Weight perception in VR

Shengyi Gong

Supervisor: Slyvia

Submitted in partial fulfilment of the requirements
for the degree of MA Virtual & Augmented Reality
of the University of London

Department of Computing
Goldsmiths, University of London

9th September 2024

I certify that this dissertation, and the research to which it refers, are the result of my own work.

Abstract

The size-weight illusion often distorts the perception of an object's actual weight, creating a weight illusion. While both conceptual expectations and bottom-up processing can explain this phenomenon, combining these approaches provides a more thorough understanding of findings that don't fully align with either explanation alone. This study proposes a bottom-up processing approach to elucidate the weight illusion.

In this experiment, we compared participants' predictions or assumptions about object weight based on their knowledge, experience, and cognitive frameworks with the object's weight in a virtual environment. We recorded the finger extensor muscle activity of six participants, obtaining surface EMG signals. Four virtual objects were then created, and the perception of their weight was assessed through simulated grasping and lifting with fixed gestures.

The results indicated that participants exhibited differences when using EMG signals to grasp and lift objects in a VR environment where weight illusions were present. However, the consistency and significance of these differences require further investigation. Preliminary findings suggest a complex relationship between EMG signal variations and weight perception, potentially influenced by multiple factors. Future research should explore these factors to understand better how bottom-up processing affects the perception of weight illusions.

Keywords: virtual reality; haptic weight perception; EMG; flexor digitorum profundus; interface; weight illusion

Contents

1 Introduction

1.1 Motivation. 6
1.2 Aim 6

2 Literature Review

2.1 Weight illusion in virtual reality. 7
2.2 The impact of muscle bioelectrical signals on weight perception 8
2.3 The mapping between the user's physical input and the virtual response can influence the perception of weight 9
2.4 The connection between Weber fraction and pseudo-tactile feedback. 10

3 Experimental Methods

3.1 Design Process. 11
3.1.1 Focus Lifespan 11
3.1.2 Feedback Indicator 11
3.1.3 Accurate Tracking 14
3.2 Technical Implemnentation. 16
3.3 EMG Communication Process. 18
3.3.1 Acquisition of ED EMG. 18
3.3.2 EMG Signal Processing. 18

4 Experimental Methods

4.1 Samples. 20
4.2 Design. 20
4.3 Apparatus. 21
4.4 Procedure. 22
4.4.1 Physical Procedure. 22
4.4.2 Virtual Procedure. 23
4.5 Questionnaire. 25

5 Methodology

5.1 Data collection. 26
5.2 Data analysis. 26
5.2.1 Electromuscular Signal Analysis and Processing 27
5.2.2 EMG results by object strength 28

5.3 Comprehensive comparison. 29
5.4 Investigating specific hypotheses. 31
5.5 Expected conclusion. 31
5.6 Discussion. 31
5.7 Limitation and Further Work. 32

6 Conclusions

6.1 Presentation of Data. 33
6.2 All control variables affecting the experiment. 35
6.3 Some suggestions from testers. 36

7 Reference

1 Introduction

1.1 Motivation

Weight perception is a significant challenge in VR applications, primarily because it is difficult to convey the weight of virtual objects to users. While VR controllers facilitate interaction and manipulation within virtual environments, they do not provide cues about the weight of objects. In psychology, it is well-known that weight perception is influenced by visual properties, such as size, material, and color [1]. For instance, the size-weight illusion occurs when objects of the same mass but different sizes are perceived differently; a kilogram of iron and a kilogram of cotton weigh the same, but the larger volume of cotton often leads people to perceive it as heavier. Similarly, identical objects of different materials or colors can induce weight illusions; a metal container of the same mass and size as a wooden one feels lighter, and a darker object of the same specifications seems heavier than a lighter-colored one.

Pseudo-haptic feedback can effectively stimulate human perception through multiple sensory channels, creating varied user experiences by leveraging the dominance of vision over tactile sensations. In VR, this feedback can induce weight illusions due to the conflict between visual and tactile information, a challenge since VR lacks kinesthetic cues. Researchers have explored various methods to generate weight illusions in VR, such as manipulating visual feedback by altering object size or employing force-feedback devices and multisensory combinations of vision and touch.

These illusions result in varying perceptions of weight based on the appearance of physical objects, even when their actual weights are identical. This study proposes using visual manipulation in VR to create tactile illusions, with a method for objectively verifying weight perception through contraction reflections from EMG muscle activity combined with real object weight simulations.

1.2 Aim

The purpose of this research is to determine whether the analysis of muscle-generated movements through EMG bioelectrical signals can accurately predict weight perception in VR and to further verify the hypothesis that physiological and psychological judgments of objects in a VR environment are consistent.

The study aims to investigate whether the weight illusion in VR occurs as it does in the real world when only the appearance of virtual objects is manipulated and to quantify this using objective factors to increase the credibility and precision of the findings. We evaluate the feasibility of extracting relevant information from the transient phase of the EMG signal to directly obtain weight judgments during the grasping process by utilizing interactions in VR.

When the weight perception provided by haptic feedback closely aligns with the weight perception derived from muscle bioelectrical signals, the user's experience of weight in virtual reality will feel more authentic and natural, thereby enhancing the immersion and realism of the virtual experience.

Hypothesis 1 (Condition 1 - Same Size, Different EMG Thresholds):
After grasping two squares of the same size but different weights in Experiment B, participants were able to successfully predict the weight of the virtual grasped objects using EMG physiological signals, and the participants' psychologically perceived weights were consistent with the weights reflected by their physiological signals.

Hypothesis 2 (Condition 2 - Different Sizes, Same EMG Threshold):
After grasping two squares of different sizes but the same weight in Experiment A, participants were unable to predict the weight of the virtual grasped objects using EMG physiological signals, and the participants' psychologically perceived weights were inconsistent with the weights reflected by their physiological signals.

After grasping two squares of different sizes but the same weight in Experiment A, participants were unable to predict the weight of the virtual grasped objects using EMG physiological signals, and their psychologically perceived weights were inconsistent with the weights indicated by their physiological signals.

2 Literature Review

2.1 Weight Illusion in Virtual Reality

The size-weight illusion (SWI), first identified by Charpentier in 1891, occurs when two objects of same weight but differing sizes are lifted, causing the smaller object to be perceived as heavier. In a VR environment, pseudo-haptic weight perception relies heavily on visual cues like size and movement, which are more intuitive and impactful than material appearance. This makes SWI generally stronger than the material-weight illusion (MWI).

Berryman et al. [2] noted that when evaluating object size, the magnitude of the grasp force used to grasp an object does not alter its perceived size. VR studies frequently leverage weight illusions to manipulate perceived object weight. For instance, Stellmacher et al. [3] proposed a haptic VR controller called Triggermuscle, which simulates different levels of weight during VR interactions by changing the resistance of the trigger button, thus providing tactile feedback during VR interactions. However, this method's reliance on hardware can compromise accuracy.

In the study by M. S. Moosavi et al. [4], a pseudo-haptic model using passive feedback was proposed. This model relies on human cognitive characteristics to generate a sense of weight by combining visual feedback with voluntarily applied force. However, using pressure sensor methods can be less intuitive and more complex. In the research by Xupeng Ye et al. [5], computational models were trained using EEG data to implement a BCI (Brain-Computer Interface) tracking offset system for weight perception. This was the first time a BCI was used to quantify the perception of virtual object weight, allowing for real-time adjustment of the tracking offset to achieve pseudo-weight perception in VR. However, Despite its innovation, the high cost and complexity of EEG monitoring pose challenges.

Y. Ujitoko et al. [6] found that post-lift visual feedback can influence weight judgments, with lift and fall speeds affecting perceptions of gravity. Their study was the first to combine psychological and physical methods to verify consistency between physiological and psychological weight judgments in virtual settings. Robert et al. [7] developed PIVOT, a wrist-worn device that simulates haptic feedback for grasping and throwing in VR, achieving an 87% accuracy rate in evaluating the weight of various objects.

Grasping, an intricate sensory function, involves skin receptors and proprioceptive feedback from the fingers and hand, which inform expectations about object properties such as weight and density, aiding in motor planning for object manipulation[8].

2.2 The impact of muscle bioelectrical signals on weight perception

If people grasp virtual objects in VR and evaluate their weight, they can use electromyography (EMG) data to analyze the weight of virtual objects, significantly improving accuracy. Although considerable effort has been invested in interpreting users' movement intentions, estimating the required grip force (GF) generated by muscles from EMG data has not been extensively studied. From an engineering perspective, voluntary muscle contractions can be divided into two phases: transient and steady-state.

When people grasp virtual objects in VR and assess their weight, electromyography (EMG) data can be leveraged to analyze the weight of virtual objects, significantly enhancing accuracy. While substantial research has focused on interpreting user movement intentions, the estimation of grip force (GF) from EMG data has not been extensively explored. From an engineering standpoint, voluntary muscle contractions can be categorized into two phases: transient and steady-state.

Transient EMG signals are recorded during the initial phase of muscle contraction—starting from the onset until a steady state is achieved. In VR systems, transient EMG signals can be used to estimate a user's grip force in real-time, leading to a more immersive interaction. For instance, when a user grasps a virtual object, the system can dynamically adjust the feedback force of the object based on these transient signals. Itzel J.R.M et al. [9] utilized high-density surface electromyography (HD-EMG) from forearm muscles during the transient phase to predict grip force, emphasizing that capturing EMG signals at the onset of muscle activity is critical for accurately predicting grip force and estimating virtual object weight.

