

Pseudo-Haptic Weight: Changing the Perceived Weight of Virtual Objects By Manipulating Control-Display Ratio

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Figure 1: An illustration of the Control/Display Ratio manipulation utilized in the experiment. The user is shown lifting an optically tracked cube with the corresponding virtual representation, the movements of which are a fraction of the user's movements.

ABSTRACT

In virtual reality, the lack of kinesthetic feedback often prevents users from experiencing the weight of virtual objects. Control-to-display (C/D) ratio manipulation has been proposed as a method to induce weight perception without kinesthetic feedback. Based on the fact that lighter (heavier) objects are easier (harder) to move, this method induces an illusory perception of weight by manipulating the rendered position of users' hands—increasing or decreasing their displayed movements. In a series of experiments we

demonstrate that C/D-ratio induces a genuine perception of weight, while preserving ownership over the virtual hand. This means that such a manipulation can be easily introduced in current VR experiences without disrupting the sense of presence. We discuss these findings in terms of estimation of physical work needed to lift an object. Our findings provide the first quantification of the range of C/D-ratio that can be used to simulate weight in virtual reality.

CCS CONCEPTS

- Human-centered computing → Mixed / augmented reality; Virtual reality; Haptic devices; HCI theory, concepts and models; User interface programming.

KEYWORDS

pseudo-haptics; multisensory integration; virtual weight

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1 INTRODUCTION

Fully immersive virtual reality (VR) presents many technical challenges in its effort to provide the user with believable and rich experiences. One of the biggest and potentially most vexing of these is the lack of kinesthetic (force feedback) cues. When one lifts an object, the stretch and elongation receptors in the muscles and tendons convey to the brain how much load is being placed on the musculoskeletal system as well as the extension and rotation of the limb. When a user grasps a purely virtual object—that is, an object that does not exist in the physical world, but which can be interacted with in VR—the arm does not receive kinesthetic cues, and moves without being encumbered by an additional mass. In the absence of kinesthetic feedback, therefore, other means need to be used to deliver the perception of “weight”.

This paper makes the following contributions:

- Formulating the weight perception problem in VR as a physical work estimation problem
- Proposing a method for simulating the weight of virtual objects by manipulating the control-to-display (C/D) ratio
- Reporting a series of experiments that quantify the relationship between C/D ratios and the perception of weight
- Providing a predictive model of weight perception for interaction designers

The primary appeal of this work is that it provides a principled way in which to design VR experiences that simultaneously achieves two goals: a) to give users a perceptual experience of the weight of virtual objects, and b) to preserve the sense of ownership over the virtual limbs as well as the overall sense of presence. Framing the model as the result of a work estimation process provides interaction and experience designers with a way to induce a directional modulation of perceived weight of virtual objects.

2 RELATED WORK

Rendering the weight of virtual objects constitutes a challenge for VR applications. Grounded haptic devices have been proposed as a solution to this problem. Such devices can deliver forces to users to simulate mass and weight of objects, and stiffness and damping forces. However, such haptic devices must be grounded on the floor, often have a limited workspace, and thus may not appeal to the average customer. These drawbacks clearly collide with the recent development of VR, which is becoming more ubiquitous and

affordable by the year, and which aims to continue to expand the usable virtual space with untethered devices.

Some authors have proposed body-grounded devices to provide haptics to users of VR, such as the elastic-arm device [1], the FlexiFingers device that utilizes passive haptics to create a sense of stiffness for virtual objects [2], among others [25]. Relatedly, Choi et al., have recently presented “Grability”, which is a body mounted device that provides combined kinesthetic and vibrotactile feedback simulating grip forces that are cleverly oriented to always point downwards and therefore can provide a sensation of weight [4]. Despite their appeal, body-grounded devices are encumbering and can limit the user’s naturalistic range of motion.

An alternative is provided by the so-called “pseudo-haptic feedback” [13]. In general, pseudo-haptic feedback induces the illusory perception of some haptic cue by introducing conflicts across the senses. For example, introducing an offset between the real and rendered position of the hand while pushing against a virtual object conveys the illusion of stiffness [14]. Similar methods have been shown to be effective in redirected walking [18, 22] and redirected touching [3, 11, 12].

Pseudo-haptics has also been proposed as a method to simulate the “weight” of objects [5, 9, 16, 19]. In the so-called *force-causes-displacement* metaphor [16], for example, the force that is desired to be simulated can be rendered by displacing the visual object upon which the force is made to have acted. In their study, Palmerius and colleagues used a simulated spring linked to a visual cursor that participants used to pick up several virtual cubes of varying implied mass [16]. The spring conveyed the mass of the cubes in the extent of stretching it underwent. Similarly, Jauregui and colleagues investigated three different methods for simulating weight lifting [9]. The most effective method was to manipulate the control/display (C/D) ratio between the body’s movements and the visual display of those movements. Dominjon and colleagues also used a manipulation of C/D ratio along with actual physical mass and observed a systematic modulation of participants’ perceptions of mass [5]. Nakakoji and colleagues used a similar method to create the sense of mass of objects interacted with on a computer screen [15]. However, none of these studies were conducted in virtual reality. This means that they did not include a first-person perspective and visible contact between hand and object, greatly limiting the naturalism of the interaction.

In fact, when introducing conflict between the real and the displayed position of the hand in VR, there is the non-trivial risk of breaking the embodiment/“sense of presence” of the users, spoiling their experience in the virtual environments [21]. Recently, Rietzler and colleagues [19] implemented an algorithm similar to C/D ratio manipulation, and found that users’ experience decreased in quality for large differences

between the positions of the real and virtual hands. Nonetheless, their paper constitutes a strong argument in favor of pseudo-haptic illusions as a means of rendering weight in VR.

Our method marks a substantial contribution in providing a high-resolution virtual hand that is tracked at the individual finger joint level, and gives a strong sense of embodiment [21]. We apply rigorous psychophysical methods in order to obtain a direct comparison between real and illusory weight, coupled with a model for the integration between proprioceptive and visual information. Finally, we discuss our results in terms of optimal observer and multisensory integration [8, 10] and devise a predictive model of the user’s experience [23].

