Continuous VR Weight Illusion by Combining Adaptive Trigger Resistance and Control-Display Ratio Manipulation

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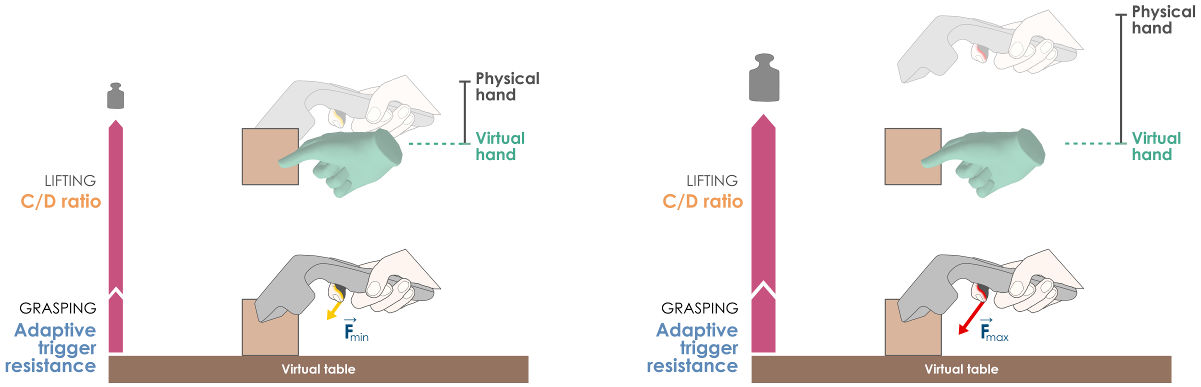

Figure 1: To simulate a continuous VR weight illusion, we apply a combined rendering technique: Adaptive trigger resistance during grasping (phase 1) and manipulation of the control-display ratio (C/D ratio) during lifting (phase 2).

ABSTRACT

Handheld virtual reality (VR) controllers enable users to manipulate virtual objects in VR but do not convey a virtual object's weight. This hinders users from effectively experiencing lighter and heavier objects. While previous work explored either hardware-based interfaces or software-based pseudo-haptics, in this paper, we combine two techniques to improve the virtual weight perception in VR. By adapting the trigger resistance of the VR controller when grasping a virtual object and manipulating the control-display (C/D) ratio during lifting, we create a continuous weight sensation. In a psychophysical study (N=29), we compared our combined approach against the individual rendering techniques. Our results show that participants were significantly more sensitive towards smaller weight differences in the combined weight simulations compared to the individual methods. Additionally, participants were also able to determine weight differences significantly faster with both cues present compared to the single pseudo-haptic technique. While all three techniques were generally valued to be effective, the combined approach was favoured the most. Our findings demonstrate the meaningful benefit of combining physical and virtual techniques for virtual weight rendering over previously proposed methods.

Index Terms: Human-centered computing—Virtual reality; Human-centered computing—Haptic devices

1 INTRODUCTION

Haptic feedback techniques for virtual reality (VR) aim to let users explore haptic qualities of a virtual object, usually supported through perceptual exploration during the interaction [23]. However, the feedback of consumer VR systems is still mostly limited to vibrotactile cues to substitute the diverse haptic sensory signals. Kinesthetic and cutaneous perceptions, such as those of an object's weight, are not convincingly conveyed since our natural weight sensation relies on the muscles, tendons and receptors in the skin [6, 26, 28]. Hence, the absence of meaningful haptic cues in VR deprives users of the ability to differentiate between lighter and heavier objects. This limits a natural and realistic user experience of haptic object properties.

As a response, weight simulation of virtual objects has received increasing attention in the research community, exploring various approaches that employ a haptic device that often requires instrumentation of the user and/or the interaction device [8, 13, 27, 29]. However, approaches with only minimal adaption (or none) of existing VR controllers constitute an opportunity to introduce haptic weight perception to the consumer market. Recent work [43] proposed a haptic VR controller *Triggermuscle* that adapts the resistance of the trigger button to simulate different levels of weight during the interaction in VR. The adaptation of resistance provides cutaneous cues [24, 28] by mimicking the variations in grasping forces encountered when interacting with physical objects of different weights. However, the findings show that the effect did not apply to 8 out of 21 users. As the resistive force is primarily presented during pulling the trigger, we hypothesise that the weight illusion was noticeable while grasping a virtual object (phase 1), but might have broken after lifting the object upwards (phase 2) due to a lack of further weight-related cues. To overcome this limitation and achieve a continuous weight illusion, additional weight cues could be presented during the lifting phase. A technique simulating weight immediately upon and throughout lifting (phase 2) is, e.g. the pseudo-haptic approach of manipulating the control-display ratio (C/D ratio). The technique applies a gain on

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users' physical arm movements, introducing a displacement between the tracked hand (control) and the virtual hand (display), inducing a proprioceptive weight sensation [34]. Recent work quantified the effect in VR and captured the relationship with a mathematical model [37]. The authors found that displacements of the virtual hand of $5cm$-$10cm$ produce a change in the perceived heaviness of $\pm 5g$ for a reference object of $185g$. While this software-based approach can be easily integrated into existing VR systems, the visual-haptic effect is limited to a small range of perceived weights. Moreover, due to the absence of physical stimuli, the effect is not applicable to eyes-free interactions.

In this work, we extend the findings and address the shortcomings of previous hardware-based and software-based works. We propose to complete the weight rendering technique of adaptive trigger resistance by additionally manipulating the C/D ratio. This combined technologies allow the integration of diverse multisensory weight cues at different moments of the weight perception process. The trigger resistance physically renders cutaneous stimuli during grasping while the C/D manipulation visually induces a proprioceptive sensation of weight during lifting (see Figure 1). We hypothesize that our new combined approach will improve the weight illusion in VR and compensate for the previously reported shortcomings of both techniques due to an additionally provided second weight cue. As both techniques utilise existing components available in consumer VR systems, our approach aims explicitly to improve weight perception with commercial handheld VR controllers.

1.1 Contributions

In a psychophysical user study, we investigate if the combination of adaptive trigger resistance and C/D ratio manipulation enhances the perception of virtual weight in VR. To do so, we compared the perceptual detection thresholds and subjective weight illusions induced by (1) adaptive trigger resistance only, (2) manipulation of the C/D ratio only, and (3) the employment of both technologies. Our findings show that participants were significantly more perceptive towards smaller weight changes in the combined weight simulations compared to the individual methods and significantly faster in determining weight differences with both cues present compared to the pseudo-haptic technique alone. The application of both weight cues also facilitated higher confidence in the weight perception and was preferred the most out of the three techniques.

Our work draws from previous research and contributes a novel technique for enabling a continuous VR weight illusion. The integration of the two technologies provides cutaneous and proprioceptive stimuli at different stages during the interaction and overcomes the previously reported limitations of the individual methods. This emphasises the meaningful benefit of incorporating multiple sensations for virtual weight simulation.

2 RELATED WORK

A wide spectrum of methods has been proposed to enhance the perception of virtual weight. The techniques can be classified as either *physical approaches* or *virtual approaches* [31]. Physical approaches simulate weight through haptic feedback. Virtual approaches, in contrast, take advantage of perceptual phenomena such as visual dominance [11] to induce perceptions of weight through visual-haptic illusions [22]. Since our proposed approach is located at the intersection of physical and virtual weight simulation techniques, we review both research paths.

