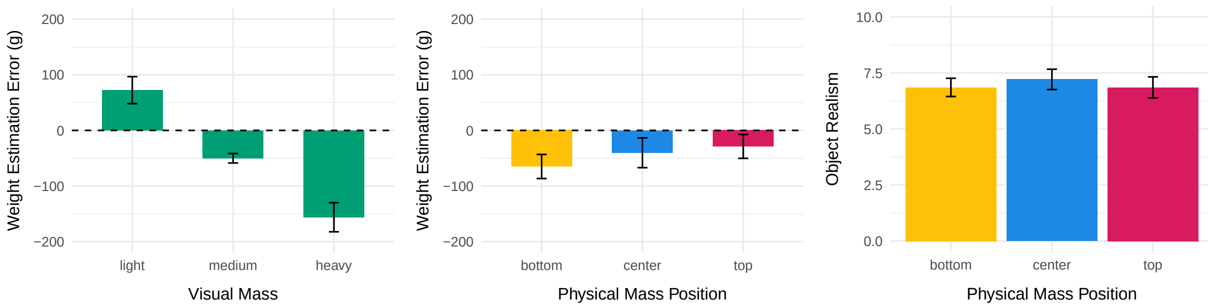

Figure 6: Weight Estimation Error by Visual Mass (left) and by Physical Mass Position (center), and mean scores for Object Realism (right). The error bars indicate the within-subjects 95% confidence intervals.

Bayesian RM-ANOVA revealed extreme evidence for a model that supports an effect of Visual Mass on the Weight Estimation Error, $BF_{10} > 100$, *error* ± 0.78%, with all pairwise post hoc comparisons showing extreme evidence in favour of differences between all levels of Visual Mass (all $BF_{10} > 100$, *error* ± 0%). This indicates that participants overweighted lightweight objects, while heavy and medium objects were underweighted, with the underweighting being larger for heavy objects as compared to the medium objects (see Figure 5).

We also found very strong evidence ($BF_{10} = 82.093$, *error*±1.04%) for a model that postulates an effect of Physical Mass Position on the weight estimation error. Post hoc comparisons showed moderate evidence in favour of a difference between the *top* and *bottom* levels of Physical Mass Position ($BF_{10} = 3.818$, *error* ± 0%), but moderate evidence against differences between the *center* and *top* levels ($BF_{10} = 0.238$, *error* ± 0.03%) and anecdotal evidence against differences between *bottom* and *center* levels ($BF_{10} = 0.476$, *error*±0.03%). This indicates that the weights chosen by the participants to represent the virtual objects were lighter in the *bottom* Physical Mass Position condition as compared to the *top* Physical Mass Position condition (see Figure 6).

There was extreme evidence against a model that postulates an effect of Visual Center of Mass, $BF_{10} = 0.005$, *error* ± 0.52%. We also found extreme evidence against an interaction between Physical Mass Position X Visual Center of Mass ($BF_{10} > 0.001$, *error* ± 0.36%), between Physical Mass Position X Visual Mass ($BF_{10} = 0.002$, *error* ± 0.87%), between Visual Center of Mass X Visual Mass ($BF_{10} < 0.001$, *error* ± 0.35%), between Visual Center of Mass, and the three-way interaction Visual Mass X Physical Mass Position X Visual Center of Mass ($BF_{10} < 0.001$, *error* ± 0.24%)

4.2 Regression Model

To derive an equation for estimating the object weighting, we performed a multiple linear regression on the absolute weight selection with the predictors Visual Mass and Physical Mass Position, as visual inspection suggested a linear trend (see Figure 7).

