Virtual Weight Illusion: Weight Perception of Virtual Objects Using Weight Illusions

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ABSTRACT

This study investigated whether weight illusions in virtual reality (VR) without haptic feedback occur as in the real world. In the experiment, we set up three scenarios to cause three different weight illusions in VR: the size–weight illusion (smaller objects look lighter but feel heavier than larger ones), brightness–weight illusion (brighter objects look lighter but feel heavier than darker ones), and material–weight illusion (lighter-looking materials, such as wood, look lighter but feel heavier than heavier-looking materials, such as metal). The experimental results indicated that the weight perceptions of the brightness–weight and material–weight illusions in VR were opposite to those in the real world. However, the weight perception of the size–weight illusion in VR was the same as in the real world. This study demonstrates how weight illusions occur in VR without haptic feedback, and classifies weight perceptions and the robustness of the illusions.

CCS CONCEPTS

• **Human-centered computing**; • **Interaction paradigm**; • **Virtual reality**;

KEYWORDS

Virtual reality, pseudo haptics, weight perception, weight illusion

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1 INTRODUCTION

1.1 Pseudo-Haptics and Weight Perception in VR

In recent years, virtual reality (VR) head-mounted displays (HMDs), such as Oculus VR and HTC VIVE, have been released and widely used. VR HMDs provide a sense of immersion in a virtual environment; however, they are highly dependent on the user's visual and auditory senses while lacking the haptic sense. Therefore, determining how the haptic sense can be integrated into a virtual environment is an important topic for the advancement of VR technology.

There are various approaches to provide haptic feedback in VR using physical actuators, such as Shifty [21], Transcalibur [17], Haptic Links [19], and CapstanCrunch [18], which can generate an actual force to the user's hands. There is also another approach that provides pseudo-haptic feedback to induce the haptic illusion without physical actuators. Pseudo-haptic feedback induces haptic sensations caused by conflicts between the visual and haptic senses and dominance of the visual sense; consequently, a haptic illusion can be induced by the manipulation of visual objects [10–13]. Pseudo-haptic feedback has great potential for stimulating human perception through multiple sensory channels and producing various user experiences [14]. This study focuses on weight perception using pseudo-haptic feedback.

Various studies have been conducted that demonstrate how pseudo-haptic feedback can generate weight perception in VR identical to that in the real world. Dominjon et al. [6] used a physical ball connected to a PHANToM device and manipulated the C/D ratio, which represents how to change the speed of physical ball movement with respect to the speed of virtual ball movement. In their study, when participants lifted the physical ball seeing the virtual ball, they perceived the difference in the weight of the lifted ball according to a change in the C/D ratio. In another study, Samed et al. [15] used a physical wooden cube with a corresponding virtual object and manipulated the C/D ratio between their movements.

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Consequently, when participants lifted the physical cube seeing the virtual object, they perceived the difference in the weight of the object depending on the difference in the C/D ratio without disrupting their sense of presence in VR. Furthermore, Rietzler et al. [16] simulated weight in VR by manipulating the C/D ratio between actual and virtual hand movements without special hardware devices and using only VR HMD controllers.

Like Rietzler et al. [16], in this study, we also simulated weight in VR without special hardware devices and using only VR HMD controllers, as it is currently common to have VR experiences while holding controllers. In addition, in contrast to Rietzler et al. [16], who manipulated the C/D ratio to induce different weight perceptions in VR, we manipulated only visual objects, without manipulating C/D ratio, to induce different weight perceptions in VR using weight illusions, which create different weight perceptions depending on the appearance of physical objects with the same weight, without haptic feedback.

1.2 Purpose of Study and Hypotheses

The purpose of this study is to investigate whether weight illusions in VR occur as in the real world in a situation where only the appearance of virtual objects is manipulated. In the field of psychology, weight perception is known to be affected by the visual properties of objects. The most famous weight illusion, called the size–weight illusion (SWI) or Charpentier illusion, reveals that the size of an object affects weight perception. When individuals compare the weight of larger and smaller objects of the same weight, the smaller object feels heavier [5]. In addition, the brightness of an object affects its weight perception. This illusion is called the brightness–weight illusion (BWI), in which people overestimate the weight of a brighter object compared to a darker object of the same weight [3]. Weight perception is also affected by an object's material, which is called the material–weight illusion (MWI). A heavy-looking material, such as metal, feels light, whereas a light-looking material, such as wood or polystyrene, feels heavy even when the objects have the same weight [4].