2.1 Physical Approaches to Weight Simulation

In haptics research, a distinction is made between two types of perceptions, tactile and kinesthetic [24,42]. Perceiving the heaviness of an object involves both: Picking up objects of varying weights involves different grasping forces, which leads to varying amounts of shear forces and pressure on the skin (tactile) as well as the muscular system counteracting gravity (kinesthetic). Researchers have explored different ways to simulate these sensations and provide users with a sense of virtual weight. Systems based on electrical muscle stimulation (EMS) [27], ungrounded/handheld systems based on air jets [35,47], propeller propulsion [13,16], or inertial effects [48] have been proposed. While supporting large workspaces, these solutions can be cumbersome to put on, generate significant noise, or require high-power requirements. Moreover, weight has been simulated with vibration [8], and skin-stretching [29]. Such solutions, however, only simulate the tactile component of heaviness.

Alternative approaches employ physical proxies (haptic props). They are spatially registered with virtual objects and provide multimodal (tactile and kinesthetic) feedback and tangibility [14]. They naturally convey weight, increase presence [15] and provide compelling illusions even when the proxies do not perfectly match their virtual counterparts due to visual dominance [15,40]. While proxies might provide the most realistic haptic impressions, this technique cannot be scaled to a larger number of interactable objects. To account for these drawbacks, researchers explored the combination of proxies' realistic feedback with the flexibility of actuation. Several introduced techniques rely on either modifications of air resistance [25,51], elastic properties [45], weight shift [39,50], absolute weight change [7], or both [30]. Most recently, researchers proposed *Triggermuscle*, a VR controller adapting the resistance of its trigger to simulate differences in virtual weight [43]. While this haptic interface has been shown to successfully convey different weights, the weight illusion did not take effect for several participants – motivating this work on improving the concept through an additional rendering of a virtual weight simulation.

2.2 Virtual Approaches to Weight Simulation

Virtual approaches to weight simulation in VR are based on visual-haptic illusions and the perceptual phenomenon of visual dominance [11,22]. In such cases, neural processing puts greater emphasis on visual information during multisensory integration than on other sensory channels such as hearing or proprioception [10]. For the simulation of weight, pseudo-haptics has proven itself highly useful in past research [21], e.g., several works explored how weight can be conveyed by manipulating the *control-display ratio* (*C/D ratio*) [9,34,37]. Moreover, previous works also showed that clearly perceivable offsets can still result in perceptions of virtual weight [33,34]. Other research contributed to a better understanding of this technique by uncovering that the size of virtual objects can have an effect on the C/D manipulation required for inducing heaviness perception [19]. A more recent approach leveraged a brain-computer interface to control the amount of real-to-virtual offset when rendering pseudo-haptic weight [49].

2.3 Combined Physical and Virtual Approaches

Only a few works combined physical and virtual approaches for weight rendering. Recent work explored the effect of EMS when combined with C/D ratio manipulation [18]. Their findings show an improvement in the perceptual sensitivity towards virtual weight when both stimuli were present. Another haptic interface was combined with haptic retargeting, showing an enhancement in the rendering of virtual weight distribution [52]. Beyond weight perception, pseudo-haptics have been combined with physical systems to convey grasping effort and stiffness [1,2]. Additionally, to enhance the haptic realism of virtual buttons, pseudo-haptic stiffness was combined with electrical stimulation of the finger tendons and tactile feedback [3]. However, the combination of a physical input device such as the controller *Triggermuscle* with software-based *pseudo-haptics* to simulate weight in VR has not been proposed nor has its potential been evaluated. With our work, we fill this gap and aim at improving weight rendering in VR.

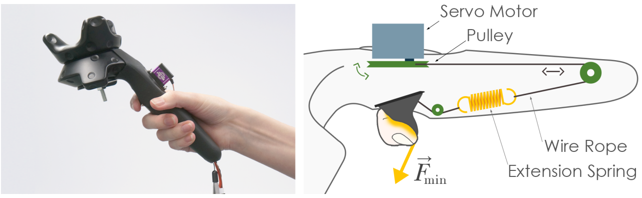


Figure 2: (Left) The modified HTC Vive controller used in the study. (Right) A servo motor and spring mechanism built into the casing dynamically change the resistance of the trigger [43].

3 COMBINING ADAPTIVE TRIGGER RESISTANCE AND PSEUDO-HAPTICS

In our work, we combine a physical haptic rendering technique with a pseudo-haptic approach to improve the perception of virtual weight in VR. To do so, we (1) apply adaptive trigger resistance when grasping a virtual object, and (2) manipulate the C/D ratio when lifting it up. This section outlines the workings of each technique and our combination of both to achieve a continuous weight illusion.

Adaptive Trigger Resistance During Grasping To provide users with a haptic weight cue while grasping a virtual object (phase 1), we adapt the resistance of the VR controller's trigger button. For this, we use a haptic VR controller identical in construction to *Triggermuscle* [43] (see Figure 2 (left)). The haptic feedback is informed by how humans modulate their grip forces according to the weight of a grasped object: The heavier a virtual object, the higher the trigger resistance, i.e., the more force needs to be applied to pull the trigger and to prevent the virtual object from falling down. At its core, the controller's mechanism uses a high-voltage (6.0V) digital micro servo motor (BMS-210DMH) to pull or release an extension spring (see Figure 2 (right)). As the spring is connected to the trigger, its current configured state is then perceived as the level of trigger resistance. The mechanism is built into a casing of an HTC Vive controller and offers a continuous resistance range of [$4.29N$, $16.36N$], allowing a total increase over 281%. An ESP32 microcontroller unit (MCU) drives the servo motor and communicates with Unity via Bluetooth. Along with an 11.1 V lithium polymer battery and a battery eliminator circuit (BEC) component, the MCU is carried in a small bag on the user's back and connected to the controller's bottom via cable. See [43] for further specifications.

C/D Ratio Manipulation During Lifting To continue the simulation of virtual weight in VR immediately upon and throughout lifting (phase 2), we apply the pseudo-haptics approach of manipulating the C/D ratio, mainly based on Samad et al.'s work [37]. A change in the C/D ratio applies a gain on the lifting movement that is inversely proportional to perceived heaviness (see Figure 1). Hence, the lifting movement is multiplied by the C/D gain and, therefore, introduces a displacement between the controller's position (control, i.e. physical hand) and the position of the virtual hand grasping the virtual cube (display). The result is a visual-proprioceptive conflict, making it more difficult to move heavier, and easier to move lighter virtual objects. To not make this perception illusion apparent, maintain the sense of ownership for the virtual hand and a high sense of presence in VR, we applied the pseudo-haptics effect within a C/D ratio range difficult to notice by users. As we focus only on heavier weights in this work, the range of C/D gain lies between 0.7 and 1.0. The modulation corresponds to perceived changes in the heaviness of a virtual cube of up to $+4.6g$, informed by the perceived-mass differences for the 0.7-1.0 range ($84.6g$-$80.0g$) [37]. The minimum C/D gain of 0.7 was informed by our pilot testing (see section 3.1).

