

Experiencing Dynamic Weight Changes in Virtual Reality Through Pseudo-Haptics and Vibrotactile Feedback

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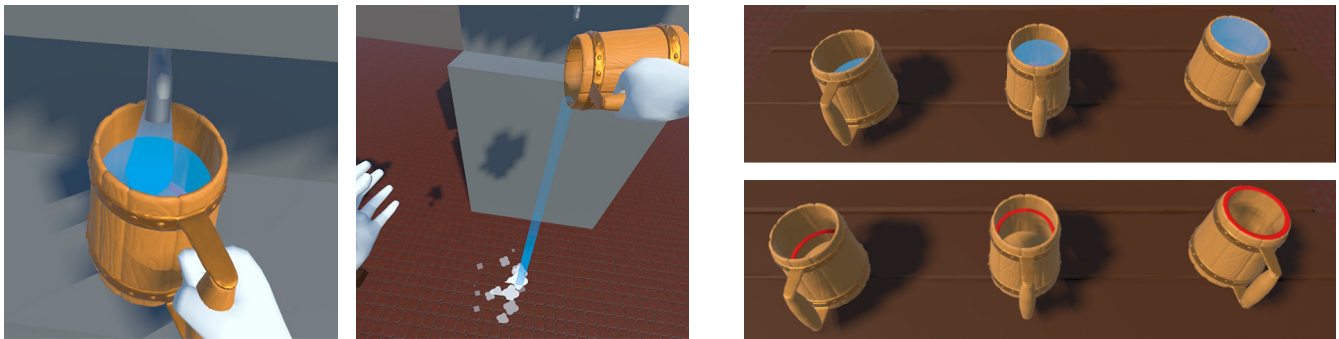


Figure 1: (left) In our user study, participants filled or poured out a virtual mug. To simulate the weight change, the VR system dynamically adjusted the control-display (C/D) ratio according to the water level. As an alternative simulation, additional vibrotactile feedback from a consumer VR controller was tested. (right) Three different levels of weight changes were tested.

ABSTRACT

Virtual reality (VR) objects react dynamically to users' touch interactions in real-time. However, experiencing changes in weight through the haptic sense remains challenging with consumer VR controllers due to their limited vibrotactile feedback. While prior works successfully applied pseudo-haptics to perceive absolute weight by manipulating the control-display (C/D) ratio, we continuously adjusted the C/D ratio to mimic weight changes. Vibrotactile feedback additionally emphasises the modulation in the virtual object's physicality. In a study (N=18), we compared our multimodal technique with pseudo-haptics alone and a baseline condition to assess participants' experiences of weight changes. Our findings demonstrate that participants perceived varying degrees of weight change when the C/D ratio was adjusted, validating its effectiveness

for simulating dynamic weight in VR. However, the additional vibrotactile feedback did not improve weight change perception. This work extends the understanding of designing haptic experiences for lightweight VR systems by leveraging perceptual mechanisms.

CCS CONCEPTS

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

KEYWORDS

weight perception, weight change, pseudo-haptics, haptic illusions, vibration, virtual reality, multisensory integration

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1 INTRODUCTION

Experiencing changes in weight during the interaction is an essential part of natural object perception [16]. In the real world, the sense of increasing or decreasing heaviness is formed through tactile and proprioceptive signals registered by receptors in muscles, tendons, joints and the skin [18]. Substituting these complex haptic sensory signals to create an illusion of dynamic weight change in VR is, however, challenging. With the emphasis on lightweight ergonomics, recent consumer VR controllers lack elaborate haptic rendering capabilities by providing only vibrotactile feedback. The user's haptic sense can, therefore, not be stimulated in ways equivalent to real-world experiences, e.g. for conveying the growing weight of a mug being filled with water. Compelling VR simulations rely on various criteria to allow users to feel "present" or "immersed" in the virtual environment (VE) and to believe that a virtual object is real. Several definitions characterise presence as "the (psychological) sense of being in the virtual environment," while immersion is often defined as "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant" [32]. As tactile sensations make interactions with virtual objects feel more natural in a way that is not achievable with visuals or audio alone [33], there is a need for new VR techniques to haptically simulate dynamic weight changes.

To mimic a sense of object heaviness in VR, prior work explored the use of pseudo-haptics [20, 27, 29], haptic devices [1, 4, 5, 34, 39] or a combination of both [14, 35]. While haptic devices often rely on complex hardware, pseudo-haptics can be easily integrated with current consumer VR systems. Pseudo-haptics create a perceptual illusion of haptic sensations by incorporating other modalities such as vision into the perception [15]. Complex and expensive hardware can then be avoided, making pseudo-haptics a cost-effective and suitable software-based technique for designing haptic experiences for consumer VR. A common approach is the manipulation of the control-display (C/D) ratio, which introduces an offset between the user's real hand and virtual hand in VR. The inconsistent hand mapping induces a positive or negative gain in users' arm movements, affording users to physically move their arms more or less. The result is a perceptual illusion of heavy and light objects [14, 27, 29, 35]. Previous approaches, however, mainly explored absolute weight in VR, meaning, that the virtual weight of an actively lifted object remains constant throughout the lifting interaction. However, ensuring a consistent haptic experience when users' actions cause a weight change, such as filling a cup with water, requires the system to dynamically render that change in real-time. Fewer works focussed on the perception of weight changes while the user holds onto the object. Different haptic systems were proposed by shifting fluids [4], which, however, also suffer from the need for additional hardware and complex maintenance. Solutions for dynamic weight changes that are suitable for off-the-shelf VR systems, such as the C/D ratio manipulation, remain underexplored.

To enable the perception of changing weights and increase immersion in consumer VR, we built upon previous work on pseudo-haptics and investigated whether dynamically adjusting the C/D ratio during the interaction simulates changes in object weight and whether additional vibrotactile feedback further enhances a sense of

weight change. We hypothesise that users will dynamically adjust their physical hand position (up- or downwards) to compensate for the tracking offset. Actively engaging the arm muscles might then alter the perception of the object's weight. Our work is informed by the following three research questions:

- RQ1 Can the manipulation of C/D ratio simulate dynamic weight changes in VR during the interaction?
- RQ2 Does additional vibrotactile feedback further enhance the perception of weight changes in VR?
- RQ3 Does an improved perception of dynamic weight changes affect the user's VR immersion positively?

We conducted a user study ($N = 18$) to compare the multimodal technique to the pseudo-haptics method alone and a baseline condition and evaluated users' perception, experience and immersion. Our findings confirm that adjusting the C/D ratio during the interaction can successfully simulate changes in an object's weight. However, additional vibrotactile feedback did not further enhance the experience, for which we discuss ideas for more meaningful improvements. With this work, we expand on the findings of prior work in the field of pseudo-haptic weight and provide new insights to enrich the perception of object heaviness and its change in VR.

2 RELATED WORK

This section summarises previous works on the perception of absolute weight and dynamic weight changes in VR. Approaches are differentiated based on software-based pseudo-haptics without external equipment, making them more suitable for consumer VR set-ups and hardware-based haptic interfaces. The former induces the illusion of weight by using, e.g. visual input, the latter applies physical stimuli to the user's body.