The impact of distance on muscle activation during grasping is also significant. Bonnefoy A et al. [10] examined how distance affects upper limb muscle activation during seated reach-to-grasp movements, focusing on the activation patterns of shoulder and elbow muscles. Their findings observed the duration and intensity of muscle activation, noting that gripping involves force expression from the back of the hand to the forearm due to grip force and hand gestures. They developed a simple, easy-to-implement haptic system to manage various grip actions in immersive VR, ensuring consistent muscle contraction effects across trials by controlling the thixotropic state of the muscles.

Proske U et al. [11] suggested that perception is influenced by the history of muscle contractions in both the lifting hand and the "indicating" hand, which affects proprioceptive feedback.

2.3 The mapping between the user's physical input and the virtual response can influence the perception of weight

One of the commonly used pseudo-haptic techniques in weight perception is to modulate the mapping between the actions of the user and the feedback provided by the system by altering the C/D ratio, such as changing the amount of movement between virtual and actual hand or the displacement of the object to generate different weight illusion. Additionly, the method of changing the control/display (C/D) ratio can also help users perceive the weight of virtual objects.

A. Maehigashi et al. [12] first introduced the concept of C/D ratio in VR weight illusions, validating the virtual illusion by requiring participants to use visuomotor cues to judge object weight. While their findings confirmed that weight perception in the size-weight illusion (SWI) in VR resembles real-world experiences, the results lacked replicability.

Mahdiyeh et al. [13] found that directly controlling the C/D ratio offers VR users more accurate weight perception than methods like velocity restriction. Their research demonstrated that the pseudo-haptic effect using the C/D ratio provides the most reliable weight discrimination cues compared to other visual effects, such as inclination angles and motion profiles [14].

Experiments by L. Dominjon et al. [15] showed that using a C/D ratio different from 1 can significantly alter perceived object mass. When the C/D ratio was less than 1, meaning the user's real motions were amplified in the virtual display, objects felt lighter than their actual weight. Altering the C/D ratio applies a gain to the lifting movement that is inversely proportional to perceived heaviness. Therefore, when the C/D ratio approaches 1, the virtual feedback closely matches the user's physical input, creating a 1:1 correspondence that accurately represents weight and motion.

2.4 The connection between Weber fraction and pseudo-tactile feedback

Weight perception has been scientifically studied in the field of psychophysics (16). The precision of weight perception is usually measured with accuracy [17], [18], expressed in PSE [19], [20] or just noticeable difference (JND), and WF[21], [22]. JND is used to measure the minimum weight difference that can be perceived by humans relative to a reference weight stimulus, and WF is the ratio of the JND to the intensity of the mass stimulus expressed as equation (1):

$$WF = JND / m_r \ (0.1 - 0.24) \tag{1}$$

Some researchers have used the Weber fraction to assess the capability of the proposed methods to allow the discrimination between virtual weights.

Previous research has identified several simple approaches for representing weight in immersive virtual environments. J. Hummel et al. [23] proposed two methods, both based on adjusting the stiffness of constraints between tracking fingers and virtual fingers through virtual coupling. The first approach sets a fixed distance between fingers and maintains a specific gesture for grasping objects, using a virtual spring to simulate grip force and friction. The second method incorporates pinch force by extending the finger-tracking device with a pinch strength sensor, effectively simulating the mass and friction of the fingertips. Both approaches demonstrated that the Weber fractions for virtual weight ($WF_{Davg} = 15.48\%$ and $WF_{Pavg} = 16.25\%$) are within a normal range, enabling effective differentiation of virtual object weights. Enhancing the robustness of hand motion tracking is therefore essential for achieving reliable pseudo-haptic effects.

The key difference between weight simulation feedback and force simulation feedback lies in their dimensional capabilities: force simulation feedback can replicate forces in multiple dimensions, while weight simulation feedback is limited to vertical force simulation, making it a subset of force simulation feedback.

3 Experimental Methods

3.1 Design Process

The design of pseudo-haptics in the experiment is the key factor influencing the weight illusion and represents the biggest design challenge in this study.

3.1.1 Focus Lifespan

Pseudo-haptics rely on purely virtual sensations rather than real physical changes. All pseudo-haptic effects are dependent on vision and cease to exist when the focus of attention shifts. A good experimental design needs to take into account the user's muscle fatigue values. Therefore, highly interactive mechanisms are designed to keep participants engaged.

The Oculus Integration SDK was used in this experiment, allowing the participants to avoid using a controller for hand tracking, which facilitates direct observation of hand positions in the virtual environment. The accuracy factor of reducing pseudo-haptics is one of the control variables affecting this experiment. To match the uvrms value of EMG in Unity for accurate physiological signal analysis, the time-logged information during the execution of the Unity scene will be exported in txt format. The exported information consists of four parts: the frame rate of the Unity runtime, the corresponding time of each frame, the coordinate statistics of the four squares moving on the Y-axis in each frame, and the uvrms value of each frame. All information was recorded in real-time to match the EMG physiological signals with the spatial information of the objects moving up and down the Y-axis in the time series. EMG values were not recorded if the participant did not read them within the requested time.

The size and weight of the objects in the virtual and real environments were also among the control variables affecting the experiment. Therefore, the weights and sizes of the squares in the real and virtual environments also need to be consistent to minimize errors in the data resulting from the experiment. The weights of the two squares in Experiment B are 80g and 60g, while the weights of the two squares in Experiment A are both 60g, and their dimensions are the same as in the real world. The gestures and arm guidance animations in the experiments will minimize the time it takes for the user to perceive the weights in the virtual environment, thus providing a more concise and intuitive guide for the user to grasp and lift the cubes, and reducing experimental errors due to complex manipulations.

3.1.2 Feedback Indicator

Another challenge for pseudo-haptics is the absence of feedback indicators that guide or constrain participants' actions to achieve the desired weight perception effect. In this experiment, the design involves simultaneously limiting the speed of lifting objects in both physical and virtual spaces, while using EMG devices to transmit the real-time muscle contraction force of the brachioradialis to lift objects, thereby presenting a sense of weight.

The data exchange between OpenBCI GUI and Unity occurs in real-time, eliminating concerns about user errors due to latency. Whenever participants lift a square, the object rises when the perceived weight matches the force exerted by the user. In the virtual environment, users are required to lift four objects. A UI panel was implemented to display the EMG signal parameters mapped to the environment as text, with four distinct thresholds defined. Based on the signal intensity, these normalized EMG signals were set to thresholds of 0.060, 0.080, 0.060, and 0.060, respectively. Since this experiment aims to compare the weight errors caused by the two groups of agents, the first group will have different thresholds set to help participants perceive the weight changes influenced by physiological signals. In the second group, the thresholds will be set to the same value, allowing participants to directly compare the psychological expectations of size differences while minimizing the impact of errors from physiological signal control variables.

Whenever the participant lifts the square vertically upwards in reality, the displayed number increases from 0.000 to 0.120. When this number reaches a specific threshold, the square becomes graspable. If the participate moves slightly closer to the square and the text number continues to exceed this threshold, they can lift the square in the virtual environment. In Experiment B, Cube 1 and Cube 2, which have different weights, create the illusion of varying weights for the user. Conversely, in Experiment A, two cubes of different sizes convey the illusion of the same weight. As shown in Figure (1), the normalized EMG signal data is displayed using UI text for easy identification by participants.