Combining Physical and Virtual Stimuli For a simultaneous rendering of both stimuli ranges, we applied a linear mapping of the C/D ratio to the range of trigger resistance (see Figure 3). In our main study, informed by our pilot (see section 3.1), the lowest level of resistance $4.29N$ was matched with the C/D gain of 1.0, simulating the lightest weight. Vice versa, the highest level of resistance $10.96N$ was matched with the C/D gain of 0.7, simulating the heaviest weight. In the context of our analysis, we express the magnitude of weight rendering with a normalised value between 0 and 1 (0 = lightest weight, 1 = heaviest weight, see Figure 3).

Figure 3: Linear mapping between both stimuli ranges that were applied in our user study. For the analysis, we expressed the magnitude of weight rendering with a normalised value between 0 (standard weight) to 1 (heaviest weight), as indicated by the values in brackets.

3.1 Pilot Study: Determine Effective Range of Stimuli

A pilot study (N = 7) was conducted to determine the effective ranges of rendered stimuli for both feedback mechanisms for inducing a weight illusion. We followed the method of constant stimuli with a two-alternative forced choice (2AFC) paradigm [17,20] and assessed participants' ability to discriminate different (1) trigger resistances as well as different (2) C/D ratio manipulations inside VR. Results for the minimum levels of stimulus change that are required to detect a heavier weight were then applied in the main user study to set the appropriate range of parameters.

The pilot study was conducted in VR using the HTC Vive setup. Participants were informed that they will experience two kinds of weight simulations, that can occur, e.g. during grasping or during lifting. In each trial, participants lifted two cubes and responded to the question "Which cube felt heavier?". The stimulus for the lightest weight of each range ($4.29N$ and 1, respectively) was tested against 9 comparison stimuli. Rendered trigger resistances were $4.89N$, $5.48N$, $6.67N$, $7.86N$, $9.05N$, $10.24N$, $11.44N$, $12.63N$, $13.82N$ and applied C/D gains were 0.4, 0.48, 0.55, 0.63, 0.7, 0.78, 0.85, 0.93, 0.96. *Triggermuscle*'s maximum resistance was limited to $13.82N$, illustrating an increase of 222%, to prevent components from wearing out. Each stimulus was repeated 5 times, resulting in a total number of 45 trials per condition, with a randomized order. Results indicated that a range of [$4.29N$, $10.96N$] for trigger resistances and a range of [0.7, 1] for C/D gains is sufficient to perceive differences in weight.

4 STUDY

We conducted a study to evaluate users' weight perception for each VR weight rendering technique and assessed if the combined approach enhances the perception of heavier weights. To do so, the experiment had a within-subject design and compared the weight illusions by means of (1) trigger resistance only (TR ONLY), (2) manipulation of the C/D ratio only (CD ONLY) and (3) the combination of both (TR+CD). In each condition, we asked participants to repeatedly lift two virtual cubes and to identify the heavier one.

To understand users' weight perception with a focus on objective sensitivity to discriminate the different levels of heaviness as well as the subjective experience of the weight illusion, we applied a mixed-method approach. We conducted a psychophysical experiment with a two-alternative forced choice (2AFC) task following the method of constant stimuli [17, 20] to assess participants' absolute perceptual thresholds. The detection thresholds from each condition were then compared as a measure of participants' sensitivity to discriminate different levels of heaviness. Questionnaires collected additional quantitative data on participants' subjective weight experience, which was complemented by semi-structured interviews capturing qualitative reports. The study was designed in accordance with local legislation and approved by the authors' institutional ethical review board. To account for the current protective measures regarding Covid-19, this study was carried out within the legal restrictions of the local government as well as our university.

4.1 Participants

29 participants, recruited from the campus (12 f; 14 m; 2 o), completed the experiment, however, one dataset had to be excluded due to a technical error. Participants were on average 26 years old (SD = 4 years; min. 20 years; max. 38 years), 27 were right-handed and 11 reported corrected vision. Participants were compensated with 10€ . Assessed on a scale from 1 = never to 7 = regularly, our participants covered a range of previous experience levels with controllers (M = 3.11 (SD = 1.34); min. 1; max. 7), VR (M = 1.96 (SD = 1.64); min. 1; max. 6) with 22 participants reporting prior VR systems usage.

4.2 Apparatus

Participants wore the HTC Vive Pro Eye head-mounted display (HMD) and used the haptic VR controller *Triggermuscle* [43], held like an unmodified HTC Vive controller. The resistance of the trigger was only adapted in the conditions TR ONLY and TR+CD. To ensure the controller's tracking, an HTC Vive tracker 2.0 was attached to its top. To conceal sounds coming from *Triggermuscle's* servo motor, participants wore Sony WH-1000XM4 over-ear headphones with active noise-cancelling (ANC), which additionally played white noise. To respond to questions inside VR, participants used a Kensington presentation clicker that was operated with their non-dominant hand. Questionnaires were filled out after each condition on a laptop using the online survey tool LimeSurvey. The semi-structured interviews were recorded using the smartphone OnePlus 5.

The virtual environment (VE) (see Figure 4) was implemented with Unity 2021.3.4f LTS. The manipulation of the C/D ratio was applied as described in section 3. The virtual cubes used in the experiment resembled a wooden solid box with a side length of 6.23 cm, and a perceived weight of 300 grams, matching the combined weight of *Triggermuscle* with the attached Vive tracker.

4.3 Task & Procedure

Pre-Task At the beginning of the experiment, participants provided their consent and were introduced to the study's context of weight perception. We informed them that they will experience three different weight simulations, that can occur, e.g. during grasping or during lifting. However, no further details were disclosed and the controller *Triggermuscle* was kept concealed until after the experiment was completed. Following the initial introduction, participants were equipped with the HMD, the haptic controller (held in the dominant hand) and the presentation clicker (held in the non-dominant hand). We instructed participants to ignore any small vibrations or subtle impact forces within the controller's handle to the best of their ability, as these side effects can occur during the servo's adjustment and are not part of the weight simulation. As an additional precaution to prevent biases, obfuscation angles were implemented for trials in which the servo adjustment would have been absent (in CD ONLY) or trials in which only a small change in resistance would have occurred. These angles were randomly chosen from the middle three comparison resistances and ensured that the servos's adjustment occurred in every single trial. Finally, we asked participants to keep an ergonomic posture in a seated position, allowing a comfortable vertical lifting motion, and hence preventing arm fatigue. To account for differences in body height and to maintain the same dimensions inside VR, the distances between the virtual table and the floor as well as between the virtual table and the user were calibrated by using the HMD-height (tracking y-coordinate). After a small pilot study (N=5), we found that ergonomic table-floor, and table-user distances were achieved by using 60% and 20% of a participant's HMD-height, respectively.

Condition Procedure Each of the three conditions followed the same procedure and consisted of four phases: The experimental task including (1) a training session inside VR and (2) a repeated lifting task following the method of constant stimuli inside VR. Post-task phases included (3) a post-task questionnaire outside VR and (4) a post-task semi-structured interview outside VR.