2.1 Experiencing Absolute Weight in VR

There is a large body of research work on the perception of absolute weight in VR. Software-based approaches that can be incorporated with consumer VR systems primarily use the manipulation of C/D ratio or velocity to convey a sense of object heaviness [17]. The common technique of changing the C/D ratio introduces an offset between the user's real hand and the virtual hand representation in VR and effectively induces an illusion of object heaviness. C/D ratios below 1 apply a negative gain on the arm movement, affording users to invest more effort into moving their physical hands, thus, creating an illusion of heavier objects. C/D ratios above 1 apply a positive movement gain and create an illusion of lighter objects. The effect was illustrated early on in a non-VR setting, in which users compared the weight of virtual balls displayed on a screen while lifting a physical ball on a stationary hardware device [6]. Rietzler et al. applied such offsets to the tracking of a consumer VR controller to render the weight of a virtual ball in a VR game and found an increased user enjoyment and immersion [27]. They also observed that users still enjoyed the weight simulation with stronger movement gains and perceivable offsets. In contrast, Samad et al. successfully adjusted the C/D ratio in VR within a smaller range and created the illusion of a prop changing its weight [29]. Besides the manipulation of the virtual hand's position in VR, changes to an object's visual appearance also affect users' sense of weight. A previous study testing common real-life weight illusions in a VR

setting found that objects appearing dark and made out of metal were thought to be heavier than bright objects [20]. Despite the benefit of the software-based technique to be easily integrated with off-the-shelf VR systems, the pseudo-haptic weight effect can be limited, as illustrated by Samad et al., quantifying the possible range of altered perceived weight to 5g.

The combination of pseudo-haptics with haptic devices allows the integration of not only visual but tactile sensations and widens the range of simulated weights. Manipulating the C/D ratio simultaneously with electrical muscle stimulation (EMS) enabled Kim et al. to double the span of simulated weights [14]. While a multisensory approach injects perceptual benefits to strengthen the weight illusion in VR, it also allows the presentation of different weight cues at different moments during the object interaction. Stellmacher et al. adjusted the physical resistance of the trigger button while grasping an object and manipulated the C/D ratio throughout lifting, which allowed users to discriminate smaller weight differences [35].

Higher attention was directed on hardware-only solutions, with many proposed devices generating active forces to the user's body to create an experience of object weight. Their form factors range from being handheld to being worn on users' hands, upper body or feet which offers a variety of physical sensations. Handheld devices often render haptic feedback to users' hands by, e.g. shifting the weight or weight distribution of the handheld device itself. By transporting a movable weight along a physical prop called "Shifty", Zenner et al. enhanced the perceived realism of virtual objects [40]. Shigeyama et al. reconfigured the structure of their handheld prob "Transcalibur" to alter the perceived shape and weight of objects [31]. Users' realism and enjoyment were also enhanced by changing the weight of a handheld prop itself by pumping liquid in or out of the device [12]. A different technique was used for the "Drag: on" system, which increases or decreases its surface area to change its air flow resistance when moved through space [39]. Another concept was applied with the VR controller "Triggermuscle" which solution is much closer to consumer VR hardware. Stellmacher et al. utilised the trigger button as a common input component and adapted the level of resistive force according to different virtual weights [34]. Incorporating a commercial VR controller into the solution was also done in the device "STROE", connecting users' feet with the handheld controller via a string that can be pulled downwards [1]. In contrast, proposed hardware worn on users' hands typically targets individual fingers or finger pads. A common technique is to render tactile sensations such as shear forces or gravitational pull at the fingertip by stretching [21] or deforming the skin [30]. Impacting hand posture, the finger-mounted device "Grabity" locks fingers in place during grasping and renders vibrations to convey a sense of heaviness [5]. A very different approach stimulates users' arm muscles through EMS [19]. Another approach has also been presented as a pseudo-haptic method called "HEMP", which stands for Hand-displacEMent-based Pseudo-haptics, with the main idea to provide haptic-like sensations by dynamically displacing the visual representation of the user's hand for changing perception of force [25].

While these hardware solutions provide a rich and diverse field of haptic stimuli for weight simulation in VR, they suffer from drawbacks such as mechanical complexity, high costs, hygienic aspects and high barriers to mass consumer production. Moreover,

despite the high focus on absolute weight perception in VR, dynamic weight changes have been underexplored so far.

2.2 Experiencing Dynamic Changes in Weight

Only few works investigated solutions to render virtual weight in more dynamic ways. Cheng et al. developed "GravityCup", a handheld device that can be filled with water from an additional container carried on users' backs [4]. By shifting the fluid between the handheld cup and a water tank, the mechanism changes the actual weight of the device that users hold in their hands. A very similar concept was followed by Monteiro et al. with their system "FluidWeight", which was, however, designed to be attached to a consumer VR controller [22]. Their setup increased user enjoyment and immersion. A complementary hardware extension to a commercial VR controller was also proposed by Wang et al. [38]. In contrast to the previous systems, "VibroWeight" incorporates liquid metal as well as additional vibration. While some previous techniques for simulating dynamic weight changes can be combined with existing VR hardware, they still rely on additional custom equipment. Despite the discussed benefits of pseudo-haptics for weight perception in VR, no software-based solution has yet been investigated to convey a sense of dynamic weight change in consumer VR systems.

3 PSEUDO-HAPTIC WEIGHT CHANGE

This research focuses on simulating changes in weight by adjusting the C/D ratio and rendering additional vibrotactile feedback from a VR controller. To do so, we chose an interaction scenario in which users fill a virtual mug with water from a tap or pour the water out again. This section outlines our implementation of the pseudo-haptic method and its combination with the controller's vibration to form a multimodal sensation of weight change.

3.1 Control-Display (C/D) Ratio Manipulation

Our implementation of the C/D ratio manipulation is based on previous work [27, 29], which we adapted to our novel purpose of conveying dynamic weight changes. Previous simulations of pseudo-haptic weight adjusted the ratio before users lifted an object, and maintained the value throughout the interaction. To account for real-time changes in object weight, our approach goes beyond that and increases or decreases the C/D ratio *during* the interaction. More specifically, we alter the value during the filling or pouring of the mug. In contrast to a C/D ratio of 1, where users maintain a consistent arm effort to control their hand's vertical position, our pseudo-haptic technique disrupts this by dynamically adjusting the system's responsiveness to the applied effort. Users must now adapt their control effort to maintain their hand at the same display position. We based this concept on the following idea. In real life, both interactions require stabilising arm movements to grab a mug and hold it steady in mid-air while controlling the water flow going in or out of the mug. As the mug's weight increases or decreases, the arm effort is dynamically adapted to sustain the mug's secure lift in mid-air. We incorporated this concept into the VR interaction and hypothesised that users would also dynamically adjust their arm posture to stabilise the virtual mug, compensating for the growing/shrinking displacement between the visually perceived virtual hand and the proprioceptively perceived physical hand.

This posture adaptation engages users' arm muscles and increases muscle effort, generating sensory signals as substitutional weight cues. Larger virtual weight changes then demand more extensive posture corrections, hence more effort, while smaller virtual weight changes require less effort. In our VR interaction, the extent of the hand's vertical displacement is directly influenced by the water level and its corresponding weight ($CD\ ratio = 1 - (waterLevel * (1 - maxCDRatio))$). We describe the water level between 0 (empty) and 1 (filled). To maintain users' sense of ownership over the virtual hand during the simulation, we apply a maximum C/D ratio of 0.6 for the heaviest weight (filled), which is informed by Samad et al. [29]. Hence, our C/D ratios simulate dynamic weight changes in a range between 1 and 0.6 (mapped to water levels 0 and 1). Therefore, a value change of 0.6 along the local y-axis illustrates our maximum weight change. To replicate realistic water dynamics, we adjusted the water level and its flow speed during the pour interaction. As the angle of the mug is tilted to pour water, the flow rate increases, slightly speeding up the process of emptying the container. When filling the mug with tap water, the liquid consistently flows into the container at a uniform speed, mimicking real-life behaviour.