3 CONTROL/DISPLAY RATIO MANIPULATION

In our study, we induced and modulated the perceived weight of objects by visually manipulating the control/display (C/D) ratio of the hand movements. Our method applies a gain on the limb’s rendered movements while grasping an object. The gain is inversely proportional to the weight of the virtual object that we wish to render. For example, if an object is intended to be perceived as heavy, we would set the C/D ratio to be <1 such that rendered movements are compressed (see Figure 2). The manipulation is applied to all 3 Euclidean components of the rendered movement, but in a weighted fashion such that the horizontal and depth movements received 65% of the manipulation of the vertical dimension, in order to approximate the combination of inertial and gravitational forces that act on real objects.

Collision detection was implemented by a custom function that detected when any of the nodes of the rendered hands came within 1 cm of any of the faces of the cubes. A collision event triggered the C/D ratio manipulation to begin, which applied a gain on the movements in accordance with the assigned value for that cube. This was achieved by numerically integrating instantaneous velocity, thus maintaining a running measure of the total distance moved while in contact with the object. This measure was multiplied by the desired C/D ratio—weighted by the 3 spatial dimensions—and was then used to apply an offset on the render location of both the virtual hand and the virtual cube. When the hand broke contact with the cube, if there was any residual offset that lead to the hand being rendered at a location different than its true location, the algorithm began a process of rapid reduction of the offset.

4 EXPERIMENT 1: C/D RATIO MANIPULATION AFFECTS WEIGHT PERCEPTION

In the first experiment, we investigated the use of visual manipulation of the C/D ratio for providing participants with an illusory sensation of increased or decreased weight

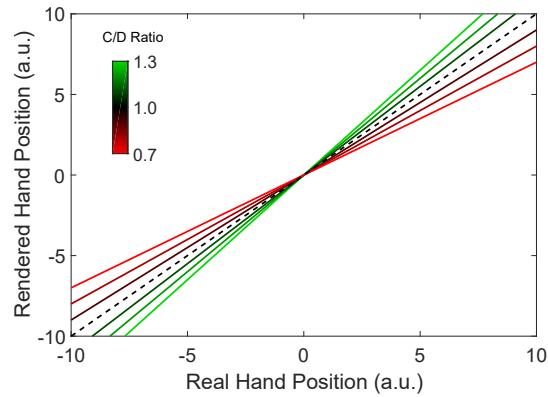


Figure 2: Manipulation of control/display ratio (C/D ratio). In this graph, we plot the rendered hand position as a function of the true hand position as measured by the optical tracking system. We depict the C/D ratio range from 0.7 to 1.3, which was the range tested in the experiment. The dashed line plots the identity line and represents the C/D ratio of 1, where there is no manipulation. a.u. signifies arbitrary units.

using qualitative and quantitative methods. The hypothesis was that the cube for which the C/D ratio was set to a value less than 1 would be perceived heavier than the cube with the C/D ratio set to a value greater than 1.

Participants

A total of 8 participants (age: $\{M = 29, SD = 8.4\}$, 3 female, 7 right handed) were recruited for this study from the general population. Study protocols and materials were approved by the Western Institutional Review Board and complied with the Declaration of Helsinki.

Apparatus

Materials for this experiment included a table measuring 100 cm by 60 cm and placed in the middle of a cubic aluminum cage with linear dimension of 183 cm. To capture and track participants’ movements, 17 cameras (OptiTrack Prime 17W, 1664x1088 pixels, 70 degree FOV, 120 FPS, 2.8 ms latency) were mounted to the cage. Additionally, a regular camcorder was also attached to the cage at a location that had optimal viewing angle of the participants’ hand movements and was used to record audio and video of the entirety of the interview process. The virtual environment consisted of a virtual replica of the real table that was co-located with it and displayed on a head-mounted display (HMD; Oculus Rift, 2160x1200 pixels, 110 degree field-of-view, 90 Hz refresh rate) marked by a unique three-dimensional arrangement

of fiducial markers on its upper surface allowing for head tracking using the OptiTrack motion-capture system. Participants wore a pair of flexible powermesh tracking gloves that were fitted with 19 fiducial markers each to enable hand tracking [7]. Two wooden cubes with linear dimension 6.23 cm and mass of 185 g each that were also each marked on the upper surface with a unique three-dimensional arrangement of fiducial markers for motion tracking were also used (see Figure 3a). The cubes were represented in the virtual scene as white and black cubes that were co-located with their physical counterparts and which participants could interact with by grasping with virtual hands that were also co-located with their own hands (see Figure 3b). These cubes were selected because their mass coincides approximately with the mass of consumer handheld VR controllers.

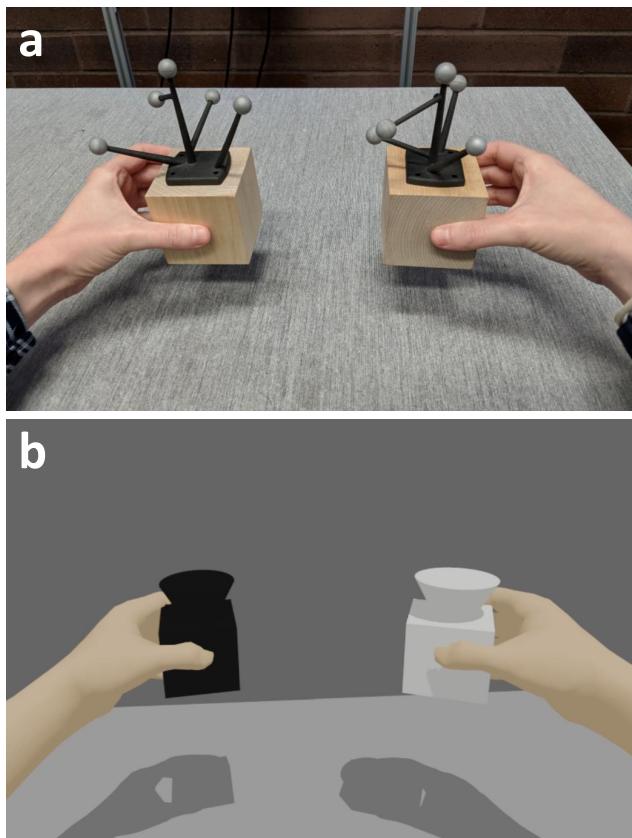


Figure 3: Experiment 1 Methods. a. The wooden blocks that participants interacted with. Participants wore custom motion capture gloves not pictured here. b. The virtual representation of the cubes that participants interacted with. The conical shape on their upper surface was included to match the tracking markers that were present on the physical cubes.