Task The experimental task started with the training phase (1) which consisted of 3 trials rendering the maximum weight difference of the respective condition. Participants got familiar with the exact lifting procedure (see Figure 4) and with using the presentation clicker for logging their responses inside VR. The testing phase (2) consisted of 25 trials, in each of which participants lifted cube A and cube B once. After lifting each cube, the trial concluded with three questions: "Which cube felt heavier?" (A or B), a 7-item Likert scale question asking "How confident are you in your decision?" (1 = Not at all confident, 7 = Extremely confident) and "How much was the weight change?", for which the response was given on a continuous slider (lower limit = no weight change, upper limit = max. weight change). The max. weight change corresponded to the maximum weight change that participants experienced in the training trials. We expected that conditions with better weight simulation lead to higher user confidence and higher perceived weight changes.

Post-Task After completing the experimental task, a post-task questionnaire (3) was completed on a laptop outside VR, which evaluated the subjectively perceived quality of weight sensation for each condition based on 9 aspects (see Table 1). The set of questions drew on Samad et al. [37] and was extended to include additional aspects to cover a more comprehensive perception of weight. Specifically, we expected certain qualities, such as Body Ownership or Effectiveness, to be increased in conditions with better weight simulation. In addition, the Borg CR10 scale [5] measured participants' arm fatigue, similar to previous C/D ratio studies [32, 46]. The post-task semi-structured interview (4) enquired how the virtual weight as well as the difference in weight was perceived.

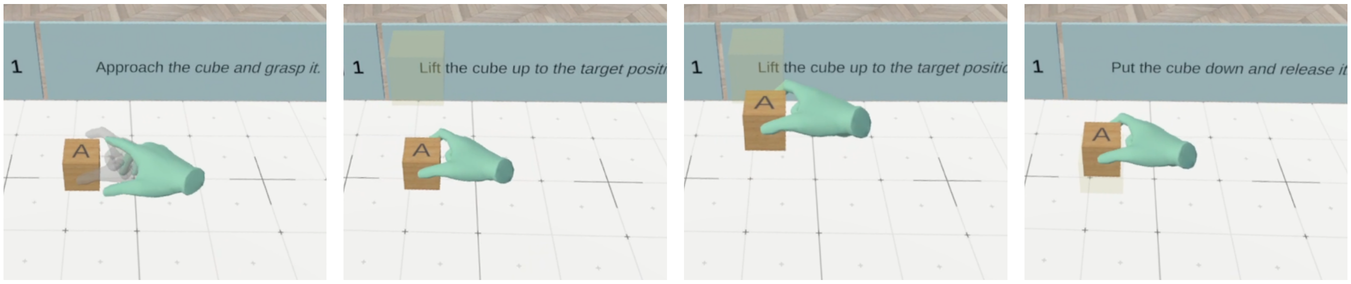
Post-Experiment After completing the condition procedure for all three conditions in VR, we conducted a post-experiment semi-structured interview to gain deeper insights into participants' final assessments regarding all three weight sensations. The interview covered questions concerning if participants noticed a difference between the three conditions, in which condition they experienced the heaviest and lightest weights, their preference for a condition in regard to their weight sensation and open comments. Furthermore, participants filled out a post-experiment presence questionnaire (SUS [41]) and were asked about any experienced simulator sickness ("Did you feel sick during your time in the virtual environment?"). Both measures were used to ensure that the experience is sufficiently immersive and free of sickness issues. The study took around an hour and concluded with a demographic questionnaire.

4.4 Stimuli

We applied the method of constant stimuli with a 2AFC task [17,20]. In each trial, participants lifted two cubes, one after the other, and identified the heavier one. The cubes' virtual weight was haptically rendered based on the current condition. For condition TR+CD, values of both techniques were applied. The ranges of each stimulus range were informed by the pilot study, meaning [4.29N, 10.96N] for the trigger resistance, [1.0, 0.7] for the C/D gains. One of the cubes was always rendered with the same standard stimulus, the second cube was rendered with one of five preselected comparison stimuli. For the trigger resistance, the standard resistance was 4.29N (0% of range), the comparison resistances were 4.89N (9%), 5.96N (19%), 7.36N (48%), 9.92N (72%), and 10.96N (100%). For the

Table 1: Questions presented after each condition to evaluate participants' subjective weight illusion on a 7-item Likert scale (1 = Strongly disagree, 7 = Strongly agree), which were complemented by the Borg CR10 scale [5] to measure arm fatigue.

Aspect of Weight Illusion	**Question**
Effectiveness:	I experienced different weights during the task.
Efficiency:	I could quickly determine whether the objects were of the same or of different weight.
Haptic Realism:	Differences in weight of the virtual objects felt the same as differences in weight feel in the real world.
Grasping Effort:	In tasks where I perceived one object to be heavier than the other, I had to grasp the heavier cube more firmly than the lighter one.
Lifting Effort:	In tasks where I perceived one object to be heavier than the other, I had to put more effort with my arm into lifting the heavier cube than the lighter one.
Time of Weight Illusion:	I experienced the weight of the cubes... (1 = already when grasping the cube, 7 = only after having lifted the cube completely)
Unintuitiveness:	In tasks where I perceived one object to be heavier than the other, I had to think a lot before I was able to decide on my answer.
Limb Ownership:	The virtual hand seemed to belong to my body at all the times. (Adapted from Samad et al. [37])
Surfaces (Control):	I experienced different surface textures during the task.



(a) Approaching the cube in order to grasp it. A semi-transparent grey hand acts as a visual target for this step.

(b) A successful cube grasping by pulling the trigger. A semi-transparent yellow cube above acts as target for the next step.

(c) Lifting the cube upwards towards the yellow semi-transparent target indicating the required lifting height.

(d) Placing the cube by moving it downwards towards the last semi-transparent target cube.

Figure 4: Individual steps of the lifting procedure during the task in VR. Written instructions and semi-transparent target objects (grey hand, yellow cube) guided participants through the lifting procedure.

C/D ratio manipulation, the standard C/D gain was 1.0 (0% of range), the comparison C/D gains were 0.97 (9%), 0.93 (19%), 0.85 (48%), 0.78 (72%), and 0.7 (100%). Each comparison stimulus was tested 5 times, resulting in 25 trials per condition. The order of all trials and the appearance of the standard and comparison stimuli within one trial were randomised. After completing all conditions, each participant performed 75 trials in total (5 levels of stimuli × 5 repetitions x 3 conditions). The order of the conditions was counterbalanced across participants.

5 RESULTS

The results of the presence questionnaire for the SUS count ($M = 1.29$, $SD = 1.56$) and SUS mean ($M = 4.08$, $SD = 0.97$) confirm our VR study to be sufficiently immersive (answers ranging from 1 to 7). Participants also reported minimal simulator sickness ($M = 1.33$, $SD = 0.64$; 1 = Not at all, 7 = I felt very sick).

5.1 Thresholds for Weight Perception

We mapped the resistance range of the trigger to the continuous range of [0, 1], where 0 represents the minimum intensity of $4.29N$, and 1 the maximum intensity of $10.96N$ (see Figure 3). To compute the detection thresholds (i.e., just-noticeable differences) for the virtual weight of each technique, we fitted a psychometric function to the 2AFC data. We removed data sets of conditions for which the curve fitting failed, in which data points were all either above or below the threshold of 75%, or presented a noisy response pattern. In total, 38 out of 84 condition data sets were excluded.