3.2 Vibrotactile Feedback

In real life, the discrimination of weight improves with more sources of sensory information [11]. We, therefore, applied additional vibrotactile feedback from the VR controller, aiming to enhance the weight change illusion created by the pseudo-haptic method alone. The approach of using a consumer VR controller to provide physical stimulation for weight changes differs from previous works that include additional haptic hardware [9, 10, 23, 24, 28, 37]. However, Rietzler et al. demonstrated in their earlier works that vibration enhances immersion and the "feeling of interacting with real objects" when provided alongside pseudo-haptics [26]. In our combined technique, the vibration is always rendered whenever the mug's water level changes. We adjust the vibration's amplitude linearly to the water flow for a meaningful and distinguishable simulation of weight changes. In the case of filling a mug, an initial high amplitude mimics the high impact of the water stream hitting the inside walls of an empty mug. It lessens with the growing water volume, i.e. decreasing impact force ($amplitudeFill = 1 - waterLevel$). This mimics the real-life sensation of filling a physical mug. When a mug is empty, a person can feel the impact of the water towards the mug more significantly, as opposed to a mug with a higher volume. When pouring water out of the mug, the high amplitude mimics the initial strong water flow and lessens with the shrinking amount of water ($amplitudePour = waterLevel$). This mimics a physical water stream running out of the mug until the mug is empty.

4 USER STUDY

Our user study investigated whether modifying the C/D ratio and rendering additional vibration replicates a change in weight perception in VR, and if the experience of dynamic weight shift enhances users' feeling of immersion. To do so, the experiment followed a within-subject design, where each participant experienced the pseudo-haptic approach alone, the combined technique and a baseline condition with no weight simulation. The order of all three conditions was balanced out using the Latin square.

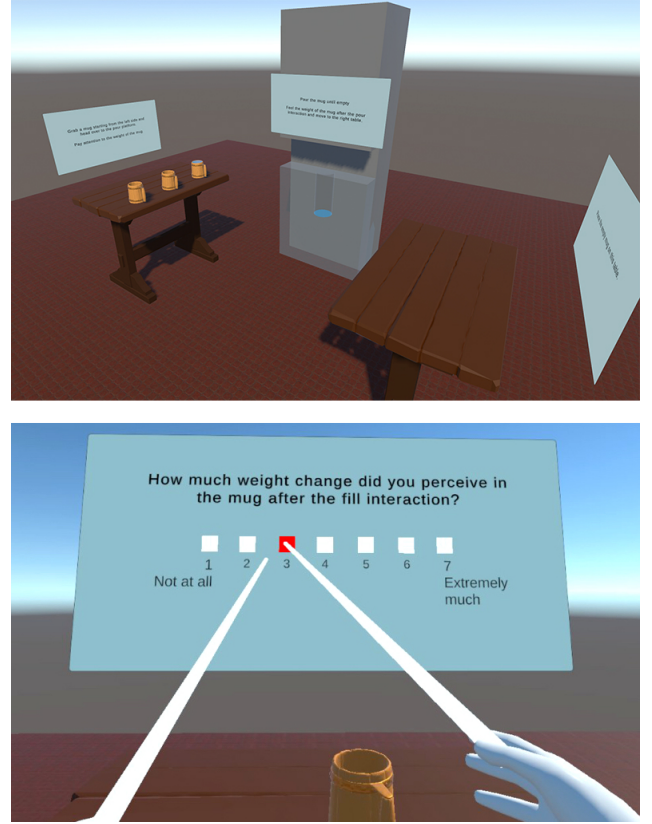


Figure 2: (Top) VE of our user study showing the three initial mugs and the platform that either catches the mug's content (pour scenario) or provides a virtual water tap (fill scenario). Participants placed the mugs after each interaction on the table on the right side and responded to the questions hovering above. **(Bottom)** The Likert scale question presented to participants after each fill or pour interaction to assess their perceived weight change.

4.1 Participants

We recruited 18 participants (10 female, 8 male), with four persons reported for themselves to be in the age category of 18-24 and the remainder in the age category of 25-34. Two individuals had high school diplomas, 12 people had a bachelor's degree, and four people had a master's degree. Participants' fields of work are fairly broad, ranging from politics over science to business administration, with five of them coming from an engineering background. The level of participants' VR experience was mixed ($M = 3.44$, $SD = 1.92$), with three being "not at all experienced" (min rating of 1), and one being "extremely experienced" (max rating of 7). The remaining 14 participants distributed their ratings as follows: five rated themselves as 2, one rated themselves as 3, three rated themselves as 4, three rated themselves as 5, and two rated themselves as 6 out of 7. After an initial screening of the ethics board of our University of St. Gallen, our research was exempt from a formal full review. Participants took part in the study voluntarily and did not receive monetary compensation for their participation.

4.2 Apparatus

The VE was developed in Unity (see Figure 2). During the experiment, participants were equipped with the Meta Quest 2, including an HMD and handheld controller. A laptop was used by participants to fill out questionnaires between conditions and observe participants' views in VR via the Meta Quest's casting feature.

4.3 Task

To create a realistic experience of different weight changes, participants performed two types of interactions inside VR: filling a mug with water and pouring water out of a mug. Both interactions were performed with three weight simulations: Base, CD and CD+Vib. In the Base condition, no weight simulation was applied. The CD condition simulated the weight change through the manipulation of the C/D ratios. Additional vibrotactile feedback was rendered in condition CD+Vib. In total, six versions were tested: Fill-Base, Fill-CD, Fill-CD+Vib, Pour-Base, Pour-CD, and Pour-CD+Vib.

In the *fill* scenario, participants were instructed to fill three mugs with water up to a predefined target level. In the *pour* scenario, participants were asked to empty three mugs initially containing water by pouring out the water. In total, we simulated three changes in weight with mugs filled to $1/3$, $2/3$ and filled. The respected target volumes (filling) or initial volumes (pouring) are represented by $V_{1/3}$, $V_{2/3}$ and V_1 . A red ring inside the mug indicated the respective target level in the filling task, and an initial water volume inside the mugs illustrated the initial water level in the pouring task (see Figure 1). At the beginning of the *fill* task, participants grabbed the first mug on the table. They then proceeded to a platform, at which they filled the mug with water using a virtual water tap up until the indicated target level was reached, which was confirmed by a green ring colour. In case the mug was overfilled, participants needed to pour part of the content, until the correct target level was reached. During the moment when the mug contained more water than the target level, the simulated weight remained true to the maximum correct water volume of that interaction. After completing the task, participants placed the mug on a second table. Finally, participants then indicated their agreement on a 7-item Likert scale of "How much weight change did you perceive in the mug after the pour interaction?" (1 = Not at all, 7 = Extremely much), see Figure 2.

Upon completion, participants repeated the process with the next mug, until all three mugs were on the second table. In total, the procedure of filling the three mugs was repeated three times, with the target water level assigned to the mugs across rounds according to the Latin square. The same task and repetitions were followed in the *pouring* task. In contrast to the previous setup, the three mugs were already filled with the initial water level (see Figure 1). Participants proceeded with emptying the mugs at the platform, now equipped with a container catching the virtual water and, again, rating their perception of the weight change after placing the empty mug on the second table. To ensure a correction of arm posture during the hand displacement and test its impact on the perception of weight change, we specifically designed the affordances of the virtual fill- and pour platforms (see Figure 2) to create a confined space into which the mug needed to be moved for the water transfer. As the mug's size resembled that of a 1-litre pitcher, the platforms' gaps provided sufficient space for comfortable manoeuvring, while

requiring the correction of arm posture during the weight change to prevent collisions with the platforms. In the fill-interaction, the water tap would also automatically shut off when the mug was moved too far away.

4.4 Procedure

At the beginning of the experiment, participants provided their consent and were informed about the study's purpose. They were then equipped with the HMD and VR controller. As participants moved between the virtual standing desks and platforms in the study, we utilised Meta Quest's internal calibration feature to calibrate the scene. This process accommodated differences in body height among individuals, ensuring a comfortable and consistent body posture when grasping and lifting the mugs away from the desks. To familiarise themselves with the system, participants then completed a tutorial inside VR. The tutorial involved navigating the VE, picking up a mug, filling and pouring it, and choosing options on the Likert scale question. Participants would later use this Likert scale question inside VR to indicate their perceived extent of weight change after each interaction with a mug. No weight simulation was applied during the tutorial.