For the regression analysis, we used ordinal scaled Visual Mass values (360 g / 720 g / 1080 g). Using treatment coding for Physical Mass Position yielded a significant regression ($F(3, 1616) = 843.84$, $p < .001$), with the model explaining a substantial proportion of variance (Adjusted $R^2 = 0.61$). Visual Mass ($p < .001$), as well as the Physical Mass Position contrasts ($p = .011$ for *bottom* vs. *center*, $p < .001$ for *bottom* vs. *top*) were significant predictors. The regression equation was:

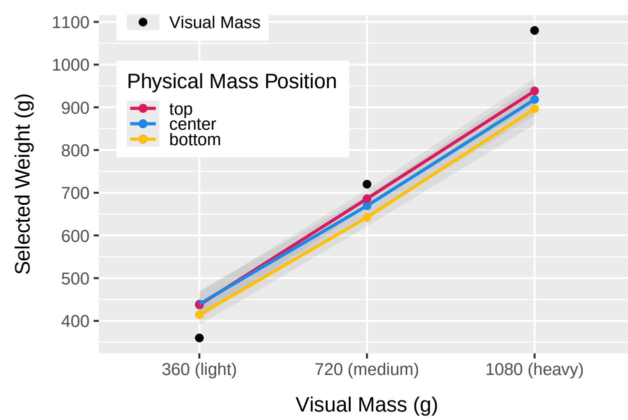

Figure 7: Mean weight selected by Visual Mass and by Physical Mass Position. The shaded areas show the within-subject 95% confidence intervals.

$$\widehat{\text{selected weight}} = 163.7\ g + 0.68 \times \text{visualMass} + 24.63 \times \text{physMassPos}_{\text{center}} + 36.11 \times \text{physMassPos}_{\text{top}}$$

Where visualMass is the Visual Mass of the virtual object in grams and physMassPos acts as binary indicator: $\text{physMassPos}_{\text{center}} = 1$, when weight is rendered at the *center* Physical Mass Position, otherwise $\text{physMassPos}_{\text{center}} = 0$. Likewise $\text{physMassPos}_{\text{top}} = 1$, when weight is rendered at the *top* Physical Mass Position, otherwise $\text{physMassPos}_{\text{top}} = 0$. If both $\text{physMassPos}_{\text{center}} = 0$, and $\text{physMassPos}_{\text{top}} = 0$, the model assumes a *bottom* Physical Mass Position

Treating the levels of Physical Mass Position, as a continuous variable, i.e. the distance of the center of mass to the center of the grip, also yielded a significant regression (Adjusted $R^2 = 0.61$,

$F(2, 1617) = 1265.75$, $p < .001$). Both, Visual Mass ($p < .001$) and Physical Mass Position ($p < .001$) were significant predictors. This gives the following equation:

$$\widehat{\text{selected weight}} = 183.95\ g + 0.68 \times \text{visualMass} + 1.75 \times \text{physMassDistance}$$

Where *physMassDistance* is the distance of the center of mass to the center of the handle in centimetres (assuming a zero angle) and visualMass is the Visual Mass of the virtual object in grams.

4.3 Object Realism

There was a mean *object realism* score of 6.86 for the *top* Physical Mass Position ($SD = 1.69$), of 7.21 for the *center* Physical Mass Position ($SD = 1.71$), and of 6.86 for the *bottom* Physical Mass Position ($SD = 1.94$). A Bayesian RM Anova indicated moderate evidence against accepting a hypothesis that postulates an effect of Physical Mass Position on *object realism* ($BF_{10} = 0.212, error \pm 0.24\%$). Figure 6 shows the object realism for each level of Physical Mass Position. This suggests that the position at which the weight is provided did not affect the average realism of the virtual objects.

5 DISCUSSION

Our study revealed several insights into the perception of weight in VR and offers practical guidance for the development and utilization of more effective weight interfaces, which we discuss in the following.

5.1 Predictive Models

To facilitate practical application of our findings, we derived two regression formulas that may guide designers of haptic VR experiences. As opposed to models presented by related work, which optimize the shape for VR controllers or proxies [18, 44], our models assume a controller that cannot change its shape to account for a visuo-haptic mismatch. This assumption is particularly important, as most weight interfaces, especially those that focus on wide ranges of weight are not capable of adjusting their shape due to the increased base weight these functionalities entail [31, 39]. Additionally, our models take controller designs with the weight rendered at the bottom of the handle [1, 43, 64] into account, which were previously not addressed.