Procedure

The first experiment used a mix of qualitative and quantitative research methods. As we were interested in determining whether our method would manipulate the weight perceived by participants, we opted for a design that minimized observer-expectancy effects. Specifically, we allowed participants to freely explore the cubes guided by a few motion constraints. If participants experienced a phenomenology of weight, they should spontaneously report it even if not cued to do so by any explicit questions to that effect. Conversely, if their free, uncued reports did not contain any reference to the phenomenology of weight, then we would have to revise our expectations regarding the potential use of this method.

The entire experimental session was recorded in audio and video to support the qualitative research methods that are described below. Additionally, participants' hand positions and those of the two cubes were recorded during the entire experimental session using the motion capture system.

Free Exploration. The first phase of the experiment consisted of presenting one black and one white virtual cube (see Figure 3b) and allowing participants to freely explore them. Note that participants were not allowed to see the real physical cubes before the beginning of the experiment to minimize expectancy. The virtual cubes received opposing C/D ratio manipulations such that one of them had a C/D ratio of 1.25 and the other had a C/D ratio of 0.75, counterbalanced across participants. Thus, for half of the participants, the black cube was manipulated to feel heavier than its true weight and the white cube was manipulated to feel lighter, and vice versa for the other half.

The constraints on the movements that participants could make while holding the cubes were as follows. They were not permitted to grasp them from the top so as to avoid them touching the fiducial markers (see Figure 3a). They could not use two hands to grasp a single cube because of the offset that would have been accumulated for the hand that had picked it up from the table, and the lack thereof for the newly grasping hand, which would lead to a differential visual-proprioceptive incongruence across the hands. Nevertheless, they were encouraged to repeatedly swap which hand was holding each cube to get a better sense of the differences between them. Finally, they were advised to pick up the cubes and lift them up to eye-level and then set them back down. This was to allow enough of the offset to accumulate to make the desired effect apparent, as it was noticed in pilots that participants preferred to keep them in their hand and look at them without moving them.

During this phase, participants were instructed to vocalize freely anything they noticed or any thoughts that arose. After they had explored the cubes for a couple of minutes, a short interview was conducted while they continued to interact

with the cubes. They were asked questions such as: “How do the two cubes compare to each other?”, and “Was there any difference in the way they behaved or reacted to you?”. If they spontaneously mentioned anything relating to the perceived weight of the objects, they were probed to follow up by saying more about their specific feeling.

Following this phase, a short psychophysical experiment was conducted, described below. After that, participants could take a break and were debriefed about the manipulation and allowed to see the physical cubes. At this point, they were told that the cubes had identical mass. Then, they were instructed to freely explore the black and white cubes again in VR exactly as before, but this time were specifically probed to report on whether the effect persisted despite their knowledge of the fact that the cubes were physically identical. Again, they were instructed to freely report on any other insights they might have had while freely exploring.

Weight Discrimination Task. To determine the robustness of the illusion of weight in a psychophysical task and in order to quantify the relation between the C/D-ratio and the illusion, we administered a weight discrimination task in between the two free exploration phases mentioned above. Here, participants performed a 2-alternative forced choice experiment where they compared a randomized sequence of pairs of gray cubes and selected the heavier one. The cubes that participants held were the same physical cubes as before and therefore always had the same physical mass. However, the C/D ratio was manipulated across trials ($N = 24$) such that one cube (the standard stimulus) always had a C/D ratio equal to 1 while the other cube (the comparison stimulus) could take one of the following values: 0.7, 0.8, 0.9, 1.1, 1.2, 1.3. The virtual cubes were both textured with a gray color making them visually indistinguishable, thus avoiding any possible confounding effect of a crossmodal correspondence between color/luminance and weight [17].

Trials started with participants placing the two cubes at marked positions indicated as the starting positions on either side of the table. The virtual cubes then disappeared briefly and reappeared; participants were instructed to treat the newly appeared cubes as entirely new and not to respond with the same cube on each trial. The cube that was assigned a C/D ratio of 1 was counter-balanced across trials to ensure that there was equal proportion of trials where the left cube was heavier and trials where the right one was heavier. They were then instructed to lift the cubes and make the same sort of motion described above: pick them up, bring them to eye-level, set them back down. They were to place the cube that felt heavier in a newly marked position indicated as the response position in the center of the table.

Questionnaire. Following the second free exploration phase, participants were asked to fill out a questionnaire that was

implemented in the software and administered the questions shown in Table 1. Participants could respond along a continuum ranging from “strongly disagree” to “strongly agree”, using a slider that they could adjust with the thumb-stick on the right touch controller. The order of presentation of the questions was randomized. The questionnaire was composed of 14 questions, divided into three topics: weight, limb ownership, and object believability. Each topic had some diagnostic items and one or more control items, which were included to control for suggestibility and observer-expectancy effects. Importantly, participants were asked to respond with their level of agreement for the statements related to their average experience during the free exploration phases only and not to think about their experience during the weight discrimination task.

	Category	Abbrev.	Question
Weight		Wf	One cube felt heavier in my hand than the other.
		Wv	One cube visually appeared heavier than the other.
		Wcon1*	One cube felt warmer than the other.
		Wcon2*	Disregarding their color, the cubes felt like they were made of different materials.
Limb Ownership		LO1	The virtual hands appeared in the same location as my hands.
		LO2	The virtual hands seemed to belong to my body.
		LO3	Grasping the cubes made my hands not feel like my own.
		LO4	I could touch the cubes using my hand.
		LOcon*	My hands felt like they were becoming virtual.
Object Believability		OB1	The cubes that I grasped were not the same cubes that I saw.
		OB2	The cubes that I saw were always in the same location as the cubes that I felt.
		OB3	My interaction with the cubes felt natural.
		OB4	The cubes were believable.
		OBcon*	The cubes were immaterial or ghostly.