Participants then performed the study task and tested all six versions: 2 types of interactions (filling and pouring) $\times$ 3 conditions (Base, CD and CD+Vib). Participants were instructed to pay attention to the mug's weight throughout the experiment, however, the hand displacement was not disclosed. After completing a condition, participants set aside the VR equipment and transitioned to a laptop to fill out a post-task weight experience questionnaire, capturing their weight experience, their immersion, and their workload. Participants then proceeded with the next condition and were again equipped with the VR hardware. The same procedure was followed until all conditions were completed. The experiment was concluded with the demographic questionnaire, completed on a laptop.

4.5 Measurements

To understand participants' perceptions and experiences of the virtual weight change, we applied a mixed-method approach and collected quantitative and qualitative data. This section provides an outline of all taken measurements.

Extent of perceived weight change. We assessed the extent of the perceived weight change after each mug interaction and fill level on a 7-item Likert scale, presented to participants inside the VE.

Weight experience questionnaire. We evaluated the weight experience of participants after each condition based on a set of 10 custom 7-item Likert scales ranging from 1, "Strongly disagree" to 7, "Strongly agree" (see Table 1). This questionnaire was completed outside VR on a laptop.

Immersion. After each condition, the Slater-Usch-Steed presence questionnaire was completed on a laptop to measure immersion [36]. Based on variations on one of three themes (the sense of being in the VE, the extent to which the VE becomes the dominant reality, and the extent to which the VE is remembered as a place), participants rated each of the six questions on a 7-item Likert scale. Completing this questionnaire three times during the study, its concise length and short administration time enabled an efficient

Table 1: Weight experience questionnaire presented after each condition, comprising ten 7-item Likert scale (1 = Strongly disagree, 7 = Strongly agree).

#	Question
Q1	I felt all mugs had the same weight before their volume was changed.
Q2	I felt all mugs had the same weight after their volume was changed.
Q3	As the volume of the mugs changed, it required more effort to keep my arm and hand steady.
Q4	As the volume of the mugs changed, I could feel the weight pulling my arm down.
Q5	I focussed to get the volume of the mugs to be as close to the target ring as possible.
Q6	My hand was getting tired.
Q7	I felt the mugs have different weights during the task.
Q8	I felt the weight of the mug changing as the volume of the mug changed.
Q9	I could quickly determine whether the mugs changed their weight.
Q10	The virtual hand seemed to belong to my body at all times.

assessment of participants' immersion levels without straining the study duration.

Workload. After each condition, participants sat down in front of a laptop and completed the NASA TLX [8] questionnaire to rate their perceived workload. We expected the results to identify whether participants' workload is affected by conditions and whether it increases throughout the study.

Participants' thinking-aloud and study conductor's observations. Qualitative data was collected using the thinking-aloud approach. Participants expressed their opinions about the tested weight simulations during the study task which were noted by the study conductor. Additionally, notes were taken on participants' activities inside VR which were observed through the Meta Quest 2 casting feature. Finally, at the end of the experiment, a free-text input form, integrated into the demographics questionnaire, collected concluding thoughts on the weight experience and experiment.

Demographics. Finally, demographic data was gathered, including additional questions regarding VR usage and experience. This questionnaire was completed on a laptop.

5 RESULTS

This section presents our results of participants' perceptions of different weight changes, weight experience questionnaire, immersion and workload. Qualitative findings are summarised of participants' expressed opinions. For the statistical analysis, quantitative responses were processed by performing a one-way ANOVA for repeated measures and Tukey-Kramer t-test for post-hoc analysis. We used ANOVA for parametric and non-parametric data, as it has higher statistical power compared to non-parametric tests and is also quite robust to violation of normality [2], applying it as such to all later presented results.

5.1 Perception of Weight Changes

After each mug interaction, we asked participants to rate their perception of how much change in weight they felt on a 7-item Likert scale (1 = Not at all, 7 = Extremely much). Results are summarised in Figure 3, and descriptive statistics are presented in Table 2.

Perception of different weight changes. Results are summarised in Figure 3a. In the Base condition, participants' responses on perceiving a weight change after *filling* the mugs to different target levels were significantly different ($F(2, 159) = 4.596, p < .05$). The post-hoc analysis showed a significance between filling the mug up to $VD_{1/3}$ and up to VD_1 ($p < .01$). No significant differences were found between target volumes of $VD_{1/3}$ and $VD_{2/3}$ ($p = .186$), nor $VD_{2/3}$ and VD_1 ($p = .421$). In the same Base condition for the *pouring*-task, participants' responses on perceiving a weight change were significantly different for the water volumes ($F(2, 159) = 7.349, p < .01$). The post-hoc test showed the perceived weight change to be significantly smaller after emptying a mug filled with $VD_{1/3}$ than with VD_1 ($p < .01$). No significant difference was found between $VD_{1/3}$ and $VD_{2/3}$ ($p = .065$), and $VD_{2/3}$ and VD_1 ($p = .269$).

In the CD condition, responses after *filling* a mug were significantly affected by the target level ($F(2, 159) = 16.099, p < .001$). Post-hoc tests showed that participants rated their perceived weight change significantly smaller when filling the mug up to $VD_{1/3}$ compared to $VD_{2/3}$ ($p < .01$), as well as compared to VD_1 ($p < .001$). We found no significant effect on responses between $VD_{2/3}$ and VD_1 ($p = .508$). Likewise, responses showed a significant effect for the three volumes of *poured* water ($F(2, 159) = 13.539, p < .001$). Post-hoc test show that participants' judgements were significantly different between emptying the mug with $VD_{1/3}$ and $VD_{2/3}$ ($p < .05$), with $VD_{1/3}$ and VD_1 ($p < .001$), and with $VD_{2/3}$ and VD_1 ($p < .05$).

In the CD+Vib condition, results showed a significant effect of *filled* water level on participants' judgements ($F(2, 159) = 19.074, p < .001$). Post-hoc processing showed that participants perceived significantly smaller changes after filling $VD_{1/3}$ compared to $VD_{2/3}$ ($p < .01$), and compared to VD_1 ($p < .001$), as well as smaller changes for $VD_{2/3}$ compared to VD_1 ($p < .05$). Moreover, we found a significant effect on participants' responses after *pouring* out the mugs among the water volumes ($F(2, 159) = 12.445, p < .001$). Post-hoc analysis showed a significance between emptying a mug with $VD_{1/3}$ and $VD_{2/3}$ ($p < .01$), and between $VD_{1/3}$ and VD_1 ($p < .001$). We found no significant differences between $VD_{2/3}$ and VD_1 ($p = .136$).

Perception of same weight changes across conditions. Results are summarised in Figure 3b. When comparing participants' responses across conditions after *filling* the mug by $VD_{1/3}$, we found a significant effect for the type of weight simulation on the perceived

Table 2: Descriptive statistics for the weight perception of the three volume differences (VD) including the mean and standard deviation (SD).