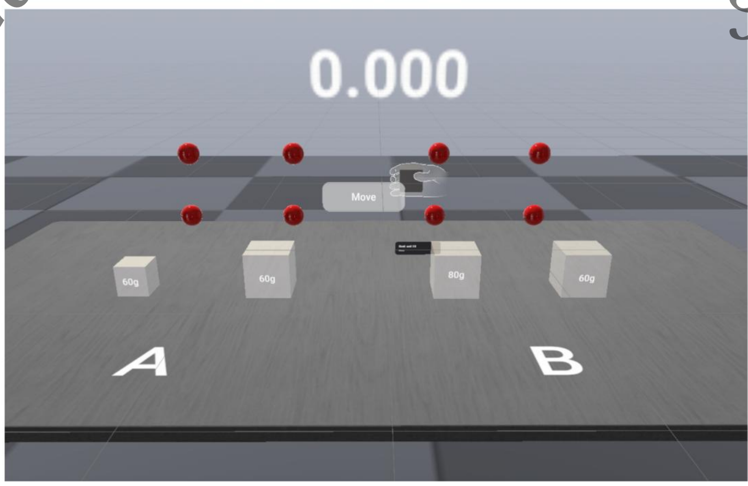


Figure 1. Experimental scene

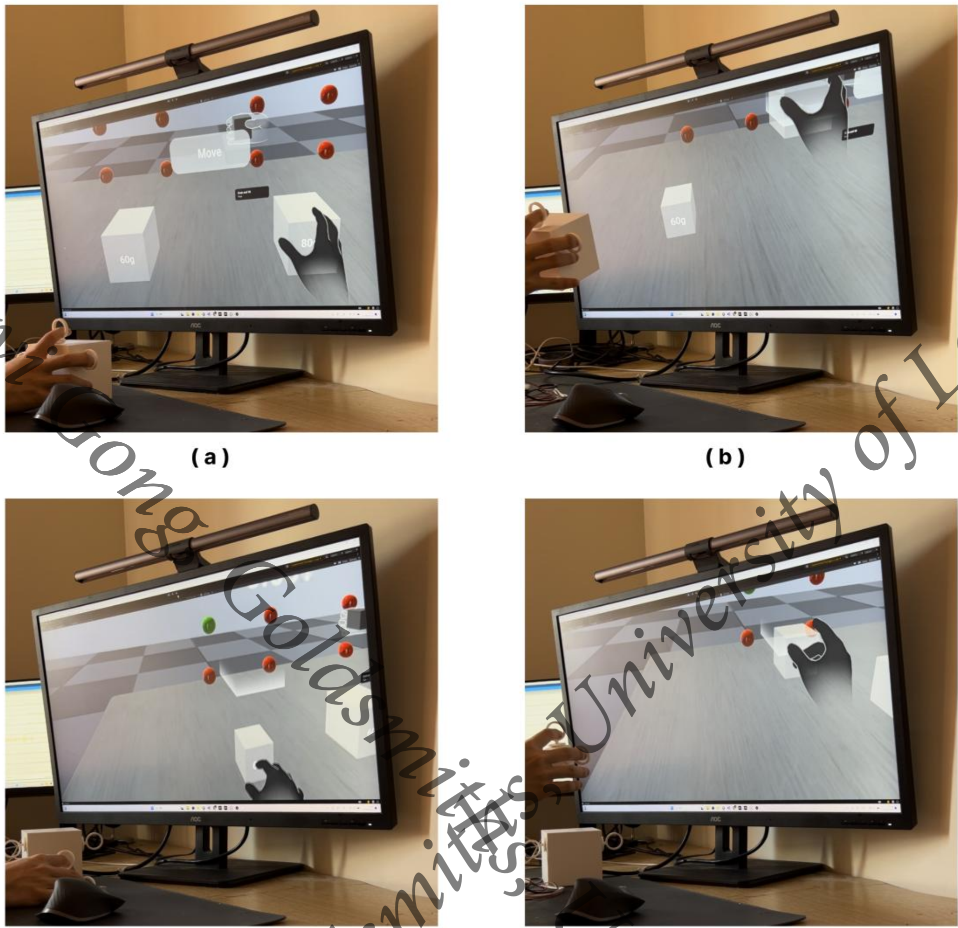
Shengyi Gong Goldsmiths University of London

Auditory and visual cues are essential elements in the environment. During the execution of the system, when the user's arm muscles are stretched, as shown in Figure (2), the red ball in front of the grasping cube in the system will turn green, and the system will emit a ‘drop’ sound. This indicates to the user to contract their muscles to lift the object upwards. As the object reaches a certain height, another red ball in front of it will turn green, and the system will emit a ‘drop’ sound again.

Considering that the vertical rise of the cube is 15 cm, special markers were set in the virtual scene within this area, and the object was lifted up for 1 second and stayed there for 2 seconds. Afterwards, when the user's muscles returned to a relaxed state, the cube would fall vertically, and allow the user to start the next cycle, continuing until the end of the experiment.

The use of auditory and visual cues not only enhances user feedback, immersion, and realism but also guides user behavior and improves attention and response speed. Additionally, these repetitive audio and visual feedbacks can enhance user memory and help improve the accuracy of the experiment.

Figure 2. Overall structure of the proposed method in this study



(a) (b) (c) (d)

(a) The large-sized square is resting on the tabletop (b) The large-sized square is raised on the tabletop
(c) The small-sized square is resting on the tabletop (d) The small-sized square is raised on the tabletop

Limiting the experimental error caused by the movement of the user's body in the virtual and real world is a challenge, and the Poke function in the programme avoids the effect of this error as much as possible. Users can trigger a button four times in the programme, and each time they trigger a button they can navigate to the next position in the virtual environment. The purpose of this feature is to minimize the number of times the user has to put the headset on repeatedly in order to reduce the fatigue of the system and increase the accuracy of the experiment.

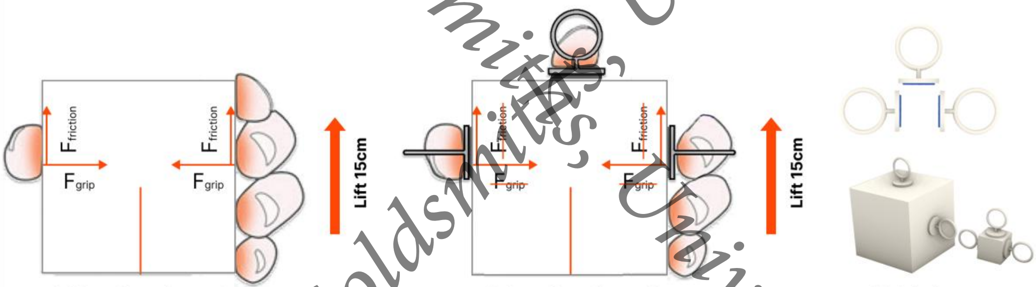
3.1.3 Accurate Tracking

In experiments using C/D ratio offsets to represent weight, precise tracking is essential. Even minor inaccuracies can lead to unpredictable perceptions, affecting the ability to accurately judge the weight and potentially reducing the sense of presence. To address this issue, the experiment will employ techniques to ensure precise relative motion, using hand-tracking algorithms in VR for enhanced real-time monitoring of objects.

Another control variable in the experiments was the consistency of the trajectories of objects lifted in both virtual and real environments. Hand-grip interaction primarily controlled the vertical movement of objects, which were restricted to the Y-axis in the virtual space, with a maximum range of 15 cm, matching the real desktop. Once objects are moved virtually, the program exports a txt file recording the trajectories of the four squares and the thresholds at the moments they are raised.

To achieve accurate VR tracking and precise weight perception when grasping objects, synchronizing real-life and virtual grasping gestures is crucial. The robustness of the grasp gesture, as shown in Figure (3), was key to ensuring accuracy. Natural grasping of the square helps avoid friction and grip force from directly holding the object. To mitigate this, a ring-like device was designed on the left, right, and top surfaces of the object, with fixation gel at the bottom to prevent slippage. This setup aimed to minimize the effect of muscle force contraction due to finger movement and maintain consistency between virtual and real gestures.

Figure 3. Force visualization during the lifting process of an object

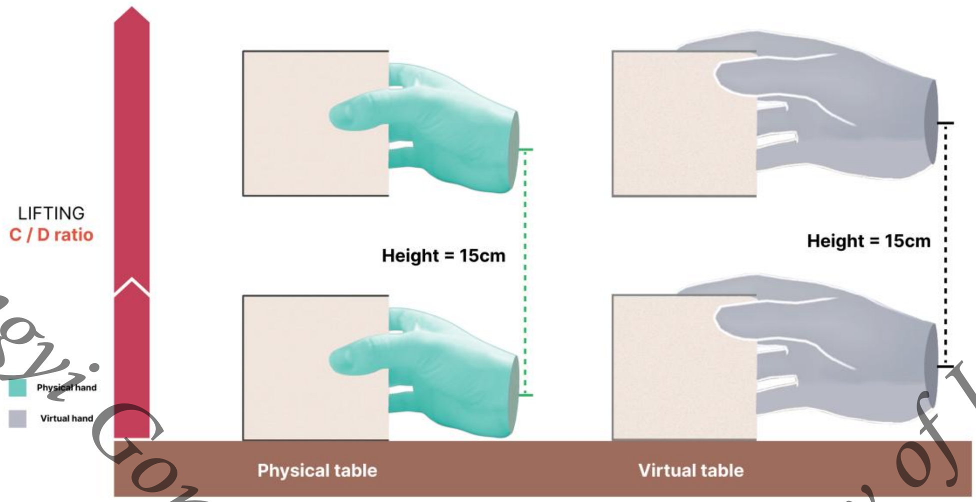


(a) Grasp force diagram 1 (b) Grasp force diagram 2 (c) Grip rings

(a) The hand is subjected to external forces from objects (b) The hand is not subjected to external forces from objects (c) Hand grip device

In this experiment, the function of grabbing objects by touching their surface was developed using the Oculus Integration SDK. When the surface of an object is grabbed and the threshold value is exceeded, the object can be lifted. As shown in Figure (4), the updated hand tracking technology in the experiment not only realistically replicates real-world hand movements and enables natural interaction, but also effectively solves the challenge of maintaining a C/D Ratio equal to one.

Figure 4. Manipulation of the control-display ratio (C/D ratio = 1) during lifting