In this study, three scenarios were set up to induce different weight illusions (i.e., SWI, BWI, and MWI) in VR to test the following hypotheses:

Hypothesis 1: The weight illusion in VR occurs as in the real world.

Hypothesis 2a: The weight illusion in VR does not occur as in the real world. A difference in the weight of visual objects is not perceived.

Hypothesis 2b: The weight illusion in VR does not occur as in the real world. The weight of visual objects is perceived as opposite to that in the real world.

2 SYSTEM CONFIGURATION

In this study, we implemented a VR environment that allowed users to lift virtual objects using a video see-through HMD (Oculus Quest; Oculus, Menlo Park, CA, USA) and a controller, OculusTouch, which weighed 130 g. In addition, we used the Unity real-time three-dimensional development platform for HMD control and virtual object drawing. We manipulated the size, brightness, and material of virtual objects. First, with respect to size, in consideration of lifting with one hand, we set the parameter values of the sizes based on the size of the virtual hand. The virtual hand was 17.2 cm long from the tip of the middle finger to the bottom of the palm, and 2.7 cm thick, while the palm was 7.8 cm wide. These values were set assuming the average hand size of a Japanese individual. Based on the hand size, we set the parameter values to 5.0 cm for a small object to fit in the palm of the virtual hand, 12.5 cm for the standard object to fit on the fingers of the virtual hand, and 17.5 cm for a large object to completely cover the palm of the virtual hand while allowing the user to see the wrist (Figure 1a).

In addition, we manipulated the objects' brightness using the display brightness level, which ranged from 0 (black) to 255 (white). We used the maximum and minimum values for brighter-white and darker-black objects, respectively (Figure 1b). Moreover, regarding the material, we used wood and metal texture images to change the appearance of the objects. We also adjusted the texture size, smoothness, and light intensity to be perceived as a wooden and metal cube (Figure 1c). These textures were selected because they were easier to correctly identify among various other textures in our test experiment.

3 EXPERIMENT

An experiment was conducted to test our hypotheses. In the experiment, we manipulated the C/D ratio between the movements of the controller and the virtual object. In contrast to previous studies, which manipulated the C/D ratio to generate weight in VR [6, 15, 16], we manipulated the C/D ratio to test our hypotheses at different ratios to verify the robustness of the results.

We used a C/D ratio of 1.0, which is the same mobility as in the real world, as the standard value; the values of the parameters used in the experiment were 0.4, 1.0, and 1.6. The objects moved more slowly than the actual hand movements with a C/D ratio of 0.4 and more quickly with a C/D ratio of 1.6. The three ratios were selected because they induced different weight perceptions in our test experiment; therefore, the C/D ratios were manipulated to test the robustness of the results.

3.1 Participants

We recruited a total of 13 male participants with a mean age of 21.84 (SD = 0.95) for this experiment. Ten of them were right-handed, while three were left-handed.

3.2 Procedure

First, we welcomed and thanked the participants for participating in the experiment. The participants read and signed a consent form, and we informed them that the experiment concerned weight perception when lifting a virtual object. After that, we trained the participants to lift a virtual object. A standard-sized white object was used in the training to avoid biasing participants to size and color.

In this experiment, we set the object's initial position to 40 cm horizontally away from the body and 30 cm vertically away from the shoulders in the VR environment. In addition, the end position was lifted 30 cm vertically above the initial position. These positions were set assuming a person with the average arm length of a Japanese individual (approximately 70 cm) with their hands raised

Figure 1: Virtual objects used in the first experiment: (a) small and large objects, (b) white and black objects, and (c) wooden and metal objects.

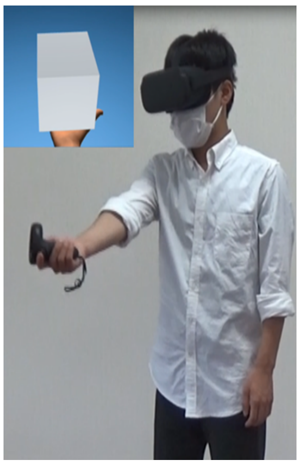

Figure 2: Image of a virtual object and a participant lifting the object. The participant could see his virtual hand and the object in the virtual environment.