Condition TR ONLY presented a perception threshold of 0.35 and lead to the heavier object being correctly identified in 76.86% of all trials. Condition CD ONLY produced a threshold of 0.56 and correct identifications in 70% of all trials. The condition TR+CD produced a threshold of 0.17 and correct identifications in 85.68% of trials (see Figure 5).

After pooling individual thresholds per participant and condition (see Figure 6a), we performed an analysis of variance for TR ONLY ($M = 0.46$, $SD = 0.31$, $SE = 0.08$), CD ONLY ($M = 0.54$, $SD = 0.33$, $SE = 0.09$), and TR+CD ($M = 0.17$, $SD = 0.09$, $SE = 0.02$), based on a generalized mixed Gamma regression and post-hoc tests by pairwise comparisons using Z-tests, then corrected with Holm's sequential Bonferroni procedure. The results indicated a statistically significant effect of Condition on Threshold ($\chi^2(2, N = 16) = 17.376$, $p < .001$). The counterbalanced presentation order for the conditions in our experiment prevented an order effect ($\chi^2(2, N = 16) = 0.356$, $p = .837$). We hypothesised perceptual sensitivity to be improved by our combined technique compared to TR ONLY and thus expected the thresholds of TR+CD to be closer to 0.0 (the standard stimulus) than those of TR ONLY. This would allow for rendering more distinguishable levels of weight within the same range of resistance provided by a VR controller like *Triggermuscle*. Pairwise comparisons indicated that the TR+CD vs. TR ONLY difference ($Z = 3.887$, $p < .001$) and the TR+CD vs. CD ONLY difference ($Z = 4.119$, $p < .001$) were statistically significant.

5.2 Quantitative Results - Subjective Weight Perception

Quantitative data comparing the subjective weight illusions include the perceived size of weight differences as well as the level of confidence for each weight comparison (both per trial) and the 9-item post-task questionnaire with an additional arm fatigue question (per condition). The subjective responses from the post-task questionnaire and the Confidence Level were processed by performing a Friedman omnibus test, and Wilcoxon-Signed Rank post-hoc tests and corrected with a Holm's sequential Bonferroni procedure. The

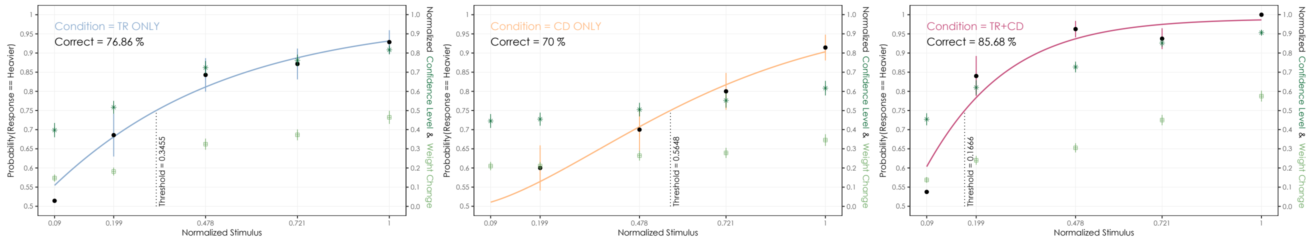
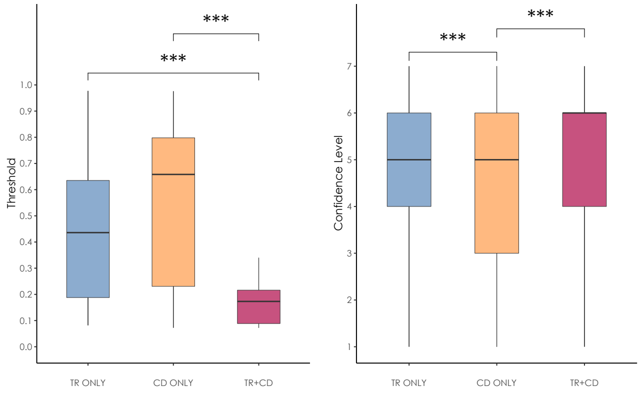


Figure 5: 2AFC data fitting for the experiment conditions. The plots show the general perception thresholds and the percentages of correct responses. Additionally, the plots contain the normalized confidence levels and perceived magnitude of weight change per stimulus.



(a) Thresholds

(b) Confidence Levels

Figure 6: (a) Box plots depicting perception thresholds by condition and the median value. (b) Confidence Levels by condition. Both plots indicate significant differences with ($p < .001$).

data for Relative Weight Changes were processed by performing a mixed ordinal logistic regression and post-hoc tests by pairwise comparisons using Z-tests, then corrected with Holm's sequential Bonferroni procedure. We report on the significant differences only. Since some participants clearly stated in the post-task interviews that they did not experience any weights or differences in weight, and due to impossible fitting for some psychometric functions due to a noisy response pattern, in combination with interview reports that did not relate to the rendered weight cues, we excluded the respective data sets from the analysis of the post-task questionnaire, Relative Weight Change, and the level of confidence (10 in total). The excluded data sets do not evaluate the rendered weight simulation; however, we will discuss them as part of our qualitative findings (see section 5.3).

5.2.1 Confidence Level

After each weight comparison, we asked participants to estimate their confidence level in their decision. The distribution of Likert responses (1-7) at a Confidence Level is shown in Figure 6b for TR ONLY ($Md = 5$, $IQR = 2.0$, $M = 5.1$, $SD = 1.70$), CD ONLY ($Md = 5$, $IQR = 3$, $M = 4.18$, $SD = 1.85$), and TR+CD ($Md = 6$, $IQR = 2$, $M = 5.11$, $SD = 1.70$). Results indicated that the Condition had a significant effect on the Confidence Level ($\chi^2(2, N = 17) = 14.9$, $p < .001$, $W = 0.439$). Participants were significantly more confident in our combined approach compared to CD ONLY ($V = 8$, $p = .004$). Furthermore, with TR ONLY, participants also felt significantly more confident compared to CD ONLY ($V = 138$, $p = .006$).

5.2.2 Relative Weight Change

After each weight comparison, we asked participants to estimate the size of the perceived weight difference. Hence, we describe the deviations in the perceived magnitude of weight differences ("How much was the weight change?") across the techniques. The analysis indicated that the conditions had a statistically significant effect on the average Relative Weight Change ($\chi^2(2, N = 17) = 16.72$, $p < .001$). The relative weight changes between TR+CD and CD ONLY were significantly higher than changes between CD ONLY and TR ONLY ($Z = 4.032$, $p < .001$) and between TR+CD and TR ONLY ($Z = -2.607$, $p < .05$). This means that weight differences in TR+CD were on average perceived 1.81 times bigger ($SD = 1.10$) than weight differences induced by CD ONLY, as well as 1.18 times bigger ($SD = 0.35$) than the changes in weight induced by TR ONLY. Weight changes in CD ONLY were perceived as 0.83 times smaller ($SD = 0.43$) than in TR ONLY.