Table 1: Questionnaire administered at the end of the experiment. Items marked with an asterisk were included as controls.

Results

Qualitative Analysis. The whole session was recorded, transcribed, anonymized, and coded by two different coders. Coders agreed beforehand on the main categories of interest in which participants comments were more likely to fall, but were unaware of each other's ratings. When necessary, coders were allowed to add a category to the list.

The following categories were selected and encompassed all participants' comments: comments on tracking quality, comments on visual rendering, perceived weight and movement, comments on the overall experience, and cognitive effects of the experience. Each category was further divided into a number of sub-categories to better represent participants' comments. Figure 4 shows the five main categories and relative sub-categories (blue, on the left), including an example from each sub-category (green, on the right).

Haptics		Visuals	
Perceived Weight	"this one feels heavier"	General Visibility of the Scene	"the images get blurry at eye level"
Perceived Work/Effort	"it is easier to make movements with the lighter cube"	Visibility of the Upper Part of the Objects	"the upper part of the object is hovering on top"
Perceived Movement	"this one looks lighter because it moves faster when I lift it"	Weight Appearance (e.g. looks heavier/lighter)	"the color black suggests the cube is heavier"
Perceived Fatigue	"the repetitive motions made my arm tired"	Size	"they look the same size"
Tracking		Cognitive	
Object Tracking	"one object is glitchier"	Realism	"they look how they feel"
Hand Tracking	"it is very fluid"	Expectations	"I expected them [the objects] to have the same weight"
Experience		Interpretations	"the cubes have physically different weights"
Positive	"this is cool"	Materials	"the heavy one felt denser"
Negative	"this is freaky"		

Figure 4: The five main categories used for the coding of the interviews during Experiment 1 and the sub-categories they were divided into, with some example statements.

Coders assigned a score to each sub-category. The score reflected, for each participant, the number of times a comment was expressed that fell into the categories. However, if the same concept was reiterated twice, the two comments were counted as one. For example, if the same participant commented on the category "Haptic: weight" as: "the dark [cube] felt heavier during the first exploratory phase", and "the dark [cube] felt heavier during the second exploratory phase", the comments were counted as separate comments in the category "Haptic: weight". On the contrary, comments such as: "the dark [cube] felt heavier during the first exploratory phase" and "the white [cube] felt lighter during the first exploratory phase" were counted as one, as they reiterated the same concept. Scores between coders were then added. Results are reported in Table 2.

Comments regarding the perceived haptic properties of the objects were predominant throughout the experiment.

Category	Sub-category	Count
Haptics	Weight	71
	Work	11
	Movement	39
	Fatigue	2
Tracking	Object Tracking	11
	Hand Tracking	17
Visuals	Visibility of the scene	13
	Upper part of the object	4
	Weight Appearance	6
	Size	16
Experience	Positive	20
	Negative	4
Cognitive	Realism	9
	Expectations	8
	Interpretations	16
	Materials	21

Table 2: Qualitative interview analysis of participants' utterances during the free exploration part of the experiment.

Often participants referred to different cubes as if they were made of different materials ("...the heavier one feels like marble, or concrete or rock..."). No visual difference in size was reported by participants ("...they look the same size to me..."). Noteworthy, participants were particularly pleased by the quality of the hand tracking, and by the overall experience ("this is so cool...").

Notably, four of the eight participants spontaneously made mention of any weight differences between the cubes during the first Free Exploration phase. This number increased to seven of the eight during the second Free Exploration phase and after the participants were cued as to the nature of the manipulation and were asked explicitly about weight.

Weight Discrimination Task. Responses to the weight discrimination task were analyzed to reflect the proportion of trials on which the comparison stimulus was reported to be heavier than the standard stimulus as a function of the C/D ratio of the comparison stimulus (shown in Figure 5). What is notable in these data is that participants could discriminate the implied weight differences despite the fact that the two cubes had identical physical mass. We also fit a psychometric function to these average responses (also shown in the figure). The slope was found to be negative and significantly different from 0, indicating that the increases in the C/D ratio reduce perceived weight. To our best knowledge, this represents the first psychometric function showing the relationship between C/D ratios and the illusion of weight.

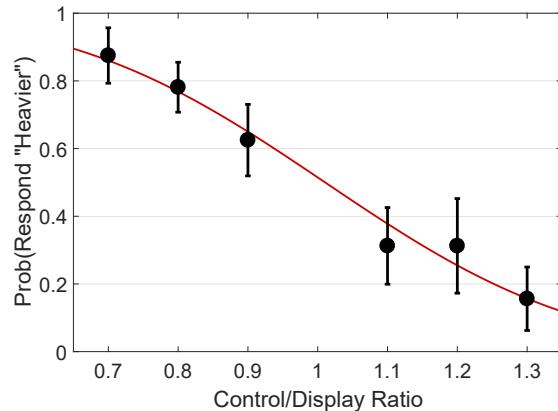


Figure 5: Psychometric function showing the probability of reporting that the comparison cube felt heavier than the standard cube (C/D ratio = 1) as a function of the C/D ratio. The plotted line in red is the fitted psychometric function.

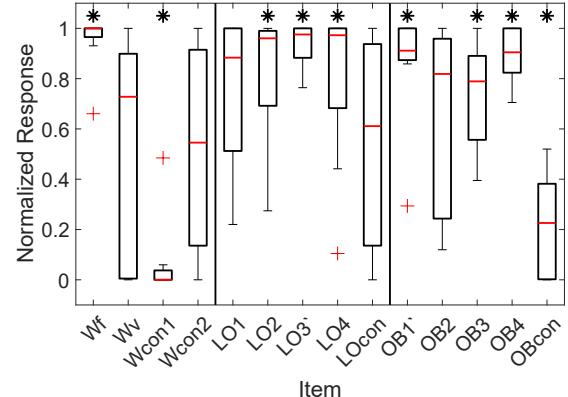


Figure 6: Responses to Questionnaire, grouped by category in accordance to Table 1. Asterisks indicate median is significantly different from 0.5 according to the Wilcoxon signed-rank test, and plus signs represent outliers.