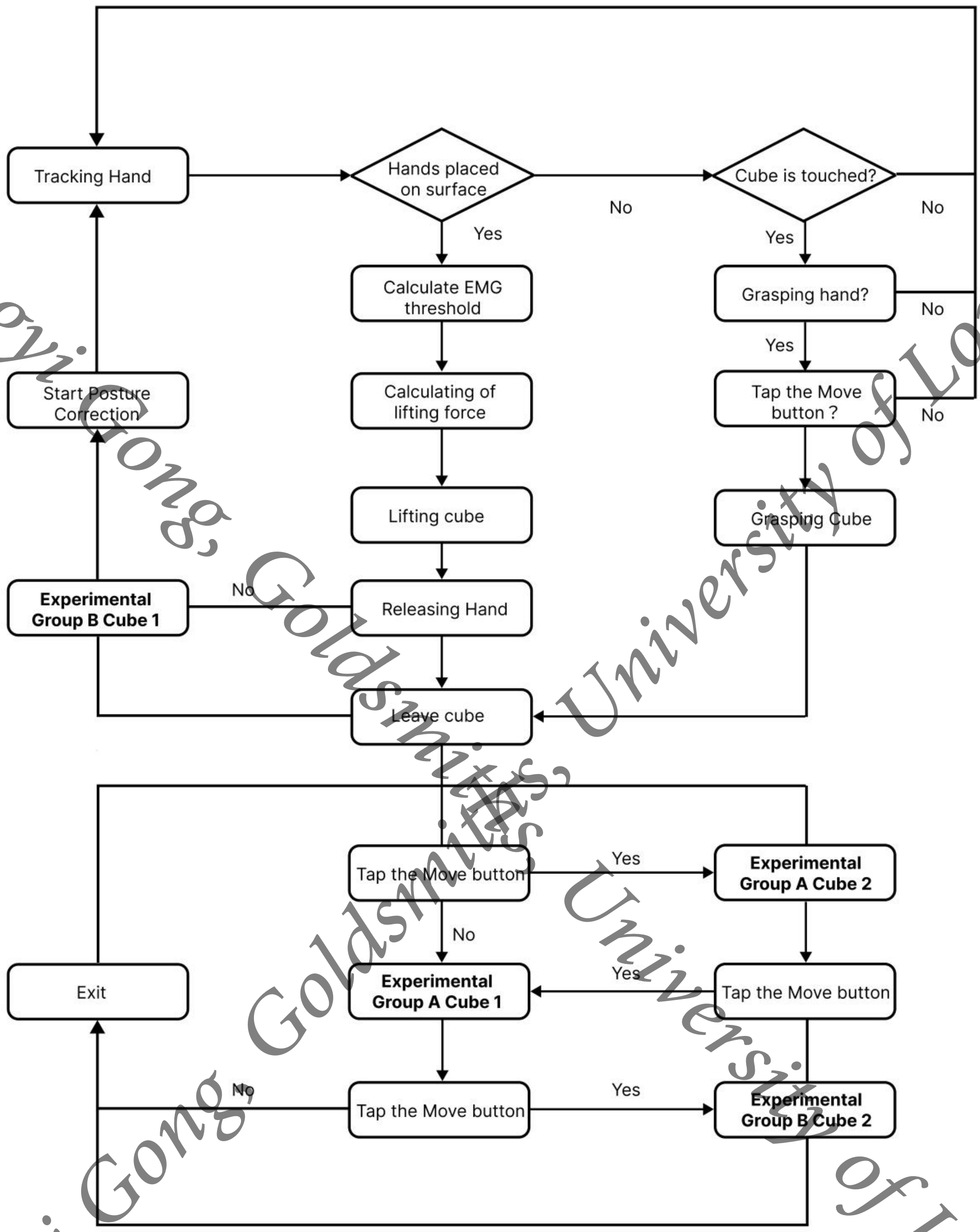
Control (C): The physical movement or action performed by the user

Display (D): The resulting movement or response displayed in the virtual environment

3.2 Technical implemnentation

The key module of the experimental design system is the weight perception module, as illustrated below. (Figure 5) This system checks the grasping state by tracking the 3D positions of the hand and the virtual object.

Figure 5. Weight Perception Module Simplified Flowchart



After any object is grasped, this module calculates the object's ascent and descent based on the EMG threshold. Once the lifting process is completed, the proposed system checks the state of the hand. When the system detects any "release" action of the hand or fingers, it triggers the "Releasing" state. When the user finishes lifting Experimental Group B Cube 1 and clicks the button, they will be automatically transported to the position of Experimental Group B Cube 2. After recording the data for Experimental Group A Cube 1 and Cube 2, the system will automatically end.

3.3 EMG communication process

3.3.1 Acquisition of ED EMG

The ED serves to help open the palm, straighten the fingers, and reverse the flexion movement against the FDP, and its electrical activity can be measured by surface electromyography (EMG). The electrodes are placed on the dorsal side of the forearm, usually at the position corresponding to the ED muscle. The Reference Electrode and the positive and negative electrodes connected to the ED are shown in Figure (6). The electrode wires transmit the acquired signals to the input channel of the Cyton Biosensing board and are connected to the computer by an infinite streaming Bluetooth module. EMG signals are known to have a major frequency band of 250 HZ.

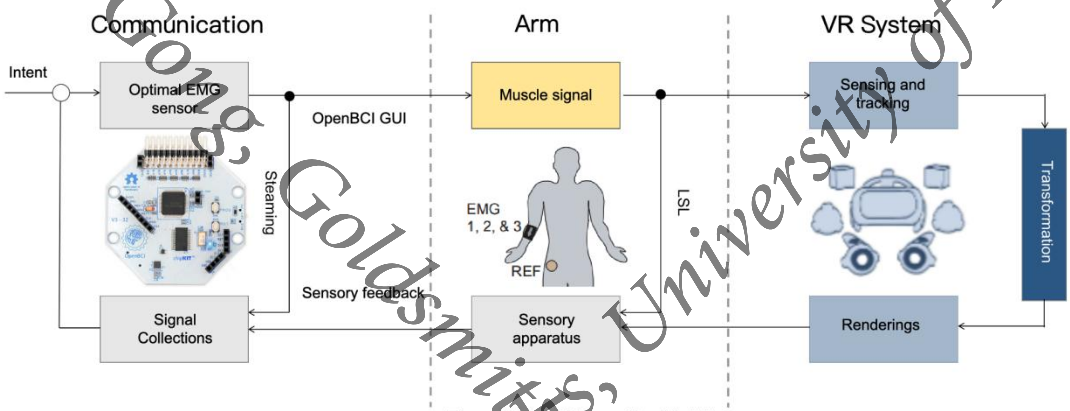


Figure 6. Weight Perception Module

3.3.2 EMG Signal Processing

This experiment is licensed under the Lab Streaming Layer (LSL), where the sensor used is the Cyton Biosensing Board, and the open-source tool for communication with Unity is Lab Streaming Layer [24]. LSL has a wide range of applications in bioelectrical signal acquisition, data synchronization, and multimodal data fusion, providing reliable support for the accuracy of the experiment. It is widely used in bioelectric signal acquisition and multimodal data fusion, ensuring the precision of experimental data.

Firstly, we acquired the original EMG signal, which is characterized as a high-frequency signal with a bandwidth of 250 Hz. This original EMG signal was then converted to a low-frequency signal in real-time in Unity using a smoothing technique to reduce noise and enhance the smoothness of the signal. Finally, the RMS (Root Mean Square) value of the signal was calculated and smoothed in real-time in Unity as a preprocessing step. Algorithm 1 shows the pseudo-code for signal smoothing in Unity.

Algorithm 1 Pseudo-code for signal smoothing algorithm

1: Define EMG data stream type and initial parameters

2: Initialize stream and signal buffer

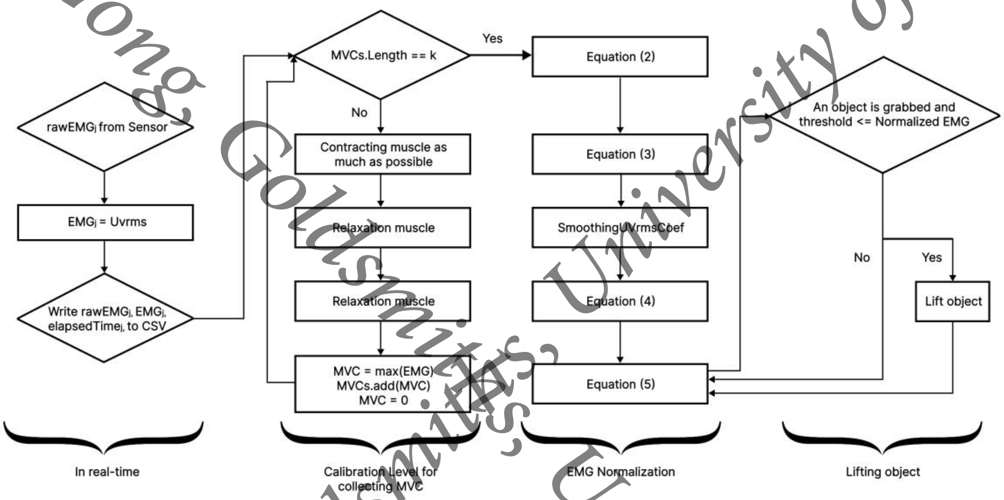
3. Parse the stream data

Shengyi Gong, Goldsmiths, University of London

4. Process and scale data samples
5. Calculate RMS values and add them to buffer
6. Add smoothing coefficients to smooth uVrms values
7. Process EMG data, scale and calculate sums
8. Calculate the mean value of the sum of squares of the data array
9. End
10. Add the smoothed uVrms values to the buffer
11. Calculate the mean of the buffer as the smoothed value
12. Map the smoothed value to the text component

Figure 7 shows the signal acquisition, signal smoothing and signal logging from the connected sensors performed in real time.

Figure 7. Experimental protocol block diagram from the perspective of EMG signal processing



During the course phase of the experiment, each participant was asked to forcefully contract the ED$_k$ times (5 times in this experiment), and the highest EMG value measured at each of the i contraction times was set as the maximum voluntary contraction (MVC) value for the i-th time, as shown in Equation (1).

$$MVC_i = \max(EMG_j),\ (i=1, 2, ..., k),\ (j = 1, 2, ..., n-1, n). \quad (1)$$

As in Equation (2), the mean MVC was calculated based on the average of the six MVC values, excluding the first two and the last two from k MVCs.

$$\text{meanMVC} = \frac{1}{(k-4)} \sum_{i=k-7}^{k-2} \text{MVC}_i . \quad (2)$$

As in Equation (3), calculate the root mean square (RMS) value of the signal, which is used to measure the RMS value of the signal.

$$RMS = \text{sqrt}((\Sigma(\text{value}^2)) / N) \quad (3)$$

As in Equation (4), calculate the average value of the signals in the buffer, and use it as the base value for smoothing.

$$\text{Mean} = \Sigma(\text{value}) / N \tag{4}$$

As in Equation (5), The values in the signal buffer were averaged to obtain smoothed signal values as EMG values. After data preprocessing, the real-time input of the normalised EMG values was used to trigger events based on the magnitude of the weight of the gripped object.

$$\text{NormalizedEMG}_j = \Sigma(\text{signalBuffer}) / \text{bufferSize} \tag{5}$$

4 Methodology

This experiment combines subjective and objective factors to achieve the perception of weight for virtual objects. By providing a physical proxy for each virtual object, a single physical agent can substitute for multiple virtual models in the environment. The implementation of hands-free interaction in VR minimizes real-world spatial constraints and creates nearly imperceptible offsets. To collect EMG signals, we used the Cyton Biosensing Board, selecting only 1 of the 10 available channels, specifically positioned near the finger extensor muscles. Two objects were placed on a physical tabletop to allow participants to initially feel the weight through the grip force exerted while holding them, and then weigh the objects using a scale. Subsequently, these real objects were represented in a VR environment, where participants could adjust the vertical position of the virtual objects by activating the finger extensors. The credibility and accuracy of the results of the study were improved by quantifying objective factors using the EMG-trained data model. Finally, the effectiveness of the technique was assessed through psychophysical experiments.