	Base				CD				CD+Vib			
	Fill		Pour		Fill		Pour		Fill		Pour	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VD _{1/3}	1.89	0.98	2.07	1.10	3.06	1.62	3.30	1.49	3.33	1.39	3.65	1.65
VD _{2/3}	2.28	1.20	2.67	1.24	4.07	1.62	4.04	1.50	4.22	1.30	4.61	1.61
VD ₁	2.56	1.24	3.07	1.68	4.78	1.51	4.87	1.72	4.98	1.47	5.22	1.70

weight change ($F(2, 159) = 17.264, p < .001$). Post-hoc analysis revealed that judgements were significantly different between the Base and CD condition ($p < .001$) and between the Base and CD+Vib ($p < .001$). No significant effect was found between CD and CD+Vib ($p = .537$). The perceived weight change was also significantly affected by the condition when *pouring* out the same volume of VD_{1/3} ($F(2, 159) = 18.017, p < .001$). Post-hoc processing shows significant differences between pouring out a mug in the Base condition and the CD condition ($p < .001$) and between the Base condition and the CD+Vib condition ($p < .001$). No significant difference was found between CD and CD+Vib ($p = .419$).

Similar results were found for *filling* VD_{2/3} into the mug, showing a significance between the conditions ($F(2, 159) = 32.887, p < .001$). Based on the post-hoc analysis, participants perceived changes in weight significantly different in the Base condition compared to the CD condition ($p < .001$) as well as in the Base condition compared to the CD+Vib condition ($p < .001$). No significance was observed between CD and CD+Vib ($p = .844$). The same significant effect of the conditions was observed in the *pouring* task with VD_{2/3} ($F(2, 159) = 24.825, p < .001$). Post-hoc tests showed significantly different responses between the Base and CD condition ($p < .001$) and between the Base and CD+Vib condition ($p < .001$). No significant effect was found for responses between CD and CD+Vib ($p = .530$).

Moreover, we found a significant effect on responses after *filling* VD₁ across the conditions ($F(2, 159) = 48.946, p < .001$). Post-hoc analysis showed that the perceived weight change was significantly different in the Base condition compared to CD condition ($p < .001$) and in the Base condition compared to the CD+Vib condition ($p < .001$). We found no significant differences among responses of CD and CD+Vib ($p = .735$). Participants' responses also showed a significant effect of conditions after *pouring* VD₁ ($F(2, 159) = 24.825, p < .001$). Post-hoc tests revealed a significance between the Base and pseudo-haptic approach ($p < .001$) and between the Base and the combined technique ($p < .001$). No significant differences were observed between CD and CD+Vib ($p = .530$).

5.2 Weight Experience Questionnaire

After each condition, participants rated their general experience of weight changes on ten 7-item Likert scales (1 = Strongly disagree, 7 = Strongly agree, see Table 1). Normality testing results in sufficient evidence that the data set is not normally distributed ($p < .05$). Questions demonstrating similar effects are reported in groups.

Contrasting significant effects in Q1 & Q2 for fill- and pour-responses. Participants' responses to Q1, whether they felt all three mugs had

the same weight before they *filled* the mugs, showed no significant effect across conditions ($F(2, 51) = 0.058, p = .943$). In contrast, responses significantly differed in the *pour* interaction among conditions ($F(2, 51) = 7.793, p < .001$). Post-hoc analysis revealed significantly higher ratings for CD ($p < .01$) and CD+Vib ($p < .05$) compared to the Base condition. We found no significant effect between CD and CD+Vib ($p = .650$). Results for Q2, regarding whether participants felt all mugs had the same weight after their volume was changed, revealed a significant effect among the conditions for the fill interaction ($F(2, 51) = 10.587, p < .001$). Post-hoc processing showed that participants' agreed significantly more in the Base condition compared to CD ($p < .01$) and CD+Vib ($p < .001$). We found no significant effect among responses between CD and CD+Vib ($p = .975$). Results for the pour interaction did not show significance ($F(2, 51) = 1.956, p < .152$).

Similar significances in fill-responses for Q3, Q4, Q7 and Q8. Agreements were significantly impacted by conditions with weight simulations compared to the Base condition for Q3, heightened sensation of arm effort, ($F(2, 51) = 13.798, p < 0.001$), Q4, feeling of the arm being pulled down, ($F(2, 51) = 22.770, p < 0.001$), Q7, the recognition of different weights, ($F(2, 51) = 11.914, p < .001$) and Q8, the simultaneous perception of changes in weight alongside volume, ($F(2, 51) = 24.318, p < 0.001$). Post-hoc testing for Q3-Fill revealed significant differences in perceived arm effort between the Base condition compared to CD ($p < .001$) and CD+Vib ($p < .001$). Post-hoc analysis for Q4-Fill showed significantly higher agreement for the feeling of the arm being pulled down in CD ($p < .001$) and CD+Vib ($p < .001$) compared to no weight simulation. Post-hoc processing for Q7-Fill showed participants to agree significantly more with having felt different weights in CD ($p < .01$) and CD+Vib ($p < .001$) compared to the Base condition. Post-hoc analysis for Q8-Fill showed significantly higher agreement for feeling the mug change its weight alongside the volume change in CD ($p < .001$) and CD+Vib ($p < .001$) compared to the Base condition. We found no significant effect among fill-responses between CD and CD+Vib for Q3 ($p = .931$), Q4 ($p = .833$), Q7 ($p = .615$) and Q8 ($p = .923$). Moreover, same observations were made for the *pour* interaction for Q3 ($F(2, 51) = 5.238, p < 0.01$), Q4 ($F(2, 51) = 6.752, p < 0.01$), Q7 ($F(2, 51) = 6.770, p < .01$) and Q8 ($F(2, 51) = 9.123, p < 0.001$) in which agreements were also significantly impacted by conditions with weight simulations compared to the Base condition. Post-hoc testing for Q3-Pour revealed significant differences in the perceived increased arm effort between the Base condition compared to CD ($p < .05$) and CD+Vib ($p < .05$). Post-hoc analysis for Q4-Pour showed significantly higher agreement for feeling the arm being pulled

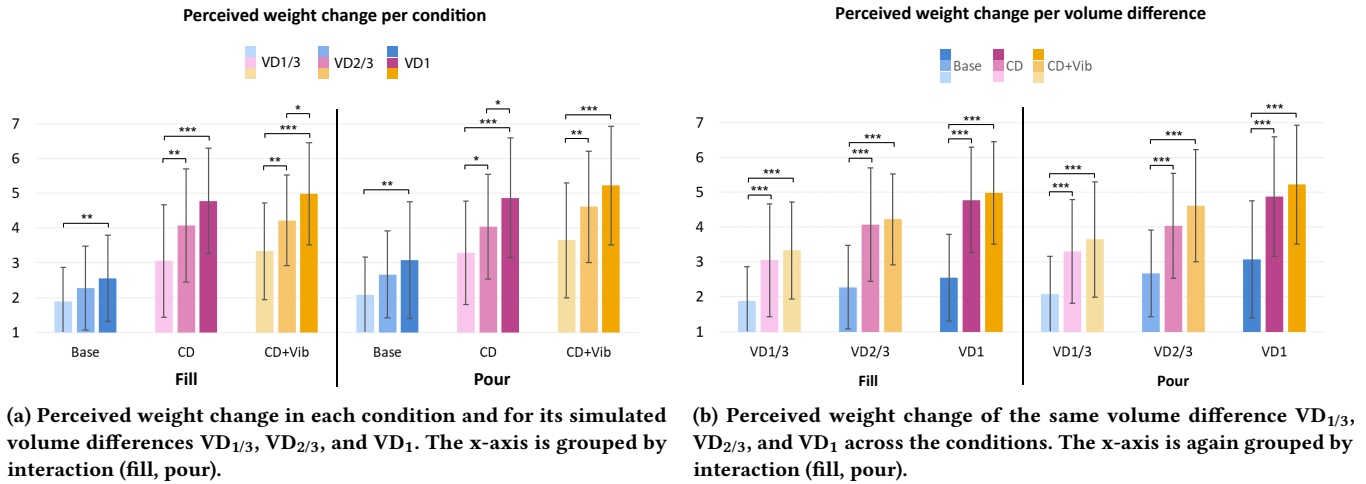


Figure 3: Likert scale responses for "How much weight change did you perceive in the mug after the pour interaction?" (1 = Not at all, 7 = Extremely much). The colour represents the applied weight simulation (blue = Base, magenta = CD, orange = CD+Vib). The saturation indicates the change in water volume. Statistically significant differences are indicated with $p < .05$ (*), $p < .01$ (), and $p < .001$ (***).**

down in CD ($p < .05$) and CD+Vib ($p < .01$) compared to no weight simulation. Post-hoc processing for Q7-Pour showed participants to agree significantly more with having felt different weights in CD ($p < .01$) and CD+Vib ($p < .05$) compared to the Base condition. Post-hoc analysis for Q8-Pour showed significantly higher agreement for feeling the mug change its weight alongside the volume change in CD ($p < .01$) and CD+Vib ($p < .01$) compared to the Base condition. We found no significant effect among pour-responses between CD and CD+Vib for Q3 ($p = .931$), Q4 ($p = .961$), Q7 ($p = .885$) and Q8 ($p = .907$).