Questionnaire. First, responses to the questionnaires were aggregated across subjects. Here, because items LO3 and OB1 were worded in the negative, they were inverted by computing $LO3' = 1 - LO3$, and $OB1' = 1 - OB1$. The aggregated responses were then analyzed by using a Wilcoxon signed-rank test. We tested whether the median differed significantly from 0.5, which would have indicated a neutral response. These data are plotted in Figure 6, and the asterisks indicate the items that were found to be significantly different from 0.5. As can be seen in Figure 6, ratings on all LO and OB items were significantly different from 0.5, except those that referred to locations (Items LO1 and OB2; the cubes/virtual hands I saw were at the same location as the cubes I felt/my hands).

For the weight items, ratings on the item stating that one of the cubes felt heavier than the other (Item Wf) were significantly different from 0.5, whereas the item stating that one of the cubes visually appeared heavier than the other (Item Wv) produced a much larger variety of ratings that were therefore not significantly different from 0.5.

Discussion

To summarize, this first experiment was aimed at replicating the effects of C/D ratio manipulation reported in the literature, and to evaluate the extent to which these effects may be used to simulate the sensation of the weight of virtual objects. To that end, we modulated the control/display ratio of the movements of participants' hands—and the motion tracked physical cubes they held—while they lifted the cubes. When the C/D ratio was smaller than 1, this resulted in the

compression of these movements, and when it was larger than 1 the motion was amplified.

Before participants were cued to report any phenomenology of weight, four out of the eight participants spontaneously reported that one cube felt heavier than the other. After having experienced the effect longer and then being asked specifically about weight, that number increased to almost all participants, or seven out of eight. This gives an indication that the modulation of perceived weight may be more than just metaphorical, as has often been assumed, but rather a perceptual effect. Adding support to this is the large number of mentions of weight-related statements, as shown in Table 2.

As regards the results of the weight discrimination task, shown in Figure 5, participants consistently judged the object with a C/D ratio less than 1 to be heavier than an unmanipulated object for the more extreme, and thus easier, comparison stimulus levels.

Therefore, making use of both qualitative and quantitative methods we have provided converging evidence of pseudo-haptic feedback as a cue to the weight of virtual objects. Given these promising results, we next wanted to quantify the effect of C/D manipulation on perceived weight. Thus, we conducted a second experiment where participants estimated the weight of a cube that was subjected to this C/D ratio manipulation.

5 EXPERIMENT 2: QUANTIFYING C/D RATIO MANIPULATION OF ACTUAL WEIGHT PERCEPTION

In this experiment, for the first time in VR, we performed a direct comparison between illusory and actual weight. In particular, we show that pseudo-haptic feedback can lead to overestimation or underestimation of real weight. We discuss the results in terms of multisensory integration and argue for a new perspective in explaining this particular effect, delivering a predictive model that starting from the notion of physical work explains how mass gets overestimated or underestimated as a function of C/D ratio.

Participants

We enrolled 14 participants from the general population using ads placed by recruitment agencies (age: $\{M = 34.4, SD = 9.3\}$, 7 female, 12 right handed). Study protocols and materials were approved by the Western Institutional Review Board and complied with the Declaration of Helsinki.

Apparatus

Materials for this experiment were the same as in Experiment 1 but also incorporated a PHANTOM force feedback device, with a small foam cube (linear dimension = 5 cm) affixed to its end effector (see Figure 7a).

Procedure

To assess the extent to which C/D ratio manipulated the perception of weight, we used a method of adjustment where participants directly reported the weight of the cube under that manipulation. To do so, they adjusted the mass simulated by the PHANTOM until it matched the mass of the physical cube. They used two virtual buttons rendered on the table's surface to either increase or decrease the PHANTOM's simulated mass in increments of 10 grams, and a third one which they used to record their response. The control/display ratio manipulation was applied to the cube across 7 different levels: $\{0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3\}$, and each was repeated 12 times, in a randomized order.

On a given trial, participants had 25 seconds to make the adjustment, and did so as follows. They first grasped and lifted the physical cube vertically with the right hand to a height of 20 cm that was specified by a visual marker in the virtual scene. The marker changed color to a dark shade of blue to indicate that they had fulfilled the requirement to lift the cube to that point, as shown in Figure 7b. Then, with their left hand they picked up the foam cube that was attached to the PHANTOM—they were guided by the experimenter to this foam cube at the start of the experiment and kept their left hand continuously grasping it as there was no visual representation of it. They then used their right hand to click

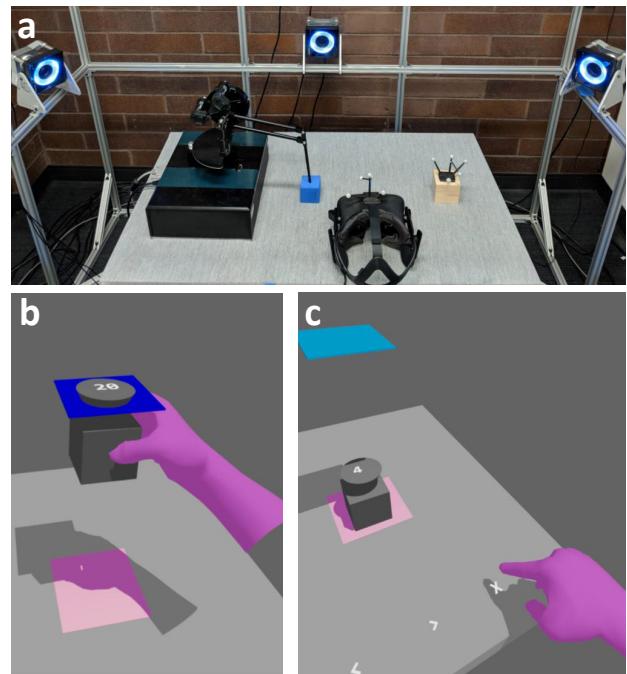


Figure 7: Experiment 2 Methods. a. The tabletop setup showing the PHANTOM on the left, the Oculus Rift HMD in the middle, and the wooden block on the right. b. The virtual scene from the perspective of the participant as they lift the cube towards the floating visual marker (in blue). c. The participant interacting with the three virtual buttons used for adjustment of the force delivered by the PHANTOM. The numbers displayed on the top side of the cube show the remaining time to complete the trial in seconds.