5.2.3 Questionnaire

Results are summarized in Figure 7, Moment of Weight Perception in Figure 8a, and descriptive statistics are presented in Table 2.

Test results for *Efficiency* indicated that participants determined differences in weight significantly faster depending on which condition they experienced ($\chi^2(2, N = 17) = 13.5$, $p < .01$, , $W = 0.396$). TR+CD significantly outperformed CD ONLY ($V = 3.5$, $p = 0.01$). Responses showed a significant effect of the conditions on *Haptic Realism* ($\chi^2(2, N = 17) = 7.17$, $p = 0.0278$, $W = 0.211$). Participants found TR+CD significantly more haptically realistic compared to TR ONLY ($V = 3.5$, $p = 0.015$). We found no significant differences among the conditions for *Effectiveness*, *Grasping Effort*, *Lifting Effort*, *Limb Ownership*, *Surface Textures* nor *Unintuitiveness*. Finally, the three rendering techniques showed a significant main effect for the *Moment of Perceived Weight* between grasping and lifting ($\chi^2(2, N = 17) = 14.1$, $p < .001$, $W = 0.415$) (see Figure 8a). Weight was experienced significantly closer to the moment of grasping with TR+CD compared to CD ONLY ($V = 98$, $p = 0.013$) and in TR ONLY over the change in the C/D ratios ($V = 5.5$, $p = 0.01$).

5.2.4 Preference Ranking of Weight Illusion

Results are summarized in Figure 8b. With almost 60%, the majority of participants voted TR+CD (16) in the first place, more than a third chose TR ONLY (10) and only a few (2) chose CD ONLY as their preferred weight illusion. For the second place, TR ONLY was most often favoured by around 40% (12) and TR+CD (8) and CD ONLY (8) received equal approval. The least preferred weight illusion was experienced in CD ONLY, with almost 65% of the participants (18) placing it in the third place. Only every fifth participant chose TR ONLY (6) to be in the last place and even fewer chose TR+CD (4).

5.2.5 Arm Fatigue

For all three conditions, participants reported weak arm exertion according to the Borg CR10 scale categories. A Friedman rank sum test found no significant differences between conditions ($\chi^2(2, N = 28) = 1.92$, $p = 0.38$), while comparing TR ONLY ($M = 1.99$, $SD = 2.13$), CD ONLY ($M = 1.87$, $SD = 1.65$) and TR+CD ($M = 2.11$, $SD = 2.11$). Furthermore, using Kendall's W Value, we found a small effect size ($W = 0.03$).

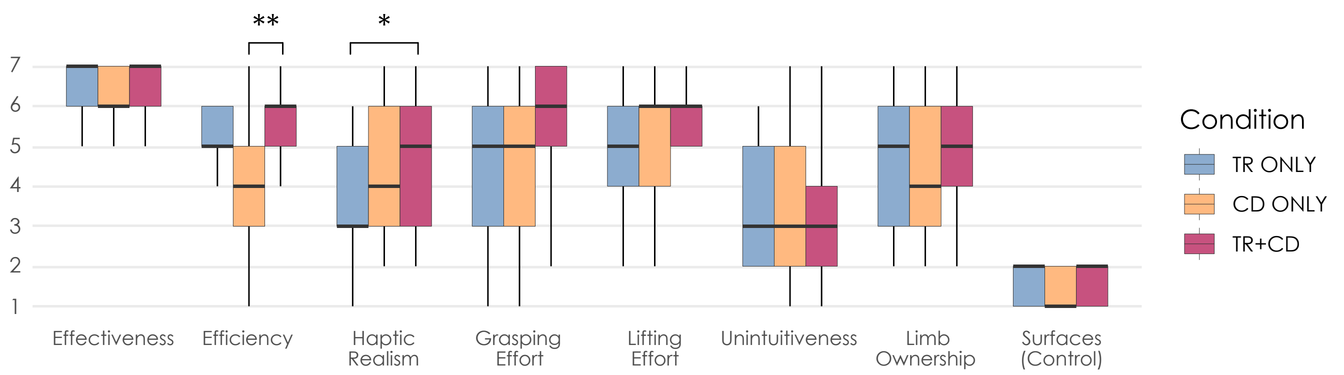
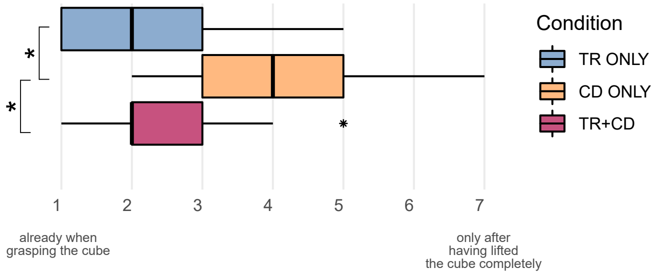


Figure 7: Results for the subjective questionnaire on weight illusion presented after each condition. The x-axis presents 8 out of the 9 categories, according to Table 1, and the y-axis presents the values for the selected Likert scales. Higher values are better for all categories, except for Unintuitiveness and Surfaces (Control). Statistically significant differences are indicated with $p < .05$ (*), $p < .01$ (**), and $p < .001$ (***).

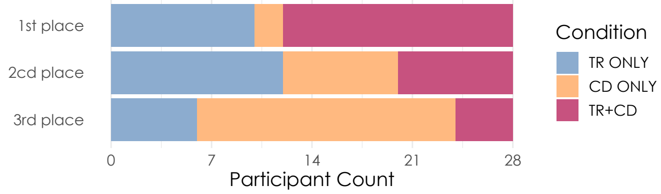
5.3 Qualitative Findings - Subjective Weight Perception

The interview recordings were transcribed and analysed with MAXQDA data analysis software, applying an inductive technique [4, 38]. An additional open coding with thematic analysis [4] was performed by three researchers and enabled a more in-depth and data-driven discovery.

Weight Illusion All participants reported differences in their weight illusions across conditions. Specifically mentioned weight sensations for TR ONLY included grasping effort (4 participants), heaviness of pressing the trigger (5), general feeling of heaviness in hand (2), combined with vibrations (6), lifting-related aspects (4), or no specific identification (1). Weight in CD ONLY was identified based on movement speed/acceleration/duration (15), more effort to reach the top (2), strain in arm muscles (2), reduced precision (2), vibrations (1), or pressing the trigger (2). Reported weight cues in TR+CD included grasping combined with lifting effort (6), trigger resistance with lifting effort/speed (4), strain in arm muscles (2), speed/acceleration/duration alone (5), grasping effort alone (2), trigger resistance alone (1), general feeling of heaviness (1), reduced precision (1), vibration (1), or no specific identification (1). When being asked in which condition the heaviest weights were perceived, TR+CD was chosen most often (16 participants) followed by an equal number of votes for TR ONLY (5) and CD only (5). The lightest weights were experienced mostly in CD ONLY (14), followed by TR ONLY (10) and a few times in TR+CD (2). In four cases, participants were unable to say.



(a) Questionnaire results for Moment of Weight Perception. Statistically significant differences are indicated with $p < .05$ (*), $p < .01$ (**), and $p < .001$ (***).



(b) Preference ranking of the three weight simulations.