Developers can use our predictive models to estimate the weight to be rendered based on the virtual object's mass and the position on which their weight interface can provide the physical mass relative to the handle. As our Bayesian analysis indicated extreme evidence for a model that postulates no effect of the visual center of mass on the assigned weight, our models do not include the visual center of mass of the virtual object. By using our models to more closely align the perceived weight of virtual objects with users' expectations, developers could create more realistic and immersive VR experiences.

5.2 Effect of Visual Mass

One of the key findings is that participants overweighted lighter objects and underweighted heavier ones. This insight demonstrates that realism can be maintained even when the simulated weight is less than the object's true weight. For instance, rendering 845 g could effectively create the sensation of a 1 kg object. This finding is particularly useful in reducing several issues associated with simulating heavy weights in VR. Weight interfaces that utilize liquid mass transfer operate at a flow rate of 19.62 g/s to 235 g/s, which can introduce latency issues when rendering heavy weight [31, 32]. Weight interfaces based on motor-actuated weight forces require constantly running motors, leading to high power consumption for heavy weights [1]. Additionally, weight interfaces using propeller propulsion produce substantial noise, that increases with the force generated. For instance, *Thor's Hammer* approaches critical noise exposure limits when simulating weights of 400 g [16, 23]. These issues could be mitigated by leveraging our finding and prompting weight interfaces to render a lesser weight than the accurate weight when simulating heavy objects.

Our findings regarding the relationship between visual mass and weight estimation error may be interpreted as consistent with the SWI. The SWI posits that the smaller of two equally weighted objects is perceived as heavier than the larger object, indicating that the weight of smaller objects is overestimated, whereas the weight of larger objects is underestimated [50]. Contrary, it can be argued that insights from the SWI can not explain our results, as our experiment, unlike the SWI procedure, involved participants adjusting the weight of the object to create their expected weight perception before making their decision. When participants lifted a large virtual object in our experiment, they would, according to the SWI, perceive it as lighter than expected. This would typically lead them to subsequently revise their choice and select a heavier weight to represent that large object. However, this would result in the overweighting of heavy objects, contrary to our observation of underweighting heavy objects. This discrepancy suggests that additional factors, beyond those accounted for by the SWI, affected the observed tendency to overestimate the weight of objects with lower visual mass while underestimating the weight of objects with more visual mass.

5.3 Effect of Weight Distributions

Moreover, we found that the position of the physical weight relative to the handle influences a virtual object's perceived heaviness. Participants chose heavier physical weights to represent the virtual objects, when the physical weight was at the top of the grip, compared to when it was at the bottom of the grip. This suggests, that objects with physical weight concentrated at the top were perceived as lighter than those with weight at the bottom. This insight allows designers of weight interfaces to adjust the perceptual weight range. Weight interfaces that are capable of rendering large weight ranges typically have a high empty weight [31, 39], which causes the user to feel weight despite no weight being rendered. Designing them to apply the weight at the top of the grip could make their empty weight feel lighter. Conversely, for light-weight interfaces with low weight ranges, conveying the weight at the bottom of the grip can amplify the perception of the provided weight. We found that the average object realism remained unaffected by the position of the physical mass within the objects. Consequently, designers of weight interfaces may prioritize extending the perceptual weight range and addressing practical aspects over the potential impact of realism when determining the optimal position for providing the weight force.

While our analysis revealed differences between the top and bottom positions of physical mass, findings concerning differences between the center and bottom or center and top positions were less clear-cut. Regression analysis indicated significant differences for all physical mass position contrasts, whereas Bayesian post hoc comparisons suggested anecdotal to moderate evidence against differences between the center and bottom or center and top positions. This outcome contrasts the established findings of Amazeen and Turvey [2] and Kingma et al. [36, 37], who demonstrated that objects with mass concentrated at the ends are perceived as the heaviest. However, it's important to note that their experimental setup involved manipulating weights along rods of 60 cm to 1 meter in length, whereas our study varied the physical center of mass by only 10.3 cm. This setup likely diminished the effect of the inertia tensor and static moment, which may explain the discrepancy to previous studies. Given these differences, more research is necessary to fully understand the weight perception of virtual objects beyond the tested object lengths and static moments.