on the virtual buttons on the table (see Figure 7c) increasing or decreasing the mass simulated by the PHANTOM until it matched the mass of the physical cube. The starting mass was randomly chosen to either be 70 grams heavier or lighter than what they perceived the cube's mass to be when the C/D ratio was set to 1, which was determined in a pretest phase of the experiment for each participant (see below for the details of this procedure). Participants were instructed not to lift the PHANTOM's cube in synchrony with the physical cube so as to minimize direct comparisons of the lift height, and to instead direct their attention to the perceived mass itself.

After registering their response, there was a mandatory timeout of 12 seconds in between trials, to ensure that the PHANTOM did not overheat. If the participant failed to provide a response within the allotted time, the trial repeated itself after the timeout. There were six 1-minute breaks during the experiment.

Participants were able to adjust the mass simulated by the PHANTOM within a range defined based on their own estimation of the physical cube's mass. They completed 16 practice trials with no C/D ratio manipulation (i.e., it was set to 1). The mean reported mass on the last 12 of these trials was used to define the range, such that a range of 140 grams was centered around the participant's mean.

After the trials were completed, participants were asked to respond to a shortened version of the questionnaire used in Experiment 1 (see Table 1). The questions were changed to the singular form as in this experiment there was only one cube, and the questions assessing weight comparisons between the cubes were removed, leaving just those questions assessing the feelings of limb ownership and object believability.

Model of Physical Work and Multisensory Integration

We conducted a principled analysis of the modulation of perceived weight that is produced by manipulation of the C/D ratio—a manipulation that has the consequence of changing the distance that the user's arm must move in order to achieve a target extent of movement in the virtual scene. Thus, in seeking a natural connection between displacement and mass, we made use of the notion of work from physics, which provides a direct relationship between the two.

First, we begin by assuming that the hand moves vertically in a straight path while grasping the cube. Assuming that the path begins and ends in stationary points—i.e., points at which the kinetic energy is zero, the work done, W , is simply calculated as the change in potential energy. Thus, it is a function of the change in height, h , the mass of the hand and grasped cube, m , and the constant of gravitational acceleration, g .

$$W = m \times g \times h \quad (1)$$

Let us first consider the situation from the perspective of the physical reality. In the experiment described in this paper, participants were required to lift the cube until its rendered position was level with a floating visual marker that was placed 20 cm above the surface of the table. Therefore, participants moved their actual hands by $0.2/\lambda$ meters, where λ represents the control/display ratio. Let us call this true hand trajectory h_{prop} , signifying that the sensory signal arrives to the nervous system via the proprioceptive modality. We similarly call the proprioceptive sensation of the mass of the cube m_{prop} . Equation 1 can be amended to calculate the physical work done by the participants' arms, as follows.

$$W = m_{prop} \times g \times h_{prop} \quad (2)$$

Although the hand's true trajectory covered a distance of $0.2/\lambda$ m, the virtual hand would have moved a distance of 0.2 m visually. As it is known that signals from proprioception

and vision are integrated [6], this implies that participants will perceive their arm to have covered a distance that is a weighted combination of the two, namely

$$h_{per} = \alpha h_{prop} + \beta h_{vision} \quad (3)$$

$$= \alpha(0.2/\lambda) + \beta \times 0.2 \quad (4)$$

with α and β denoting the proprioceptive and visual combination weights, respectively, and constrained such that $\alpha + \beta = 1$. Note that this assumes that the two cues are always integrated, a scheme known as Forced Fusion [8] (but see [20, 24] for alternative approaches).

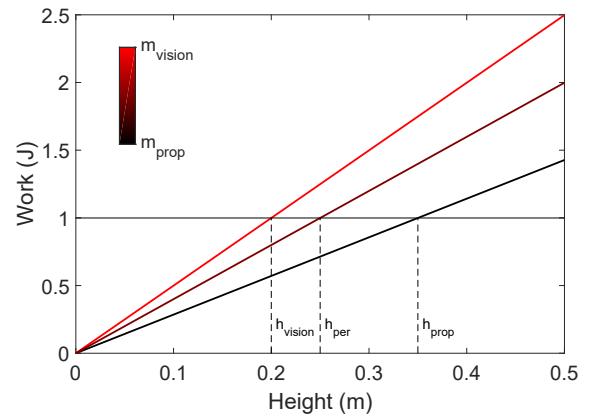


Figure 8: A schematic simulating the modeled relationship between work, mass, and height of the cube lift. We assume that the nervous system estimates work from the proprioceptive signals, h_{prop} and m_{prop} (black horizontal line). That estimate of work is then used in conjunction with the perceived height, h_{per} , of the lifted cube in order to infer the perceived mass, m_{per} , of the cube (the slope of maroon colored line). h_{per} is obtained by multisensory integration of the proprioceptive and visual signals. Values used in this simulation were chosen for clarity of the illustration and do not represent our choice of experimental values.

Similarly, the perceived mass, m_{per} , will be a multisensory percept that emerges based on the inference regarding the total amount of work done (equation 2), and the perceived distance moved by the hand (equation 3).

$$m_{per} = \frac{W}{g \times h_{per}} \quad (5)$$

Equation 5 represents the core of the model we are here proposing as it relates weight perception to displacement via the estimation of the work done by the arm.