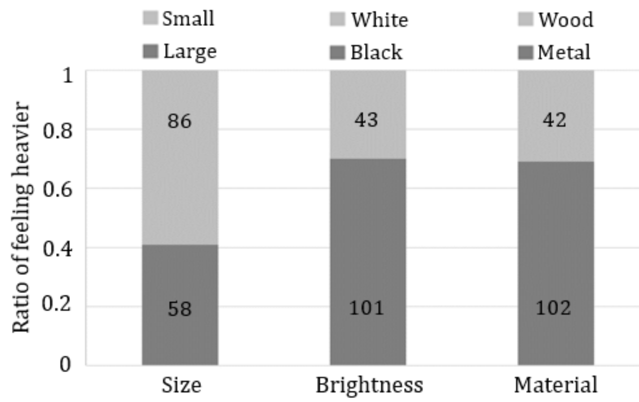

Figure 3: Ratio of feeling heavier in each condition. The values represent the total number of objects reported as heavier objects.

to shoulder height. When the object was lifted and its bottom edge exceeded the lift end position, a beep sounded. We instructed the participants to place the virtual right hand under the object, begin to lift the object when the experimenter said "please lift it," and stop lifting the object when the beep sounded. We also instructed the participants to lift the object at a speed with which they could properly evaluate the weight. Therefore, all participants lifted the objects the same distance. Figure 2 presents an image of the virtual object and a participant lifting the object.

After the training, the experimental task was performed. The participants continuously lifted two objects: small and large objects in the size condition, white and black objects in the brightness condition, and wooden and metal objects in the material condition (Figure 1). After the first object was lifted, the sight temporarily turned dark, and immediately thereafter, the second object appeared. After lifting each of the two objects, the participants reported which object they considered heavier, and rated their confidence in each answer based on a five-point scale (1: not confident at all to 5: definitely confident). The participants lifted each of the two objects four times in a different order at three different C/D ratio levels: 0.4, 1.0, and 1.6. Therefore, each participant lifted the objects 36 times, with a break after every six lifting instances during the task. The order of the objects was randomized. In addition, before the participants lifted the wooden and metal objects the first time, they were asked what they believed the objects were made of. If they answered incorrectly, they were told the correct materials.

After the participants lifted all the objects and had a break, they were instructed to report their impression of which object looked heavier without lifting it by looking at each pair of virtual objects. In addition, the participants lifted a standard-sized white object with each C/D ratio and answered two questions regarding the sense of ownership ("I felt that the hand in VR was my hand") and agency ("I felt like I was moving the object") based on a seven-point scale (1: definitely disagree to 7: definitely agree), respectively.

3.3 Results

One participant arrived late for the experiment and could not perform all the tasks. Therefore, the incomplete experimental data of this participant was collected preliminary and eliminated from the following analysis.

3.3.1 Impression and Feeling of Weight. First, we calculated the percentage of the participants' impressions in terms of which object appeared heavier in each condition. The results indicated that large, black, and metal objects appeared heavier at 66.67% in the size condition, 83.33% in the brightness condition, and 100% in the material condition. Although the tendency was weak in the size condition, the large, black, and metal objects in VR caused the impression of heavier objects for the participants, just as in the real world.

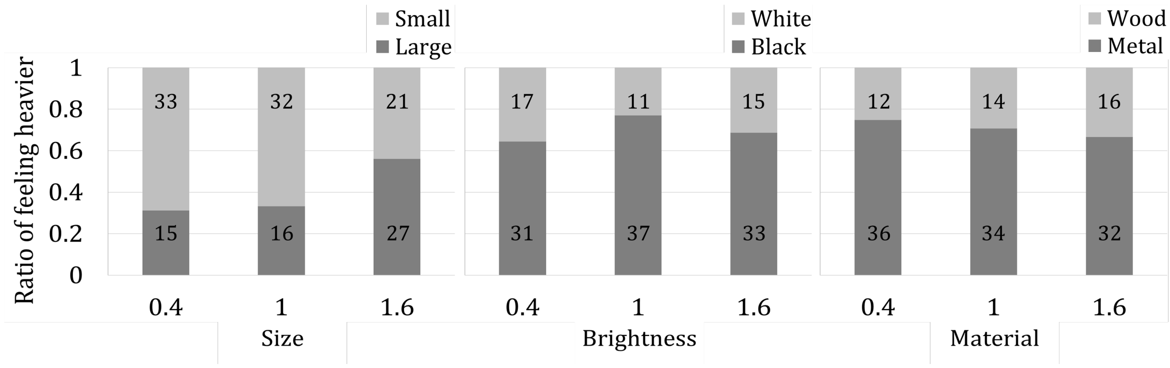

Figure 4: Ratio of feeling heavier with three C/D ratios in each condition. The values represent the total number of objects reported as heavier.