4.1 Samples

To evaluate the differential feedback of visual and physiological perception of object weight in a VR environment, we conducted a study with eight able-bodied participants who had no history of neuromuscular disorders. All participants had prior experience with VR systems, were fully briefed on the experiment, and consented to participate. One participant was excluded from the analysis for not adhering to the task instructions, leaving a final sample of seven participants. All were right-handed postgraduate students who were asked to complete two questionnaires following the trial.

4.2 Design

The experiment required us to set the initial position of the object in the VR environment to be 40cm horizontally from the body and 30cm vertically from the shoulder. The vertical cue was set at the end position 15cm above the initial position, and then the testers were required to fixate the position. All tests were conducted with the participants in a fixed stance, concluding with an arm swing test on a table. A key limitation of this study is that the validity of the results relies heavily on the accuracy of the data captured from the EMG signals, and we must account for potential errors inherent in surface EMG-based techniques. Additionally, in the context of virtual reality, user fatigue during interaction is a critical factor in assessing the effectiveness of the interaction method. Therefore, it is essential to design efficient interaction techniques that enable users to complete tasks swiftly without easily experiencing fatigue.

In this experiment, we propose a method to synchronise the virtual and real environments by fixing the finger distance. J. Hummel et al. [23] proposed a method to distinguish the weight of an object in a virtual environment by means of finger distance, and the result proved that the WFDavg = 15.48%, which is in the normal and reasonable range.

4.3 Apparatus

In this study, we implemented a method for spatial pairing of real objects and VR environment objects. The experimental equipment includes an Oculus Quest3 headset, OpenBCI Cyton Biosensing Board, 3 EMG SNAP electrode cables and 3 KENDALL EMG FOAM solid gel electrodes. A square box containing a white square with a volume of 3cm * 3cm * 3cm and another white square with a volume of 6cm * 6cm * 6cm and make sure that the true weight of the two square boxes is the same before the experiment. Each box was fitted with finger holders on the left, top, and right sides to ensure that participants could ignore the friction and passive grip forces of the hand gripping the square directly, and a gram-reading scale and a computer were placed on the experimental table. (Figure 8)

Figure 8. Apparatus required diagram

A single grip position requirement was used for this experiment and subjects were excluded if they had structural changes in their upper limbs. Participants were fully aware of the protocol.

4.4 Procedure

4.4.1 Physical Procedure

Firstly, we welcomed and thanked participants for their participation in the experiment. Participants read and signed a consent form, and were informed that the experiment involved weight perception when lifting virtual objects. Afterwards, participants were asked to finely grasp and lift two real-life objects. The positions of the objects in VR and the real objects were kept the same. Two white square boxes were used in the weightlifting exercise to avoid participants being influenced by the color and material of other boxes. The aim of the procedure was to assess the EMG of the upper limb during seated reaching and grasping movements. The task involved fixing the arm in the initial position, and the target reaching movement was performed in the sagittal plane, corresponding to the lifting and lowering movements of the cube, thus obtaining EMG recordings of the upper limb during specific movements.

Participants were asked to maintain an ergonomic sitting position to comfortably perform the vertical lifting and lowering movements, thereby preventing arm fatigue. To account for height differences and maintain the same dimensions in VR, the distance between the virtual table and the floor and the distance between the virtual

Shengyi Gong, Goldsmiths, University of London

table and the user were calibrated using the HMD height (tracking y-coordinate). Ergonomic table-to-floor and table-to-user distances were achieved using 60% and 20% of the participant's HMD height, respectively.

Participants were seated at the table: (i) Measurements were taken from the right upper limb. In the initial position, the right forearm was kept on the table, the shoulder was stabilized in an anatomically referenced position, and the elbow was bent at 90 degrees. (ii) The arms were relaxed before starting the movement. The distance to the target on the table was set at 40 cm. For all distances, the subject was seated in the initial position with the back straight, the trunk unmoving, and only the elbow could be flexed, with the angle of flexion limited to 90 degrees. The objective was to grasp and lift two square boxes. (iii) Each participant was asked to grasp the target in a fixed position. Subjects were instructed to lift the two cubes vertically to a point approximately 10 cm to 15 cm above the tabletop and were told not to feel or explore other aspects of the boxes with their fingers. Any violation of the experimental instructions would result in the test being invalidated. (iv) Each participant was required to perform 3 sets of grasping and lifting training on the two cubes in the order of grasping once before entering the virtual environment. The small and large cubes were used in one set. Each time an object was grasped, it lasted for about 2 seconds before being put down. (v) The lifting height values of the grasped cubes in the virtual environment were recorded each time the cubes were lifted in VR. (vi) After the experience, participants could place the two cubes on a scale and observe the weighing (Figure 9).

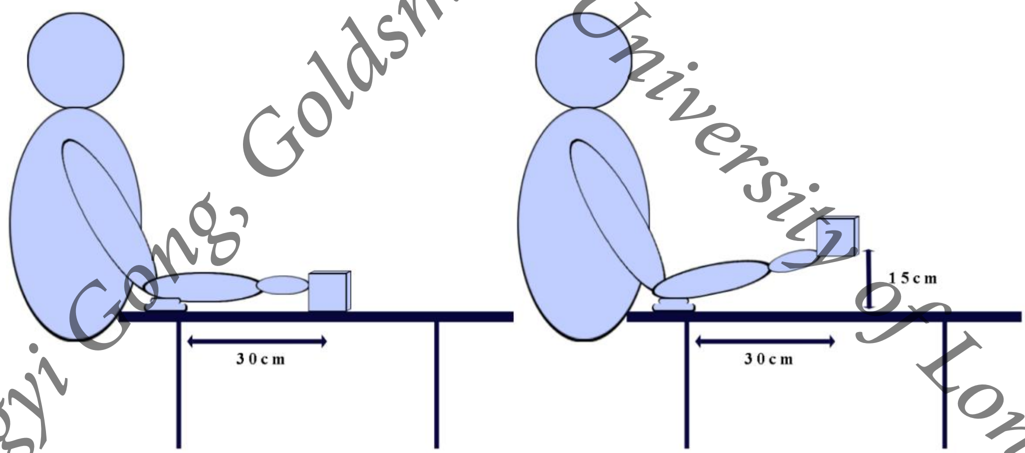


Figure 9. Participant's sitting posture and liftinging diagram

4.4.2 Virtual Procedure

In the VR environment, the user's position was pre-calibrated to align accurately with the real desktop. The first step involved positioning the user's hand in front of the first square of Experimental Group B. When the value on the system interface ranged between 0.000 and 0.030, the participant was prompted to use a grip gesture to grasp the object. The object was considered grasped when the user's instantaneous grip force reached the required threshold. Once the value stabilized below 0.030 again, the participant could lower their arm, causing the object to fall automatically. If the participant was unable to accurately perceive the weight during the initial grasp, they could repeat the grasping task until the cycle was completed.

During the experiment, participants were required to complete the two grasping tasks of Experiment B, estimate the weights of the two objects, and communicate their assessments to the experimenter. After a short break, they observed each pair of virtual objects and then proceeded with the grasping tasks of Experiment A. Finally, participants reported the weights of the two objects to the experimenter and completed the experimental questionnaire. Each participant lifted the objects four times from right to left (Figure 10).

stage	Unity running status	Physical Object	Virtual Object	Time (sec)	Muscle activity	Physical Cube state	Virtual Cube state
1	Not Running	60g large box	————	0	relaxation	Stay still on desktop	————
2	Running	60g large box	————	0 - 10	relaxation - contraction - relaxation	Stay still on desktop	Stay still on desktop
3	Running	60g large box	Experimental Group B Cube 1	10 - 20	relaxation - contraction - relaxation	be lifted	be lifted
4	Running	80g large box	Experimental Group B Cube 2	25 - 35	relaxation - contraction - relaxation	be lifted	be lifted
5	Running	60g large box	Experimental Group A Cube 1	40 - 45	relaxation - contraction - relaxation	be lifted	be lifted
6	Running	60g small box	Experimental Group A Cube 2	50 - 60	relaxation - contraction - relaxation	be lifted	be lifted
7	Not Running	60g small box	————	60 - Nah	relaxation	Stay still on desktop	————

Figure 10. Muscle activity and Unity program time recording chart

When the object was not lifted and the participant's finger extensors were relaxed, the system emitted a beep. Participants were instructed to place their virtual right hand on the right side of the object. When the experimenter said "please lift" to start lifting the object, the participant could move their right hand slightly and grasp the virtual object. When the object was lifted to a certain height, a beep sounded, ensuring that all participants lifted the object the same distance. Figure 11 shows an image of a participant lifting both real and virtual objects simultaneously.