Significant differences in fill-responses, but no in pour-responses for Q6 & Q9. Furthermore, participants were significantly affected by the condition for whether their hand was getting tired when responding to Q6 after filling mugs ($F(2, 51) = 4.781$, $p < .05$). Post-hoc test revealed significantly higher agreement in condition CD+Vib compared to the Base condition ($p < .01$). We found no significance in the agreements between Base and CD ($p = .305$), and CD and CD+Vib ($p = .254$). Moreover, conditions had no significant effect on responses after the pouring task ($F(2, 51) = 1.502$, $p = .232$). However, the type of weight simulation had a significant effect on how quickly participants could determine whether the mugs changed their weight when filling them up, captured in Q9, ($F(2, 51) = 10.579$, $p < .001$). Post-hoc analysis showed that condition CD ($p < .01$) and condition CD+Vib ($p < .01$) enabled participants to determine a weight change significantly faster than in the Base condition. A different outcome to Q9 was observed for the pour-responses which did not show a significant effect between conditions ($F(2, 51) = 2.468$, $p = .095$).

No significant effects for Q5 & Q10. No significant effects were found between participants' assessments in Q5 for focusing on getting the volume of the mugs to be as close to the target ring as

possible in the fill-task ($F(2, 51) = 0.867$, $p = .426$) nor the pouring-task ($F(2, 51) = 0.258$, $p = .774$). No significant effect was found in responses between conditions for Q10, whether the virtual hand seemed to belong to their body at all times for filling ($F(2, 51) = 0.434$, $p = .651$) nor for pouring ($F(2, 51) = 0.139$, $p = .870$).

5.3 Immersion

Results of the Slater-Usuh-Steed presence questionnaire confirm our VR study to be sufficiently immersive in all three conditions (answers ranging from 1 to 7). Results show similar ratings in the Base condition for *filling* ($M = 4.59$, $SD = 1.76$) and *pouring* ($M = 4.38$, $SD = 1.81$), in the CD condition for *filling* ($M = 4.53$, $SD = 1.71$) and *pouring* ($M = 4.72$, $SD = 1.74$) and in the CD+Vib condition for *filling* ($M = 4.59$, $SD = 1.77$) and *pouring* ($M = 4.7$, $SD = 1.78$). Normality test results in sufficient evidence that the data set is not normally distributed ($p < .05$), while there is insufficient evidence that the data is not normally distributed in the Base condition with the pouring task ($p > 0.05$). We found no significant effect of the different weight simulations on participants' immersion ($F(5, 642) = 0.55$, $p > 0.05$).

5.4 Workload

NASA TLX results showed low workload levels in all conditions (answers ranging from 1 to 7). Similar responses were observed in the Base condition for *filling* ($M = 2.31$, $SD = 1.85$) and *pouring* ($M = 2.27$, $SD = 1.88$), in the CD condition for *filling* ($M = 2.4$, $SD = 1.91$) and *pouring* ($M = 2.38$, $SD = 1.91$) and in the CD+Vib condition for *filling* ($M = 2.46$, $SD = 1.87$) and *pouring* ($M = 2.42$, $SD = 1.95$). Normality testing results in sufficient evidence that the data set is not normally distributed for Fill-Base, Fill-CD, Fill-CD+Vib, Pour-Base, Pour-CD, and Pour-CD+Vib ($p < .05$). We found no significant difference between the type of weight simulation on participants' workload ($F(5, 642) = 0.26$, $p > 0.05$).

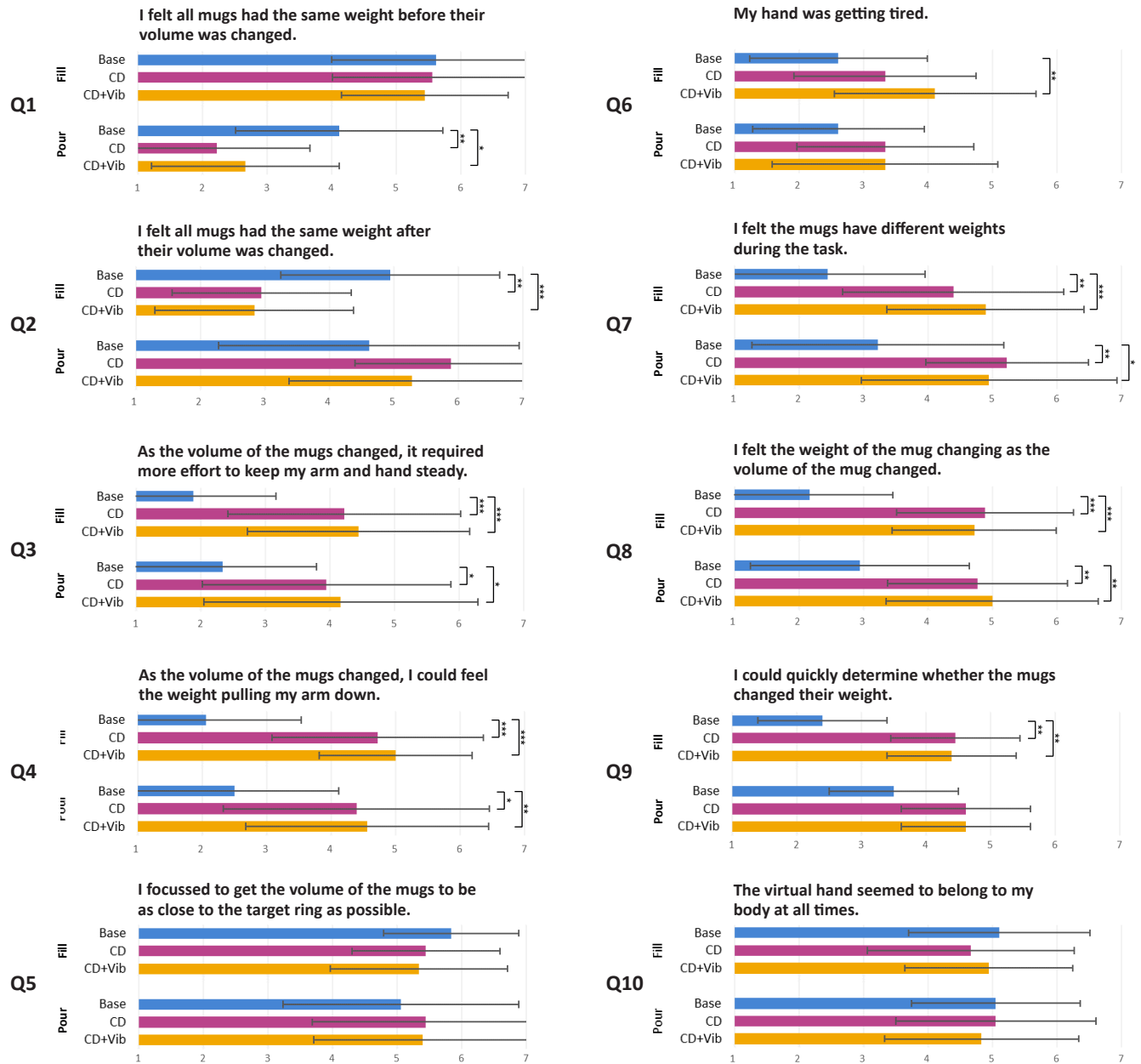


Figure 4: Likert scale responses of the 10-item weight experience questionnaire presented after each condition (Base, CD and CD+Vib). For each question, the responses are grouped by interaction (fill, pour), with responses related to *fill* at the top, and responses related to *pour* at the bottom. The colour represents the applied weight simulation (blue = Base, magenta = CD, orange = CD+Vib). Statistically significant differences are indicated with $p < .05$ (*), $p < .01$ (), and $p < .001$ (***)**