Next, to test the hypotheses as the overall tendency of each condition, we performed Fisher's exact test on the total number of objects reported as heavier objects with all three C/D ratios in each condition (Figure 3). The results revealed that in the brightness and material conditions, black and metal objects were reported to feel heavier significantly more than other objects (brightness condition: $p < 0.01$, $g = 0.20$; material condition: $p < 0.01$, $g = 0.21$). The results thus indicate that the effects of the BWI and MWI in VR contradicted those in the real world. In contrast, in the size condition, small objects were reported to feel heavier significantly more than large objects ($p < 0.05$, $g = 0.10$). This reveals that the effect of the SWI in VR was the same as that in the real world, as opposed to that of the BWI and MWI in VR.

Moreover, to investigate the robustness of the results, we performed a chi-square test on the total number of objects reported to be heavier with the three different C/D ratios in each condition (Figure 4). The results indicate that in the brightness and material conditions, there were no significant differences, signifying that there was no difference in the numbers with the three C/D ratios (brightness condition: $x2(2) = 1.86$, $p = 0.40$, *Cramer's* $V = 0.06$; material condition: $x2(2) = 0.54$, $p = 0.76$, *Cramer's* $V = 0.11$). However, in the size condition, there was a significant difference ($x2(2) = 7.679$, $p < 0.05$, *Cramer's* $V = 0.23$). The residual analysis revealed that there was a significant difference, indicating that the number of large objects reported as heavier was significantly higher with a C/D ratio of 1.6 than with the other C/D ratios ($p < 0.01$). Therefore, the SWI in VR was only observed to be influenced by manipulation of the C/D ratio.

3.3.2 Confidence in Feeling and Sense of Ownership and Agency. As additional analysis, we performed a 3 (condition: size, brightness, and material) × 3 (C/D ratio: 0.4, 1, and 1.6) analysis of variance (ANOVA) on the confidence rating of the answers regarding which object felt heavier (Figure 5).

The results indicate that there was no significant interaction between the two factors ($F(4, 44) = 0.90$, $p = 0.47$). In addition, there was a significant main effect on the condition factor ($F(2, 22) = 3.58$, $p < 0.05$). However, Ryan's multiple comparison test revealed no significant differences between the three conditions ($ts < 2.57$, $ps > 0.05$). Moreover, there was a significant main effect on the C/D ratio

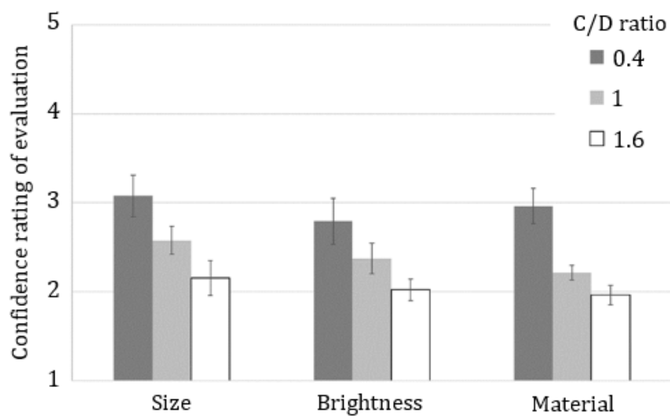

Figure 5: Confidence rating of feeling heavier with three C/D ratios in each condition.

factor ($F(2, 22) = 30.96$, $p < 0.01$). Ryan's multiple comparison test indicated that there were significant differences between the C/D ratios of 0.4 and 1.0 ($t = 4.65$, $p < 0.05$), between the C/D ratios of 0.4 and 1.6 ($t = 7.82$, $p < 0.05$), and between the C/D ratios of 1.0 and 1.6 ($t = 3.18$, $p < 0.05$). Therefore, a higher C/D ratio enhanced the participants' confidence in their answers regarding which object felt heavier.

Also, we conducted one factor (C/D ratio: 0.4, 1, and 1.6) ANOVAs on the senses of ownership and agency ratings. The results showed that there was no difference in the senses of ownership rating ($F(2, 22) = 3.27$, $p = 0.06$; 0.4: $M = 3.58$, 1: $M = 4.50$, 1.6: $M = 4.50$) and agency rating ($F(2, 22) = 1.37$, $p = 0.28$; 0.4: $M = 4.83$, 1: $M = 5.50$, 1.6: $M = 4.92$) with the three C/D ratios.