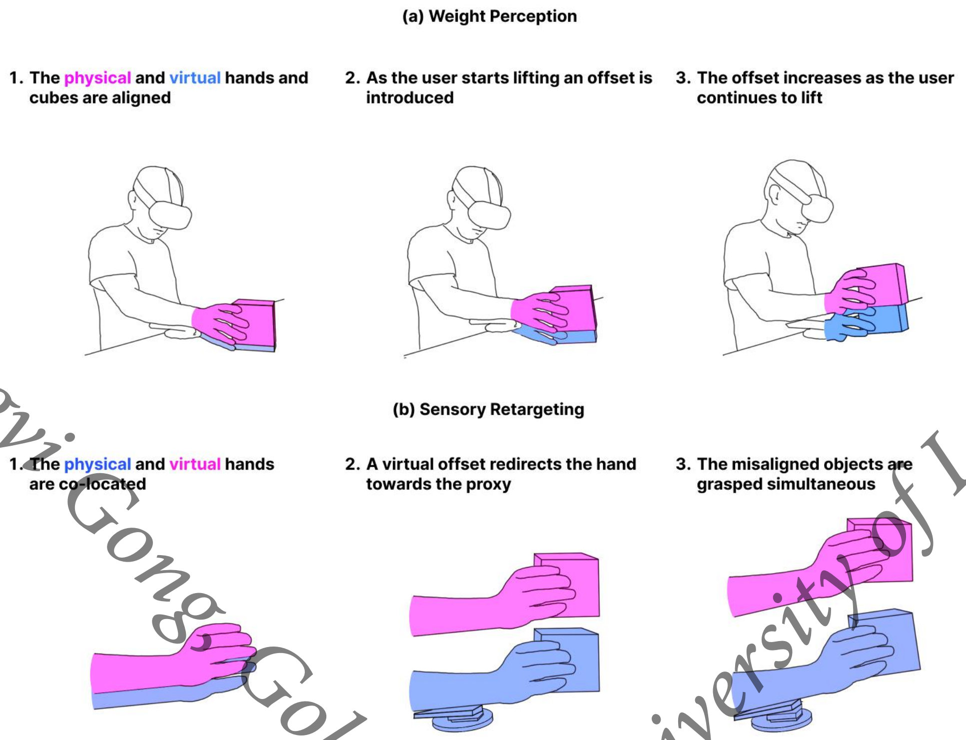


Figure 11. Real and virtual hand synchronization diagram

Each participant lifted a total of 10 times, including 4 trials in the virtual environment and 4 trials on the real table.Afterwards, two breaks were scheduled during the experiment to maintain the level of attention. The first break occurred after the participant completed the trials on the real desktop. The second break was taken three minutes after the participant completed the 4 trials in the VR environment (Figure12).

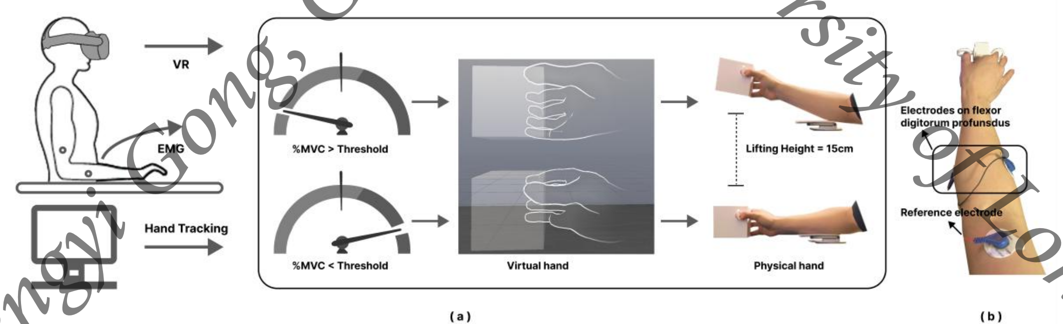


Figure 12. Overall structure of the proposed method in this study: (a) structure, (b) EMG electrodes attached to the extensor digitorum

4.5 Questionnaire

The experimental statement in the questionnaire consisted of the following: the participant was required to lift two cubes made of materials similar to those in reality, perform two sets of tasks, and then mentally assess their weight and inform the experimenter of their judgment. After a three-minute break, the participant was asked to complete two sets of tasks in VR and judge the weight of the object when it was grasped in the virtual environment. During the experiment, the participant needed to lift four squares from right to left, each time using a fixed gesture to grasp the cube.

The procedure involved the participant sitting in the correct position in front of the experimental table, using the UI to experiment. At the end of the experiment, the cubes were placed on a scale for observation. If the experimental procedure was violated, the results were invalidated.

To create the questionnaire, I collected questions from the existing literature on haptic and weight perception feedback [7], Weber Fraction [16], etc. These inspired me to tailor some of the questions to my experiments. These inspired me to tailor some of the questions specifically for my experiment. The Weber Fraction describes the relationship between the minimum perceptible difference in perception and the intensity of a standard stimulus. It can be used to assess the accuracy of human perception of weight by experimentally determining the threshold of perceptual difference for different weight units (e.g. 1g, 10g, 100g).

5 Data collection methods

5.1 Data collection

The data were collected from two sources: EMG signals and questionnaires. EMG data were simultaneously collected and saved in Unity through scripts. However, on the day of data collection, the consistency between the trajectories of the tester's hand movements in physical and virtual spaces was not maintained, leading to inconsistencies in the visual proprioception of the hands. These unforeseen circumstances necessitated a shift to an exploratory study design, where all participants were exposed to the presence condition.

In the first phase of the experiment, participants were asked to freely express their initial judgments about the weight of the two squares on the table and to focus their attention accordingly. Figure 13 illustrates the entire process of lifting the objects. After a brief rest, the squares were placed on a scale to observe their weights. To enhance the robustness of the results, participants were instructed to keep their elbows fixed and arms straight on the table, maintain consistent gestures and replicate the same movements while observing the experimental scene in Unity. After each task completion, the square was replaced, and the movements were repeated.

Participants were asked questions such as: "What was your judgment of the perceived weight of the two cubes without picking them up (same weight)?" and "After picking up the two cubes (of the same weight), placing them on a scale, and observing them, were they consistent with your initial mental conceptual judgments?" They were then encouraged to elaborate on their specific feelings. After the first round of trials, most participants reported that the two cubes weighed almost the same. This indicates a possible bias between psycho-cognitive factors and proprioceptive feedback.

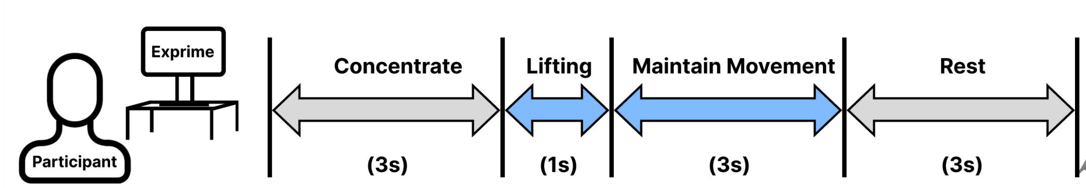


Figure 13: Experimental flow chart

In the first phase we asked participants to complete the first questionnaire. After this phase, a short VR psychophysical experiment was conducted and then we asked the participants to complete the second questionnaire. The content of the questionnaire is shown in 6.1.

5.2 Data analysis

5.2.1 Electromuscular Signal Analysis and Processing

We used the NeuroKit toolkit [25] in Python to preprocess the acquired EMG signals and the EMG_actibation() function to demonstrate the activity of signals whose amplitude exceeds a specified threshold, with parameters that are the default values of NeuroKit.

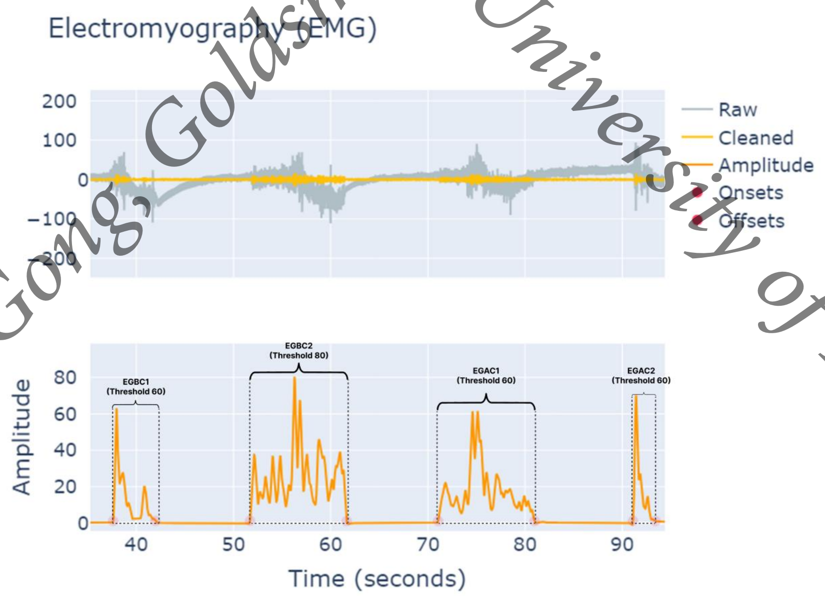


Figure 14: Results of EMG amplitude as participants lifted each object: graph of EMG amplitude fluctuations as four objects were lifted.

Figure 14: Results of EMG amplitude as participants lifted each object: graph of EMG amplitude fluctuations as four objects were lifted.