Figure 8: Results for Moment of Weight Perception and Preference.

Prominent observations for the individual rendering of the trigger resistance described that it was ”more difficult to grasp the [heavier] object” (P1), which allowed them to get an estimate of the weight immediately during grasping. ”I intuitively felt that one object felt heavier than the other” (P13) illustrates that specific weight cues were not always identified. However, some statements specifically vocalised the trigger resistance, as they ”had to press [the trigger] harder in order to enclose the hand around the object” (P1). Surprisingly, some participants reported that they felt the weight through the strain in their arm muscles. When participants experienced only the change in the C/D ratios, the effect of the amplified arm movement for heavier weights was diversely described across participants as slower, sticky, more drag, small wrist motion, taking longer for the same distance, or more energy-consuming. Observations referring to lighter weights included easier to move, faster, having a spin, higher acceleration, or increased arm radius. For lighter weights, participants were often surprised that ”with less effort, [the cube] was already much higher than expected” (P1). Since the majority of participants selected CD ONLY as the condition in which they perceived the lightest weights, these comments further emphasize that low C/D ratios might have depicted overall the lower end of the spectrum of perceived weights in our study. Other statements explained that the weight was perceived rather through the movement speed than through a strain in the arm muscle. An increased level of energy was mentioned in the context of needing to press the trigger for a longer time, as performing the lifting task took longer. However, a dominant theme in the interview reports was that the weight was ”more difficult to perceive and often only after lifting the cube upwards” (P13), the weight ”differences were generally much smaller” (P3), or considerably more concentration was needed. The weight illusion in the combined approach was explained as the need ”to grasp much more firmly, which made the cube feel heavier” (P13) and ”it took longer time to lift the heavier object” (14). An often occurring assessment described weights as ”considerably easy to distinguish” (P20) and valued differences in weight as ”the largest” (P25) compared to the individual renderings. One statement even described that ”heavier cubes felt heavier than they visually appeared” (P25). A few participants reported that they needed to hold onto the object more carefully to prevent it from dropping, and moving the cube to the top became less precise, which was associated with an increased effort for lifting the cube upwards. As this is similar behaviour of heavy physical objects in real life, the weight was found to be ”quite realistic” (P4) and ”almost like a real cube” (P4).

Table 2: Descriptive statistics for the questionnaire results.

	TR ONLY						CD ONLY						TR+CD					
	Md	IQR	Mean	SD	Min	Max	Md	IQR	Mean	SD	Min	Max	Md	IQR	Mean	SD	Min	Max
Effectivenes	7	1	6.53	0.62	5	7	6	1	6.00	1.12	3	7	7	1	6.65	0.61	5	7
Efficiency	5	1	5.18	0.73	4	6	4	2	4.06	1.60	1	7	6	1	5.59	1.23	2	7
Haptic Realism	3	2	3.71	1.61	1	6	4	3	4.18	1.63	2	7	5	3	4.71	1.65	2	7
Grasping Effort	5	3	4.59	1.87	1	7	5	3	4.53	1.84	1	7	6	2	5.41	1.50	2	7
Lifting Effort	5	2	4.94	1.52	2	7	6	2	5.18	1.59	2	7	6	1	5.12	1.65	2	7
Unintuitivess	3	3	3.24	1.44	2	6	3	3	3.82	2.01	1	7	3	2	3.24	1.75	1	7
Limb Ownership	5	3	4.47	1.77	2	7	4	3	4.47	1.74	2	7	5	2	4.59	1.54	2	7
Surfaces (Control)	2	1	2.24	1.68	1	6	1	1	1.82	1.29	1	5	2	1	2.24	1.68	1	6
Time Weight Perc.	2	2	2.06	1.20	1	5	4	2	4.24	1.68	2	7	2	1	2.53	1.01	1	5

No Weight illusion The small set of interview statements specifically stating no weight perception was derived from TR ONLY (2 participants), CD ONLY (5) and TR+CD (1). Additionally, statements describing cues that were unrelated to the provided feedback referred to TR ONLY (3), CD ONLY (2) and TR+CD (2). When being presented with the adaptive trigger resistance alone, these participants ”based [their decision] on the up and down movement” (P7), ”the acceleration of the lifting” (26) or tried to focus on the subtle vibration. For this subset of failed illusions, differences in weight were not perceived, as weights ”almost always [felt] the same” (P10). With the exposure to changes in the C/D ratios, participants ”could not feel anything” (P28) nor ”got an intrinsic feel of the weight” (P23). Focuses on ”intuition and gut feeling” (P28) and on ”how much tugging happened” at the trigger (P23) were reported, and the absence of weight perception was described as ”completely confusing” (P14). Overall, ”it was really hard [...] to decide which ones are heavier because almost both of them are the same weight” (P8).

6 DISCUSSION & FUTURE WORK

With this work, we wanted to explore if a combination of a hardware-based technique and a pseudo-haptics approach improves the perception of virtual weight. In the following, we will discuss our findings of the user study testing the integration of adaptive trigger resistance and the manipulation of C/D ratio against the individual renderings.

6.1 Combining Adaptive Trigger Resistance with C/D Ratio Manipulation Improves Perceptual Sensitivity

The results of our study show the feasibility of individually using adaptive trigger resistance and C/D ratio manipulation to render different levels of weights in VR. Further, significantly smaller thresholds for TR+CD highlight that the combined application increases perceptual sensitivity compared to the isolated simulations. In practical terms, more distinguishable levels of weight can be rendered with the controller *Triggermuscle* by adding C/D ratio manipulation. This finding is further emphasized by the relative weight change results, illustrating that weight differences in TR+CD were perceived as significantly larger compared to the pseudo-haptic technique alone. Conclusivley, the findings indicate that the weight range produced by the individual renderings was extended when combined. As findings from previous user studies using adaptive trigger resistance suffered from differences in the individual haptic weight sensing among users [43], we argue that this perceptual limitation can be overcome by introducing the visual offset between virtual and physical hand through C/D gains smaller than 1 as an additional weight cue. A possible explanation for the multimodal weight cue integration can be found in the literature: When pulling the trigger, a haptic signal (resistance) is perceived at the index finger. Upon lifting, a second sensory signal (altered visual motion of hand) is added. This moment of cross-modal interaction causes a shift in attention towards the received multisensory signal, determining the further processing of both stimuli [44]. The higher the hand is lifted, the larger and more perceptual the visual offset becomes, causing a reevaluation of the sensory estimates favouring the more reliable signal [12]. However, as the reliability of the visual signal decreases with the increasing offset, the less the perceptive system might take the visual cue into account [10]. This could explain, why the thresholds in TR+CD are not damped, which would consequently cause them to lie in-between of TR ONLY and CD ONLY. According to the maximum likelihood estimation, *”the combined [sensory] estimates should have lower variance, and therefore lower discrimination thresholds, than either the visual or haptic estimate alone”* [10]. Additionally, this might have also slightly weekend the pseudo-haptic effect of the C/D ratio manipulation, as a visual dominance is required to modulate the perception of spatial properties, in our case the lifting distance [21]. A similar reduction in the thresholds for multisensory weight simulation was also observed in previous work [18]. The authors reported a heightened sensitivity toward virtual weight when participants were exposed to EMS and the manipulation of C/D ratios. The authors also clarify that this effect was only significant for C/D gains between 0.1 and 1. We argue, that this range might be increased by an additional technology providing other haptic weight cues, such as the adaptive trigger resistance. Overall, our perceptual findings show that an additional rendering of C/D ratio manipulation successfully widens the range of perceived weight when using adaptive trigger resistance. Our work, therefore, extends the list of approaches to VR haptics that combine device-based techniques meaningfully with pseudo-haptics. Similar approaches were previously explored to support the perception of different levels of grasping effort [2] or to amplify the curling of the control hand to simulate various levels of object stiffness [1].