4 DISCUSSION

4.1 BWI and MWI in VR

The results of the experiment demonstrate that the BWI and MWI in VR did not occur as in the real world, and that the weight of the visual objects was perceived to be opposite to that in the real world. Therefore, Hypothesis 2b was supported for the BWI and

MWI. The same results were obtained at three different C/D ratios, confirming the robustness of the results.

Weight illusions are caused by unexpected haptic feedback. There is a possibility that due to the lack of haptic feedback in the VR environment, participants' expectations may be directly reflected in weight perception. Bi et al. [1] reported that the effects of the MWI in a mixed reality environment were opposite to those in the real world. In their experiments, they used a PHANToM to generate the actual force and produce the objects' weight; the force was produced before lifting the objects. As a result, there was no conflict between the user's applied force and the force to lift the objects, and the heavier-looking objects felt heavier. The results of the BWI and MWI in the present study appeared to share the same principle.

Heineken et al. [9] also demonstrated that weight perception in a highly immersive situation (i.e., HMD VR with head tracking) is the same as in the real world, whereas weight perception in a less immersive situation (i.e., desktop VR without screening) is opposite to that in the real world. In addition, the lack of haptic feedback in VR causes the weight illusion to be less likely to occur [7, 8]. Therefore, there is also a possibility that the lack of haptic feedback may reduce immersion in VR and cause weight perception in VR to be opposite to that in the real world.

4.2 SWI in VR

The results of the experiment revealed that the SWI in VR occurred as in the real world. Therefore, Hypothesis 1 was supported for the SWI. Buckingham [2] discussed the uniqueness of the SWI and stated that the SWI may be qualitatively different from other weight illusions. For example, the density of the objects or expectation of the weight strongly influences the MWI. In contrast, there is no influence of the density of objects on the SWI, and the influence of the expectation of the weight is uncertain for the SWI [2]. The results of our experiment appeared to be caused by the uniqueness of the SWI, and may contribute to clarifying the principle of the SWI in the real world.

The same results of weight perception were obtained at C/D ratios of 0.4 and 1; however, the opposite result was obtained at a C/D ratio of 1.6. At a C/D ratio of 1.6, at which the participants' confidence in their weight perception was the lowest, the participants were considered to have difficulty perceiving the difference in weight of small and large objects without haptic feedback.

Wesser and Proffitt [20] simulated the SWI in VR as in the real world without using any physical actuators. In their study, they caused virtual objects to fall when users lifted the objects faster than the set speed based on the objects' weight. Therefore, without this implementation, the SWI would be difficult to manipulate in VR.

4.3 Confidence in Weight Perception

Apart from the hypothesis testing, the results of the experiment indicate that a higher C/D ratio leads to higher confidence in the perception of weight for all weight illusions in VR. The weight induced by a higher C/D ratio is considered to increase the confidence in weight perception generated by the size, brightness, or material. The manipulation of combinations with weight illusions and C/D ratio may lead to a new means of generating weight in VR.

5 CONCLUSION

In this study, we investigated whether the weight illusions SWI, BWI, and MWI in VR occurred as in the real world in a scenario where only the appearance of the virtual objects was manipulated. The results indicate that the weight perception of the BWI and MWI in VR were opposite to those in the real world. These results were the same at different C/D ratios, thereby confirming the robustness of the results. Moreover, the weight perception of the SWI in VR was the same as in the real world; however, this result lacked robustness. This study thus demonstrates how weight illusions occur in VR without haptic feedback, and classifies weight perceptions and the robustness of the illusions. The results of this study can help clarify human perception of weight using weight illusions in VR.

6 FUTURE WORK

In this study, the SWI in VR occurred as in the real world, differing from the BWI and MWI in VR. In addition, the effect of the SWI in VR differed at different C/D ratios. In future work, detailed investigations of the SWI, BWI, and MWI in VR are necessary to control them and find a new means of inducing weight in VR. Also, the other weight illusions, such as the shape-weight illusion, in VR could be investigated. The detailed investigation of the SWI may even help clarify the principles of the SWI in the real world.

Moreover, in this study, to investigate whether weight illusions in VR occur as in the real world, the two-alternative forced choice method was used; therefore, only two levels were tested for each illusion category for size, brightness, and material. In future work, the magnitude of the weight illusions should be assessed to understand in more detail how individuals experience weight illusions in VR. Also, collecting objective data, such as lifting speed, may help clarify how weight illusions occur in VR.

Furthermore, in this study, VR HMDs controllers were used to conduct the experiment, as it is currently common to have VR experiences with controllers. However, in future work, weight illusions should be tested to determine whether the same phenomena would be observed without controllers in consideration of hands-free interaction in VR.

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