We collected real-time EMG data from a participant using OpenBCI GUI. The initial raw data included unprocessed EMG signals, which contained noise and various interferences. After applying filtering and processing, the signals were smoothed by removing noise. The amplitude variations of the cleaned signal closely resembled the uVrms values displayed in the original OpenBCI interface, though the uVrms values in OpenBCI are simulated data. The amplitude represents the height of the EMG signal waveform, indicating the intensity of muscle activity—a higher amplitude suggests stronger muscle contractions. In EMG analysis, amplitude changes help assess the extent of muscle contraction and relaxation during different movements. Figure 14 illustrates the EMG amplitude fluctuations when the participant lifted four objects, with thresholds indicated during the time intervals of each lifting action. When the threshold is approximately 60, the EMG amplitude response for one of the lifted objects exhibits higher fluctuations, closely aligning with the threshold set in Unity. The other threshold is exactly around 80, which shows a close correspondence with the Unity settings.

5.2.2 EMG results by object strength

Quantitative data, including raw EMG and smoothed signals recorded in real time, were tested using the proposed system on participants. Figure 14 shows a graph of the smoothed EMG values between the start and stop when a participant lifted each object. Participants recorded the following thresholds in Unity: 0.091, 0.099, 0.087, 0.092, 0.084, and 0.090 for Experimental Group B Cube 1 with a lifting threshold of 0.060; 0.111, 0.107, 0.097, 0.089, 0.102, and 0.091 for Experimental Group B Cube 2 with a lifting threshold of 0.080; 0.078, 0.083, 0.092, 0.101, 0.077, and 0.102 for Experimental Group A Cube 1 with a rise threshold of 0.080; and 0.082, 0.104, 0.097, 0.078, 0.076, and 0.091 for Experimental Group A Cube 2 with a rise threshold of 0.080.

Shengyi Gong, Goldsmiths, University of London

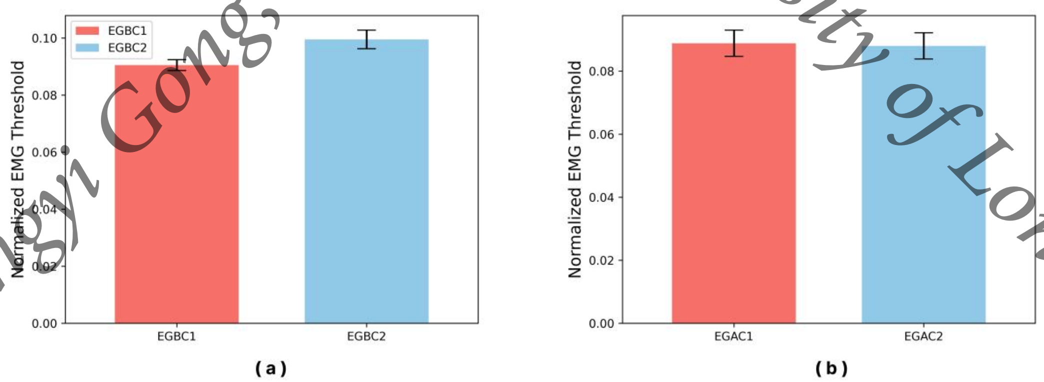


Figure 15: T-test (a)Results of the t-test between Experimental group B cube 1 and Experimental group B cube 2 (b)Results of the test between Experimental Group A Cube 1 and Experimental Group A Cube 2.

Figure 15. (a) Results of t-test between Experimental Group B Cube 1 and Experimental Group B Cube 2. (b) Results of t-test between Experimental Group B Cube 1 and Experimental Group B Cube 2.

Figure 15a illustrates the participants' attempts to raise Experimental Group B Cube 1 and Experimental Group B Cube 2, showing the mean of the smoothed EMG values. The vertical axis represents the normalized EMG thresholds, while the horizontal axis represents the two conditions, Condition 1 and Condition 2. The data are presented as t-tests, demonstrating a borderline significant difference between the two levels ($p = 0.055$). It suggests that there may be some degree of difference in the EMG responses of the participants in these two conditions. However, since the p-value is slightly higher than the traditional significance level ($p < 0.05$), this result should be considered borderline significant, and further research and validation are required to confirm the stability and robustness of this difference.

Figure 15b shows the participants' attempts to raise Experimental Group A Cube 1 and Experimental Group A Cube 2, displaying the mean of the smoothed EMG values. The data are presented as a t-test result, indicating no statistically significant difference ($p = 0.90$). Therefore, it can be concluded that there was no significant difference in the EMG responses of the participants between the two conditions. This indicates that the experimental conditions for A Cube 1 and A Cube 2 did not significantly affect the EMG values of the participants, supporting the null hypothesis that the EMG responses were essentially the same in both conditions.

5.3 Comprehensive comparison

The questionnaire included 6 items answered on a 5-point Likert-type scale (1 – strongly disagree; 5 – strongly agree), and the final results were subjected to a t-test. The sample size of this experiment was 7. For the first question, “Does the object observed by the human eye affect the weight of the grasped object?”,the mean= 0.58, sd=0.6, p=0.152, suggesting that participants generally tended to think that visual perception affects the weight of the grasped object, but not very strongly.

For the question “Do you think it feels realistic when you grab objects?” the results showed the mean = 0.43, sd = 0.79, p=0.2, indicating that participants had a slight tendency to perceive the experience of grasping objects as realistic, but this tendency was not strong.

For the question “Do you feel like your hand has caught an object?” the results were mean = 1, sd = 0.58, and p = 0.004, showing that participants overall had a strong tendency to believe that their hand had caught an object. These results were statistically significant, showing strong agreement that the hand did grasp the object.

For the question “Do the two objects in Experiment A have the same weight?” the results showed the mean= -0.43, sd = 1.40, and p = 0.448, indicating that participants slightly tended to think that the two objects in Experiment A had different weights.

For the question “Are the two objects in Experiment Group B the same weight?” the results showed the mean = -0.86, sd = 0.9, and p = 0.045, indicating that participants generally believed that the two objects in Experiment Group B did not weigh the same.

In the future, increasing the sample size or further refining the questionnaire could improve the statistical significance and the accuracy of the interpretation of the results.

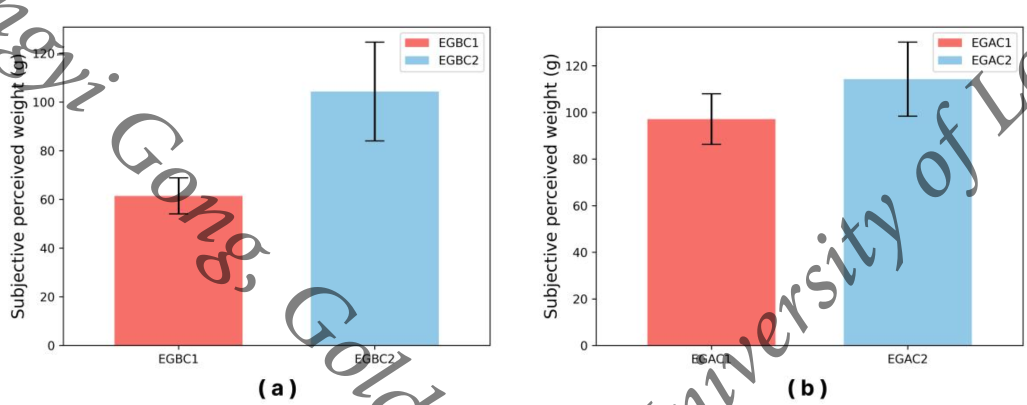


Figure 16: T-test (a)Results of the t-test between Experimental group B cube 1 and Experimental group B cube 2 (b)Results of the test between Experimental Group A Cube 1 and Experimental Group A Cube 2.

Figure 16.(a) t-test results between Subjective perceived weight and EMG threshold in Condition1. (b) t-test results between Subjective perceived weight and EMG threshold in Condition2.

The vertical coordinate is the mean value obtained from subjective perceived weight, the horizontal coordinate is the two agents in Condition1 and Condition2, and the results are presented as t-test results.

The subjective perceived weights of EGBC1 and EGBC2 were compared in Condition 1. The results showed that the mean subjective perceived weight of EGBC2 was higher than that of EGBC1, with a t-test result of p = 0.064. Since the p-value was slightly greater than 0.05, this indicated a borderline significant difference.

The subjective perceived weights of EGBC1 and EGBC2 were also compared in Condition 2. The results showed that the mean subjective perceived weight of EGBC2 was higher than that of EGBC1, but the t-test result had a p-value of 0.428, which was much greater than 0.05, indicating no significant difference between the two. This suggests that although the perceived weight of EGBC2 was slightly higher, it was not statistically significant.

These results suggest that there was a greater difference in the perceived weight of the cubes in participants' grasping in Experimental Group B, whereas there was less difference in the perceived weight of the squares in participants' grasping in Experimental Group A. This indicates that a size illusion in VR may exist, and the

Shengyi Gong, Goldsmiths, University of London

imprecision in the data may be due to subjective differences in perception resulting from varying experimental conditions or cube properties. Additionally, the small sample size of the experiment suggests that more valid samples need to be added for future evaluation.

5.4 Investigating specific hypotheses

The hypotheses of these two experiments include.

For the first hypothesis, the dependent variable is the subjective perception of the weight of objects, which is independent of the EMG signal outcomes. This perception was assessed through a user questionnaire. The independent variable consists of the EMG signals collected during the experiment.

The second hypothesis shares the same dependent and independent variables as the first hypothesis.

For the third hypothesis, the dependent variable is also people's subjective perception of the weight of objects, consistent with the first and second hypotheses. Its independent variable is the objective judgment or measurement of the object through physiological signals.