6.2 Combining Adaptive Trigger Resistance with C/D Ratio Manipulation Improves Weight Illusion

One of our key findings from the questionnaire responses is the high ratings for Effectiveness, meaning that participants perceived different weights in each type of weight simulation. This finding confirms the feasibility of using both techniques individually and in combination to induce a sensation of virtual object weight.

While, on the one hand, the combined method was valued to be significantly more *realistic* than the adaptive trigger resistance alone, on the other hand, it was rated to be significantly more *efficient* than the C/D ratio manipulation alone. This observation suggests that the additional amplification of arm movement contributed more to a sensation closer associated with how differences in weight feel in the real world, but the additional modulation of grasping force at the trigger was more successful in creating an efficient weight illusion. However, the TR+CD received relatively high ratings for both characteristics, and for confidence levels and preference. Hence, this study presents early findings that both techniques overcome the shortcomings of the individual methods and add the perceptual benefits of both approaches to the weight illusion. However, it is important to note that further research is needed to fully understand the added benefits of the combination in terms of mitigating the limitations of individual renderings.

The study indicates that the temporal moment during interaction plays a crucial role in the efficiency with which participants perceive differences in weight through haptic and pseudo-haptic stimuli. The data suggest that participants determined differences in weight more quickly when the adaptive trigger resistance was present, and significantly faster when both stimuli were present than in the pseudo-haptic technique alone, potentially due to the increased perceived size in weight difference. An improvement is also reflected in the confidence levels, as participants were significantly more confident in their choices when the trigger resistance was present. This finding is consistent with our expectation that the trigger resistance would serve as the initial weight cue, but also emphasizes that the early presentation of haptic weight cues is crucial for creating a convincing weight illusion. Based on these results, it is proposed that similar continuous weight illusions may be achieved by incorporating other haptic devices that support early weight cues during grasping, such as Grabity [8], as well as other haptic interfaces that can complement the sensation of weight during lifting, such as EMS [27]. However, it is essential to note that further research is needed to fully understand the potential benefits of different temporal moments during the interaction for enhancing the weight illusion.

The study found that manipulating the C/D ratio did not result in higher perceived lifting efforts, contrary to the initial expectations. It is proposed that the increased effort required to pull the trigger with higher levels of resistance causes also higher engagement of the flexed arm muscles and, therefore, may also have contributed to this sensation. Participants also reported this strain in the arm muscles during interviews for conditions that rendered the trigger resistance. To enhance the perceived lifting effort in future studies and simulate even heavier weights without further amplifying the arm movement, it is suggested that the use of EMS as an additional third weight cue should be considered. Recent research has demonstrated that combining C/D ratio manipulation with EMS can successfully widen the range of perceived weight by more than two times [18].

6.3 Success of Weight Simulation Technique Depends on the Person

As reported in the results, for a limited number of participants, one or two of the three conditions did not induce a sense of weight. Very often in these cases, participants were unable to identify a cue on which they could base a sense of weight. Comments derived from the interviews did not clarify the reason behind this. While a few participants hypothesized that they might have experienced a learning effect throughout the experiment and needed to get used to the simulation, the counterbalanced presentation of the conditions prevented an order effect in our study. In addition, we cross-referenced demographic characteristics with the individual thresholds, but no correlation was found. To facilitate a better understanding of the perceptual mechanism that prevented the processing of the stimuli in these cases and intercepting a weight illusion, further research is needed. For example, the intensity of the stimuli could be increased to explore, if a stronger sensory signal improves the perception.

6.4 Limitations

Our main study explored weights within a range of trigger resistances and C/D ratios. Virtual weights that lie below or above the weight spectrum of the resistance could not be considered, however, these might have a different effect on the thresholds and weight experience. Future work could explore lighter weights by modifying *Triggermuscle* to decrease the minimum resistance level. The rendering of heavier weights could be investigated, for example by applying large perceivable C/D ratios, as explored in previous work [34]. Furthermore, other haptic interfaces with absolute weights differing from our device could impact the thresholds and the weight illusion. Similarly, our study design included only one cube size, while previous work identified an effect different sizes can have on the C/D manipulation [19]. Further studies are needed to determine size-related influences. Moreover, as reported in section 5, datasets for the thresholds collected in some conditions needed to be removed due to a noisy response pattern or an impossible curve fitting. A more fine-grained sampling across the stimuli ranges, or a higher number of repetitions, might have provided a better understanding for this cases, or might have prevented the failure of the fitting. However, we decided on 75 trials in total (25 per condition, repeated each stimulus 5 times) as this represented a good trade-off in our experiment between the number of tested stimuli, repetitions per stimulus, number of conditions, and prevention of arm fatigue as each trial included lifting the arm twice (150 arm lifts in total). To maintain the data reliability of psychophysical experiments typically applying between 10 and 20 repetitions, we compensated our comparably low number of 5 repetitions with a comparably large number of 29 participants and by this ensured 145 recorded data points in total for each stimulus, which is similar to the total number of repetitions in previous studies [2, 9, 36]. However, future studies should include more repetitions and a wider range of comparison stimuli to avoid mentioned shortcomings. In addition, results of the subjective questionnaire on weight illusion only reflect the perception of participants for whom a weight illusion occurred. Finally, due to the structure of the HMD, the headphones with active noise-cancelling did not fully enclose the ears for some participants. While a few participants reported servo sounds during the interviews, this aspect was not considered for weight perception, and our data show no evidence of a confounding factor. Further, while a few participants reported vibrations, we controlled for an effect of vibrations by implementing obfuscation angles. This ensured that vibrations were independent of the level of rendered virtual weight and, thus, could not serve as a weight perception cue for participants.

7 CONCLUSION

We studied a novel combination of a hardware-based and a software-based pseudo-haptic technique to achieve a continuous VR weight perception. While a modified VR controller rendered adaptive trigger resistance during grasping, manipulation of the control-display ratio (C/D ratio) induces a sense of weight through lifting. In a psychophysical study (N=29), we tested our multimodal technique against individual renderings. Our findings show that participants were significantly more perceptive towards more minor weight changes in the combined weight simulation compared to the individual methods and significantly faster in determining weight differences with both cues present compared to the pseudo-haptic method alone. The application of both weight cues also facilitated higher confidence and was preferred the most out of the three techniques. Conclusively, our work demonstrates the meaningful benefit of virtual weight simulation when presenting multimodal weight cues at different stages during the object interaction. In future work, our findings could be applied to new combinations of haptic devices with the manipulation of C/D ratio that could further be extended by a third weight simulation, such as electrical muscle stimulation.

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