As cognitive science [2, 36, 37] has established that the physical weight distribution is a dominant factor in the perception of heaviness, we expected the participants to choose different weights based on the visual center of mass of the objects. Interestingly, our Bayesian analysis showed extreme evidence for the absence of an effect of virtual objects' visual center of mass on the weight assigned to them. One possible explanation for this is that participants, aware that VR often utilizes simplified physical representations, such as static controllers, may have accepted the haptic stimuli as a simplified physical representation. Consequently, they might have discounted the visual center of mass when it did not align with the physical weight distribution, relying more on the absolute visual mass and haptic feedback instead. The absence of an effect of the visual center of mass further suggests that VR designers utilizing weight interfaces do not need to be overly concerned with the visual distribution of weight within an object when determining the weight to render. Instead, they can focus on the overall visual mass and the physical weight distribution to achieve the desired weight perception.

5.4 Limitations

It is important to note that our models were developed based on a study with only three levels of visual mass and three levels of physical mass position. We expect the performance of our models to decrease when dealing with extremely lightweight objects, as the ability to discriminate between fine differences in weight becomes less challenging with low mass [25]. Additionally, the performance of our models may vary for objects with weight significantly heavier than the tested levels of visual mass, where weight discrimination is inherently more difficult [25].

Moreover, it is crucial to acknowledge the potential for response style bias when working with samples of a single population. In a non-extreme response style bias, respondents tend to avoid extreme options of a scale (as opposed to an extreme response style bias, where participants tend towards the extreme ends) [40]. To counteract such possible bias, we extended the scale to include weights as response options (i.e. 100 g, 200 g, 1200 g, and 1300 g) beyond the range of visual masses tested, to encourage participants to consider a broader spectrum of responses. Hence, we do not assume that a sample bias modulated the tendency to avoid the scale ends when selecting weights. Nevertheless, we cannot rule out the presence of a non-extreme response style bias affecting the participants' selections.

Furthermore, weight discrimination can be affected by the specific actions being performed [30]. While our task was designed to explore an object's weight by lifting, wielding and hefting, the models developed may not fully generalize to other contexts or tasks involving different interactions with the objects. For instance, when hammering a virtual nail, users may adjust their finger positions to stabilize their grip when exerting effort, which could lead to a different judgment of heaviness.

In sum, further research is needed to validate and refine our models across a broader range of mass levels and positions. Additionally, future work should explore the applicability of the developed models across contexts that involve different types of interactions with virtual objects.

6 CONCLUSION

In this work, we investigated how variations in the absolute mass and center of mass of virtual objects affect users' perception of weight, in order to optimize the design and application of VR weight interfaces. In a study, 30 participants were tasked with assigning the mass they perceived as most realistic to a virtual object under 54 conditions, comprising 18 virtual object configuration tested with three different physical weight distributions. Participants tended to overweight lighter objects and underweight heavier ones, suggesting that rendering lighter weights can effectively simulate heavier objects, enhancing interface responsiveness, power consumption and noise while optimizing perceived realism. We also found that the physical position of weight relative to the users' grip significantly affects perceived heaviness. Objects with physical weight at the top were perceived as lighter than those with physical weight at the bottom. Interestingly, the visual mass center had no significant effect on weight perception, simplifying the design process for VR developers. Our findings offer practical guidance that can enhance the design and utilization of weight interfaces, creating experiences that more closely align with human weight perception. By leveraging our regression formulas to determine the weight to be rendered, future designers may more realistically simulate the weight of virtual objects. However, future research should aim to validate and refine this models by testing a broader range of mass levels and positions.

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