Substituting and rearranging the equations above,

$$m_{per} = \frac{m_{prop} \times h_{prop}}{h_{per}} = \frac{m_{prop} \times 0.2/\lambda}{\alpha(0.2/\lambda) + \beta \times 0.2}$$

Finally, we arrive at the form relating perceived mass to the optimal integration weights.

$$m_{per} = \frac{m_{prop}}{\alpha + \beta\lambda} \quad (6)$$

Results

Perceived Mass. We first analyzed perceived mass by looking at the mass that participants adjusted in the PHANToM as a function of C/D ratio. We found that perceived mass of the cube was systematically affected by the C/D ratio manipulation such that lower values of C/D ratio caused the cube to be perceived as heavier and vice versa for higher values (see Figure 9).

This was further analyzed in accordance to equation 6 by fitting its 2 parameters (m_{prop} and α ; note that $\beta = 1 - \alpha$) to the data at a group level. We obtained very good fits to the data ($R^2 = 0.93$; see model fit in Figures 9 and 10). To the best of our knowledge, this is the first model of pseudo-haptic weight that gives designers the ability to predict the effect of C/D ratio on the perceived mass, provided comparable assumptions and methods are used.

$$m_{per} = \frac{0.08\text{kg}}{0.82 + 0.18\lambda} \quad (7)$$

Examination of equation 7 shows that the optimal integra-

for vision. This indicates that participants are indeed combining information across modalities when forming their estimates of weight. Interestingly, it seems that participants weighted the signal from vision substantially less than the one from proprioception. This may indicate that proprioception generally provides the more reliable cue to the weight/mass of an object. In addition, it may indicate that participants noticed that the virtual hand and cube are not completely faithfully co-located at all times with the real hand and cube, and therefore discounted the information from the visual channel.

As our primary interest was to uncover the relationship between weight and the underlying work estimation process—a process that relies on the perception of the height change when lifting objects, we next analyzed the relationship between perceived mass and the height. Since participants always lifted the physical cube to the same visual marker that was at a height of 20 cm, their real hands moved by an amount that is equal to 20 cm divided by the C/D ratio. We replotted the data shown in Figure 9 as a function of this true height change (Figure 10). This figure shows that a 5-10 cm height difference between the real and virtual hand movements corresponds to about a ± 5 g difference in mass estimation. While the figure appears to suggest that the perceived mass change grows to $-\infty$ when the physical height of the lift is reduced to 0 cm, such a large discrepancy between the movements of the real and virtual hands must cause the illusion to break down at some point.

Finally, we combined the data from Experiment 1 (Figure 5) and the data from Experiment 2 (Figure 9) to assess how the modulation of perceived mass measured in Experiment 2 relates to the psychophysical discriminability measured in Experiment 1. To do so, we used the mapping function observed in the second experiment (equation 7) to convert C/D ratios to their equivalent mass modulations in grams, and then replotted the data and psychometric function from the weight discrimination experiment as a function of the mass modulations (Figure 11). This analysis revealed that the ± 5 g mass modulation corresponds to 1.55 units of just noticeable difference. Despite the mass difference being small, it is more discriminable than would be expected if the manipulation was purely experienced as mass; it is less than the Weber fraction for this reference mass. Therefore, it is possible that there are other perceptual factors and/or cognitive biases that are involved to make these cues more salient, and allow for more subtle discriminations of mass to be possible.

Questionnaire. To analyze the responses to the questionnaire, we conducted a Wilcoxon signed-rank test to compare them against the null hypothesis that they were sampled from a distribution with median equal to 0.5. For the Limb Ownership items, participants rated items LO1, LO2, LO3', and

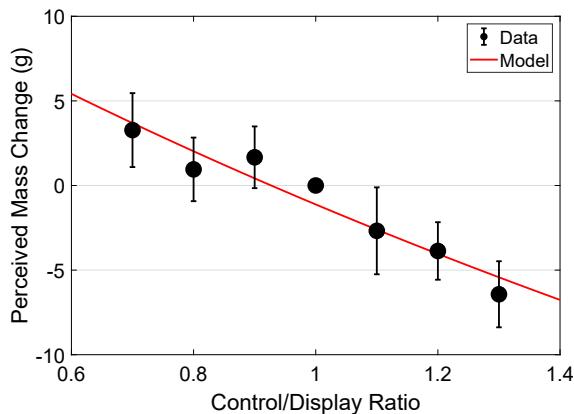


Figure 9: Perceived mass of the cube in grams as a function of the control/display manipulation applied.

tion weights for the combination of visual and proprioceptive height are $\alpha = 0.82$ for proprioception and $\beta = 1 - \alpha = 0.18$

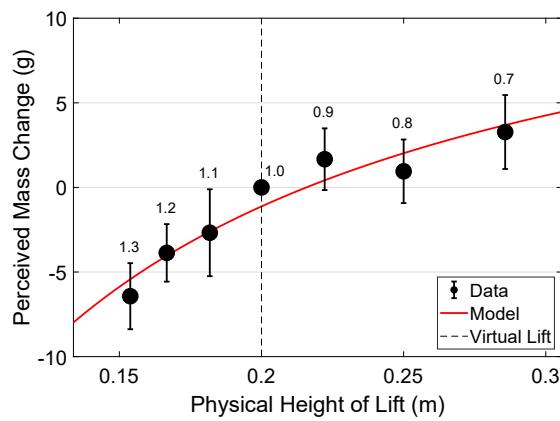


Figure 10: Perceived mass of the cube in grams as a function of the height of the lift performed in physical space. The vertical dashed line represents the height reached by the virtual hand (20 cm) and is added for clarity and to emphasize that the x-axis represents the height reached by the physical hand, and that data points away from the vertical dashed line represent greater discrepancies between the real and rendered movements. The numbers above each data point represent the C/D ratio corresponding to that height.