5.5 Qualitative Results

In the following, we summarise participants' expressed thoughts and opinions that were noted down by the study conductor during the think-aloud protocol in each condition. Additionally, we provide exact quotes that were noted in their original form. Furthermore, we report participants' concluding thoughts that they provided in a free-text input field at the end of the experiment.

One researcher analysed the qualitative data, and the presented findings were chosen based on their frequency and relevance to the experiment.

Thinking-aloud, original quotes and conductor's observations during the study task. Most participants commented on sensing the change in object weight, but they did not initially mention the

mechanics behind the simulation. Their weight awareness was expressed through comments such as *"I don't know why, but here I felt the weight change when I fill the mug."* (P6, Fill-CD), *"Wow, I felt the weight here! How?"* (P8, Fill-CD), and *"Wow this one I can feel the weight!"* (P16, Pour-CD). Throughout the task, participants started to comment on their virtual hand's behaviour, e.g. *"I felt the drag on my hand when I'm filling"* (P5, Fill-CD), *"I can see the mug moving down when I feel it"* (P6, Fill-CD) or *"When I empty the mug, my hand is getting more responsive"* (P5, Pour-CD). Additional comments on the tracking's inconsistency were mixed. Some participants did not mind it as they *"correlate it with the real physical world of giving a counter force to the object to lift it"* (P18, Fill-CD) or they did not mind *"the motion of [their] physical hand going up, because, in real life, it's also like that"* (P15, Fill-CD+Vib). One remark stated, *"For me as a VR simulation, this one felt realistic"* (P14, Pour-CD). Contrasting opinions, however, found the *"VR simulation not so realistic"* (P14, Fill-CD) and described the *"bigger offset [...] like a bug"* (P8, Fill-CD) and commented that *"when the hand moves down fast, it breaks the immersion. Otherwise, I don't mind the offset."* (P11, Pour-CD).

Mixed feedback was also articulated about the vibrotactile feedback in the CD+Vib condition. On the one hand, appreciation was expressed as they *"felt the weight difference a lot"* (P14, Pour) or they *"felt stronger weight changes"* (P9, Pour). The haptic feedback *"indicated something is changing"* (P9, Fill) and it *"really helped with the weight change"* (P6, Fill), because *"when there is vibration happening, I know that there is still water inside the mug"* (P13, Pour). Specific remarks on the vibration's pattern show that it also helped some participants to better estimate the extent of volume change as it gave *"a sense of velocity going into the mug"* (P5, Fill) or *"When the volume is less, the vibration is not as intense"* (P10, Pour). On the other hand, the controller's haptic feedback was also perceived as *"too strong in the beginning, but it's realistic that it regresses when it's getting fuller"* (P11, Fill), or *"a bit too strong and annoying"* (P18, Fill). Negative thoughts were also expressed towards the metaphor of conveying weight change through vibration, especially in the Pour-CD+Vib version as *"in real life, when you pour something, there is no vibration, so this one is not so realistic, even though I feel the weight more"* (P13, Pour). The metaphor was, however, found to be realistic for the filling interaction, because *"the vibration is more realistic since it simulates the water hitting the mug"* (P4, Fill).

Another mention was the visual appearance when participants saw the different water levels inside the mug, which led few participants to perceive the mug's weight change in the Base condition, particularly for the largest weight change. One participant felt like they had *"to walk slowly when the mug is full"* (P2, Fill), fearing that they might spill some water. Further comments underlining this observation include *"maybe the visual of the filled mug makes me feel the weight, but barely"* (P11, Pour), *"there is very little weight change, but not nothing."* (P9, Fill), and *"the fullest mug felt a bit of weight change though"* (P9, Pour). Observations of the HMD's screencasting by the study conductor also revealed for the Base condition that many participants overfilled the mug beyond the target level, which was observed only sometimes during the other two conditions and only during the first few rounds. Some argued that the lack of weight sensation made it harder for them to stop filling the mug at the correct moment. Most participants were confused as *"the weight simulation here is missing"* (P4, Fill), they *"could not*

feel any weight change" (P16, Fill) and they *"felt the mug to have the exact same weight, when they are full or when they are empty"* (P17, Pour).

Participants' written comments of the free-text input. 15 participants provided concluding comments at the end of the experiment regarding their perception of weight change. Apart from the previously reported points, two people suggested adding sound effects to the water stream to increase immersion. Statements regarding the overall experiment found the study procedure simple and easy to follow and suggested that future studies incorporate physical interactions by changing the volume of a real mug and comparing the sensation to the virtual interaction.

6 DISCUSSION

With this work, we explored if the dynamic manipulation of the C/D ratio alters users' perceived changes of weight during the interaction (RQ1), and if additional vibrotactile feedback further enhances the weight experience (RQ2). Moreover, the user study investigated if users' feeling of immersion is positively affected by an improved perception of dynamic weight change (RQ3). This section discusses our findings, limitations and future work.

6.1 Dynamic Weight Changes in VR

The results confirm that the manipulation of the C/D ratio allowed participants to perceive the initial absolute virtual weight in VR, before the dynamic adjustment of the offset during the interaction, which is in line with previous pseudo-haptic weight research [27, 29, 35]. As ratings of Q1 and Q2 show, participants believed all empty mugs to have the same weight after being poured and before being filled in the pseudo-haptic method alone and the combined weight simulation incorporating vibration. In contrast, higher ratings indicate participants were less convinced in the Base condition, which might be a result of not sensing a considerable weight in the first place after lifting the mug.

Perceiving weight changes during the interaction. Participants experienced different weights during the task in both pseudo-haptic conditions as illustrated by agreements for Q7. Moreover, responses of Q1 and Q2 reveal that the weight perception was significantly more influenced *after completing the interactions* in both weight simulations compared to the Base condition with no weight simulation. Responses for Q8 particularly emphasise that participants sensed the weight changing alongside the volume change, hence, the moment of exposure to the virtual offset and vibrotactile feedback. These findings highlight that the moment of perception-altering was directly connected to the moment of pouring or filling. Ratings for Q9 even suggest that both weight simulations allowed participants to notice the weight change faster than when no weight simulation was applied. We see two possibilities to utilise the temporal aspect for an improvement of weight change perception by complementing our pseudo-haptic technique with additional weight stimuli either *during* the interaction or *before and after* the interaction. First, previous hardware-based techniques that alter the absolute controller weight through liquid-transfer [4, 12] or that shift the weight distribution of the interaction device [40] might provide additional weight cues during the interaction and extend

the possible range of achievable weight differences. The sensation of weight change might also be emphasised through additional EMS [19] and a dynamic adaption of its intensity. Second, prolonging the exposure time to weight stimuli before and after the pour- and fill-interaction might allow a purposeful bias of the initial baseline weight and shift the level of weight changes to heavier or lighter weights. For example, prior work improved the perception of absolute weights by providing two different weight cues at different moments during the interaction. An adapting level of trigger resistance rendered weight stimuli during object grasping and the adjustment of the C/D ratio impacted the weight sensation during object lifting [35]. Understanding the perceptual integration of multiple weight cues and their cross-modal effect on our pseudo-haptic weight perception should be investigated in future work. For example, while a simultaneous increase in the weight of the interaction device could make the hand displacement too obvious due to increased hand ownership [12] and heightened proprioceptive sensation, the extra weight could also intensify the perceived change in control effort and strengthen the weight illusion.