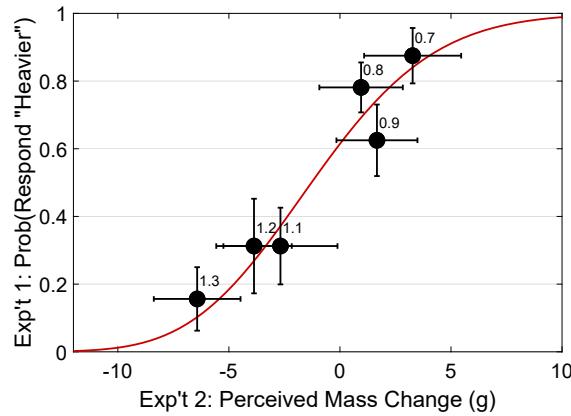


Figure 11: Discrimination results from Experiment 1 plotted against the equivalent perceived mass modulation from Experiment 2 (calculated using equation 7) for each C/D ratio tested. The numbers above each data-point represent the C/D ratio corresponding to that stimulus.

LO4 significantly higher than 0.5 indicating that they felt a sense of ownership for the virtual limb and perceived it as the same location as their own limb. In regards to the Object

Believability items, participants rated all diagnostic items significantly higher than 0.5 indicating that they believed that the cube was at the same location where they felt it and that the interaction with it was believable. They rejected the claim that the cube was immaterial or ghostly. Figure 12 plots these results.

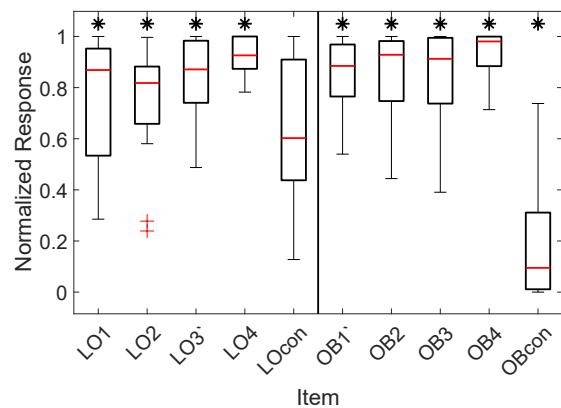


Figure 12: Responses to Questionnaire. Asterisks indicate median is significantly different from 0.5 according to the Wilcoxon signed-rank test, and plus signs represent outliers.

Discussion

In conclusion, C/D ratio manipulation produces a change in the perceived mass—and hence, weight—of a cube as measured by estimates of mass provided by participants who used a PHANTOM force feedback device to report the mass they perceived. This phenomenon can be explained as a perceptual illusion resulting from the integration of conflicting visual and proprioceptive signals regarding the displacement of the hand and its virtual representation.

6 GENERAL DISCUSSION

This paper examines the influence of pseudo-haptic feedback on mass and weight perception in virtual reality. In our investigation, we frame the problem of weight in VR as a process of estimation of work done by the user's arm. Then, we describe two experiments that collectively: a) establish that dissociating the movements of the real and virtual arms through control/display ratio manipulation is an effective way to manipulate the perceived weight of virtual objects; and b) propose a predictive model that captures this manipulation.

In the past, the effect of C/D ratio on weight has been interpreted as a metaphor—a way to communicate different

weights [16]. Here we replicate the results from the literature, and build on them substantially by applying a psychophysics-based methodology to quantify the effect of the illusion on lifting real objects. Moreover, starting from the notion of physical work, we interpret our results from the perspective of multisensory integration, shedding new light on the mechanism underlying the illusion. In fact, our results suggest that—at least for the range of C/D ratio we tested—this illusion is not a metaphor. Rather, we provide evidence that it may actually be a perceptual bias induced by the integration of conflicting sensory signals regarding the movements of one's own arm.

These results have application potential as they provide a tool to render mass in VR by simply changing the user's visual feedback. By using our model (see equation 7), designers can directly affect the perceived weight of a virtual object in a systematic way. This is particularly useful in modern VR applications since users are almost always holding controllers in their hands as they interact with the user interface. The intrinsic weight of the controller—which in most cases is close to the weight of the cube used in this study—can be modulated by changing the C/D ratio thereby making purely virtual objects seem to have more or less weight.

Nevertheless, it is a limitation of the current study that we made use of only one reference mass, namely 185 g. However, that particular mass was chosen because it is representative of many conceivable interactions as it is near the mass of consumer VR handheld touch controllers. In particular, since most interactions in VR in the near future will be performed using the handheld controllers, which have a mass near our reference mass, the model presented here and the range of manipulations described will be appropriate for modulating mass of virtual objects interacted with while grasping the controllers.

Our method might have some relevance also for situations where the user is not holding any kind of proxy object such as a controller. Indeed, the human arm itself is a mass that is in principle capable of being modulated under the current framework of work estimation. Future studies should investigate the extent to which this method is applicable for objects that are purely virtual, and when the user is just using their bare hands to interact with them.

These results nicely complement recent research showing that an ungrounded gripper-style device can be used to simulate the weight of virtual objects by providing a combination of finger joint kinesthetic feedback through the use of brakes and vibrotactile stimulation [4]. As the C/D ratio manipulation approach presented here fills the gap with regard to arm kinesthetics, in combination with the approach of Choi et al. [4], we hypothesize that the result would be very compelling.

Finally, we would like to comment on another limitation of this method, namely that the size of the perceived mass

modulation is relatively restricted. Indeed, we find that a reference mass of 185 g can be modulated by ± 5 g under conditions that induce hand displacement differences of 5–10 cm. Though this appears to be a rather circumscribed effect in absolute mass terms, it is strongly systematic and robust across participants. Moreover, considering the results of both Experiments 1 and 2, we find that these implied masses are highly discriminable, indicating that pure consideration of the perceived mass modulation may not reveal the whole story. At the very least, this method promises to be able to give directional manipulations of a reference mass that can add a layer of believability onto interactions with virtual objects not otherwise possible.

7 CONCLUSION

This research advances the ability to create immersive and believable VR experiences, specifically by providing a method for rendering objects in a way that manipulates their weight that users can feel. Many games include the manipulation of virtual objects, but this is always slightly frustrating due to the lack of a sensation of force that the user expects these objects to exert back. As much as we can simulate such forces without the need for large and specialized hardware to provide them, this will allow VR games and experiences to become that much more appealing and accessible to a large user base.

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