Perceiving the extent of weight change through changes in control muscle effort. Most importantly, our results illustrate a direct relationship between the mug volume and the extent of perceived weight change for both weight simulations. Hence, not only did participants perceive a weight change, but also how much it changed. Responses of Q3, capturing if more effort was required to keep the hand steady when the water volume changed, support our initial hypothesis that users indeed perceived an increased arm effort and that the change in control effort was interpreted as a change in the mug's weight. As our design of the virtual platforms required maintaining proximity to the mug and, therefore, compensating the displacement for a successful interaction, we observed in the majority of cases that participants instinctively corrected their hand position as they did not trigger the water tap to shut off during filling or did not collide with the platform during pouring. This confirms the feasibility of our applied maximum change in C/D ratios of 0.6 for our novel use case of dynamic weight changes as users were able to maintain sufficient control. However, noticeable displacements between the virtual and physical hand were generally accepted in previous work [7] and contributed to an increased level of enjoyment [27]. More substantial vertical shifts might, therefore, not be perceived as disrupting and could provide meaningful benefits for conveying larger weight changes. Overall, our findings support RQ1 based on the positive relationship between the simulated mug weight and participants' perceived weight change.

Handling visual water representation inside the mugs. While volume changes in the Base condition received generally lower scores, participants still perceived significant differences between the perceived weight change for the small volume and large volume in pour and fill. This might indicate that participants' impressions of the different weight changes may have been influenced by visual cues displaying the distinct water volumes inside the mugs. The impact of visually representing liquid inside a container has been observed to increase muscular activity in cases when virtual liquid was shaken in tandem with a physically co-located container filled with liquid [13]. Providing a more elaborated visual representation of water dynamics in combination with the previously

mentioned liquid-based interaction devices [4, 12], might, therefore, incorporate perceptual benefits of increased muscular activity for conveying increased weight changes. This might not only allow the simulation of dynamic changes in alterations of the weight distribution but also the simulation of heavier fluids, such as liquid metal, through the increased control effort presented as stronger horizontal weight cues. Moreover, the simulation of such water dynamics would also introduce an additional horizontal control effort along the x-axis, which would extend the concept of our study.

Increased muscle effort had no impact on workload. Despite responses to Q3 and Q4 suggesting a perceived increase in physical arm effort and strain for the pseudo-haptic interactions, the overall workload ratings remain consistent with those of the Base condition. We assume that the sensation of heightened physical effort was limited to the perception of the individual weight changes and did not contribute to an overall increase in the experience of physical strain during the study task. In a few instances, we noted additional horizontal hand movement during *pouring* which we attribute to the heightened complexity of stabilising and rotating the mug simultaneously and which might have increased the demanded focus. While an elevated concentration level might have also occurred in the Base condition due to occasional mug overfilling during the fill interaction, there was no increase in workload or impact on participants' focus to achieve the target level (Q5) in either of the two scenarios. Sometimes, when faced with surplus water after overfilling the mug, participants performed an additional pour- and a fill-interaction to reach the target volume, a scenario that was mostly limited to the Base condition. Consequently, any potential effects on weight perception are expected to be minimal. In CD and CD+Vib conditions, the weight experience should remain largely unaffected, as mug overfilling happened here rarely.

6.2 Vibration for Weight Changes

The results show some evidence supporting the hypothesis that additional vibrotactile feedback enhances the perception of dynamic weight change. Even though quantitative analysis reveals no significant difference between both techniques, a slight trend can be observed throughout the data favouring the CD+Vib condition. However, the data variability prevents definitive conclusions about the haptic feedback's impact and requires further investigation. One explanation might be that the haptic feedback itself was too distracting and too overwhelming, leading participants to rely more on the C/D ratio manipulation without fully incorporating the haptic feedback. To minimize the distraction in the future, the maximum amplitude and frequency could be reduced. Nonetheless, qualitative insights from participants' comments provide some support for the effectiveness of the vibration. Participants observed a correlation between the vibration pattern and the mug's volume and the vibration's presence helped them to determine if the mug still contained liquid or was empty. These observations suggest that the haptic feedback assisted some participants in sensing changes, but not so much to which extent. Based on these findings, we believe that an improved vibration design might enhance users' precision when changing weights. A light and constant vibration could express the state of an ongoing weight change and convey active water movement. As soon as the vibration stops, a user will know that the

target weight has been reached. Overall, while the haptic feedback may have contributed to sensing volume changes, further investigation is needed to explore its ability to effectively convey weight changes to different extents and to reach a conclusion on RQ2.

6.3 Weight Change and Immersion

Participants were sufficiently immersed in each condition for both interactions, but no differences were observed between the types of weight simulation. As the immersion measures diverse factors such as field of view, lighting, and frame rate [3], our haptic rendering might not have been impactful enough to influence the overall score. This becomes particularly relevant in a scenario, in which the Base condition had already achieved a saturated immersion rating, leaving no room for considerable further improvement. Furthermore, the VE was consistently designed with the same assets, textures, and lighting across all conditions, which might have levelled the immersion. However, the results show that adding weight simulation by adjusting the C/D ratio or in combination with haptic feedback had no negative influence on user immersion. Responses of Q10 show no significant changes between conditions in terms of participants' perception that the virtual hand continually felt like a part of their own body. A similar statement can be made about the workload, as all conditions received a reasonably low workload, implying that the C/D ratio adjustment and vibration did not have a negative impact on the task's complexity. Finally, it can be concluded that dynamic weight change did not have a significant positive or negative effect on the VR immersion (RQ3).

6.4 Limitations & Future Work

The range of participants' previous VR experience was not thoroughly investigated, leaving the effectiveness of our novel weight simulations across different VR experience levels unexplored. Moreover, the level of immersion remained fairly constant across diverse settings of the VR application, possibly due to consistent environmental design and task nature. The constant speed of the water flow during filling also removes the unpredictability factor in how water flows out of a tap in real life. The specific influence of these factors on immersion, however, remained unexplored. Future work could examine the impact of user expertise on the C/D ratio adjustment, refining the pseudo-haptic feedback through the 'just noticeable difference' principle. Furthermore, the current study maps vibration with the force of the water flow. A different implementation of mapping vibration patterns with the actual volume of the mug should be tested in future works. Experimentation with design alterations, task assignments, and the inclusion of immersive elements like authentic sound effects and physics could considerably enhance the immersive quality of future VR experiences.

7 CONCLUSION

This work explored the simulation of dynamic weight change in VR through the manipulation of control-display (C/D) ratio and additional vibrotactile feedback. We tested the multisensory technique against the C/D ratio adjustment alone and a baseline condition. Our findings demonstrate users' enhanced perception and experience of different weight changes over the baseline condition. The combined method with additional vibration, however, did not

further improve the sense of weight change. We discuss possible limitations introduced by the vibration and how to leverage the physical stimuli more meaningfully. We hope our work informs future haptic designs to achieve a more immersive and realistic experience of dynamic weight changes in consumer VR.

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In this paper, we used Overleaf's built-in spell checker and the current version of ChatGPT (GPT 3.5). These tools helped us fix spelling mistakes and get suggestions to improve the writing of the paper. If not noted otherwise in a specific section, these tools were not used in other forms.

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