5.5 Expected conclusion

If the EMG threshold significantly influences weight perception, users may report differing perceptions of weight even if the objects are of the same size. This indicates that the magnitude of the EMG signal is a critical factor in weight perception. However, for hypothesis 3 in the experiment, further research is required due to the limited sample size.

5.6 Discussion

Research on the combination of multimodal weight perception (haptics, kinesthesia) and proprioceptive feedback in VR environment is currently quite limited. The present experiment represents one of the initial attempts in this field. Given the small sample size in the current study, increasing the number of participants would likely improve the accuracy and reliability of the results. The potential for using EMG bioelectrical signals to simulate weight perception in a VR environment appears promising, but the final results regarding the psychological and physiological perceptions of weight should be explored using a mixed-methods approach, which is an area that deserves further research.

Research on integrating multimodal weight perception (including haptics and kinesthesia) with proprioceptive feedback in VR environments is currently limited, and this experiment represents one of the early efforts in this area. Given the small sample size, increasing the number of participants could enhance the accuracy and reliability of the findings. The potential of using EMG bioelectrical signals to simulate weight perception in VR appears promising, but to fully understand the psychological and physiological aspects of weight perception, a mixed-methods approach should be considered. This is a promising area for further investigation.

5.7 Limitation and Further Work

The effective sample size of participants in this experiment was small, and more participants should be recruited for future studies. Our proposed system should be validated with different groups of subjects (e.g., individuals with disabilities, people with muscle weakness, etc.). Enhancing the robustness of objective quantification of muscle activity using EMG data can assist patients in performing muscle strength and coordination assessments in a virtual environment.

To ensure the realism and consistency of weight perception in virtual environments, future experiments should measure and validate Weber fraction [26] in the VR environment to align weight perception feedback with the actual perceptual properties of humans. If the Weber fraction exceeds 0.2, it indicates that participants have a relatively low sensitivity to weight differences, making their ability to discern weight changes poor. Consequently, pseudo-tactile feedback in such scenarios may lack effectiveness. By evaluating the Weber fraction, we can assess the validity of pseudo-tactile feedback. This approach allows us to iteratively refine our current methods to achieve more accurate predictions of weight perception in VR.

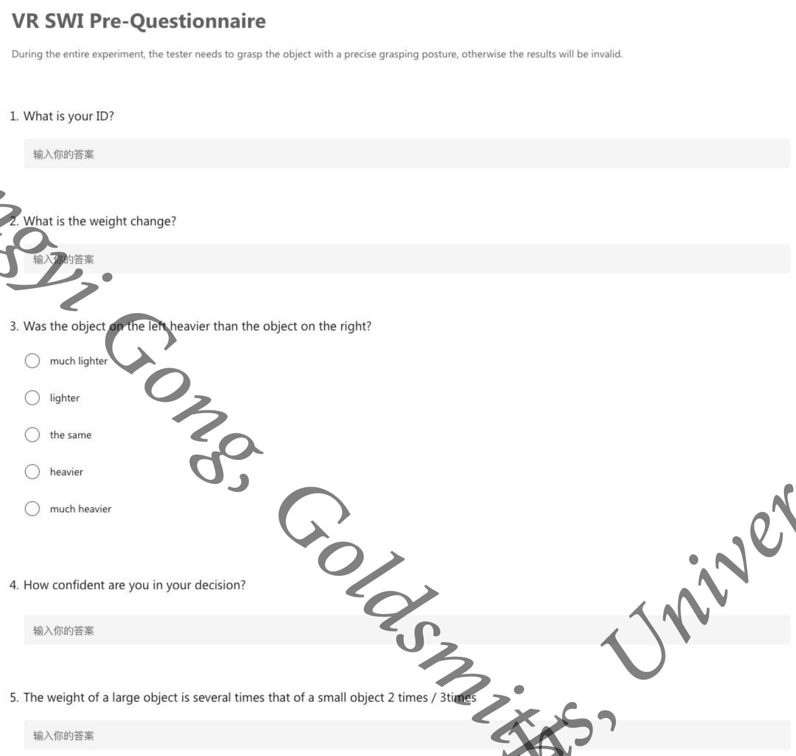
In this experiment, the weight illusion was designed by combining visual cues and tactile sensations to enhance participants' auditory feedback. In the future, more interactive auditory systems could influence user perception through psychological cues. For example, a high-frequency sound could be used when a heavy object is dropped, while lower-frequency sound could follow the drop of a lighter object.

We also plan to use the System Usability Scale (SUS) [27] in future studies to collect information on the quality of tasks performed by participants using the system, the efficiency of task performance, and user satisfaction. The system scores will be evaluated to determine user acceptance and preference for the system.

Effective interactive systems need to consider user fatigue, engagement, and comfort. Incorporating the Visual Analogue Scale for Fatigue (VAS-F) [28] questionnaire can capture the overall effects of prolonged interactions, including cumulative fatigue, which may alter weight perception and task performance over time.

6 Conclusions

6.1 Presentation of Data


VR SWI Pre-Questionnaire

During the entire experiment, the tester needs to grasp the object with a precise grasping posture, otherwise the results will be invalid.

1. What is your ID?

输入你的答案

2. What is the weight change?

输入你的答案

3. Was the object on the left heavier than the object on the right?

- much lighter
- lighter
- the same
- heavier
- much heavier

4. How confident are you in your decision?

输入你的答案

5. The weight of a large object is several times that of a small object 2 times / 3times

输入你的答案

This questionnaire assessed participants' ability to perceive weight and their confidence in their judgments, especially their subjective experience when comparing and judging the weight of different objects. Questions 2 to 4 in the questionnaire were mainly based on the research of Samad. M et al [29]. The purpose of the fifth question was to quantify participants' perceptions of weight changes. The results of this questionnaire will not be discussed in detail, but its main purpose is to help all participants understand the concept of SWI in advance.

VR Post-Experiment Questionnaire

Statement of the experiment: Participants were asked to lift two squares made of materials similar to those used in reality, and then mentally feel their weight and tell the experimenter about it. After a three-minute break, the tester was asked to complete two sets of tasks in VR, and the participant was asked to judge how much the object weighed when it was grasped in VR. Throughout the experiment, the user was required to lift four squares from right to left, each time using a fixed gesture to grasp the object. The whole process starts with the participant sitting at the table in the correct position, then the experiment is performed through the UI, and at the end of the experiment, the cubes are placed on a scale for observation. If the principle of the experiment was violated, the result was invalidated.

1. What is your ID?

输入你的答案

2. Does the object observed by the human eye affect the weight of the grasped object?

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

3. Do you think it feels realistic when you grab objects?

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

4. Do you feel like my hand has caught an object?

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

5. Do you use a fixed posture to grasp objects?

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

6. Are the two objects in Experiment Group B the same weight?

- ○ strongly agree
- ○ agree
- ○ neither agree or disagree
- ○ disagree
- ○ strongly disagree

7. How heavy do you think the two objects in Group B are?
In units of 10g Right one ( ) Left one ( )

输入你的答案

8. Do the two objects in Experiment A have the same weight?

- ○ strongly agree
- ○ agree
- ○ neither agree or disagree
- ○ disagree
- ○ strongly disagree

9. How heavy do you think the two objects in Group A are?
In units of 10g Right one ( ) Left one ( )

输入你的答案

The content of the questionnaire is all from the research of R. Kovacs et al [7]. The main purpose is to understand whether visual cues change the subjective perception of weight and the effectiveness of pseudo-tactile feedback.

Questions 7 and 9 in the questionnaire are mainly used to quantify the specific values of their perception of weight, and the units are the universal units of accurate perception of weight. It can help us analyze the accuracy of participants' weight perception and their ability to distinguish weight changes.

6.2 All control variables affecting the experiment

1) Friction between hand and object
2) Grip force generated directly by the hand and the object
3) User fatigue during the system process
4) Keep the virtual and real gesture and movement trajectory consistent
5) Keep the physical and virtual fixed gesture visualisation movement trajectory consistent
6) Keep the virtual and real object size consistent
7) Keep the virtual and real objects gravity consistent
8) Control the fps in Unity and hz in OpenBCI GUI to be consistent.

6.3 Some suggestions from testers

The first participant's suggestion was as follows: “It would be better if I could master the method of grasping the cube earlier, so that I don't have to spend time thinking about how to pick up the object”. One of the participants explained that “Weight is perceived through the speed of movement rather than the strain on the arm muscles”. Another participant commented that “A similar illusion of continuous weight could be better achieved if real haptic feedback, such as EMS, was incorporated into the device used to manipulate objects by hand”. The last participant suggested: “More elaborate desktop physics devices and markers etc. could be included to fix the arm posture prior to the experiment”.

However, the further research is needed to fully understand the potential benefits of different temporal moments in the interaction on the enhancement of the weight illusion, which would increase the validity of the experimental results.

7 Reference

[1] Ryu T, Park J, Bitkina OV. Effect on Perceived Weight of Object Shapes. Int J Environ Res Public Health. 2022 Aug 11;19(16):9877. doi: 10.3390/ijerph19169877. PMID: 36011512; PMCID: PMC9408783.

[2] Berryman LJ, Yau JM, Hsiao SS. Representation of object size in the somatosensory system. J Neurophysiol. 2006 Jul; 96(1):27-39. doi: 10.1152/jn.01190.2005. Epub 2006 Apr 26. PMID: 16641375; PMCID: PMC1800882.

[3]C.Stellmacher, A. Zenner, O. J. A. Nunez, E. Kruijff and J. Schöning, "Continuous VR Weight Illusion by Combining Adaptive Trigger Resistance and Control-Display Ratio Manipulation," 2023 IEEE Conference Virtual Reality and 3D UserInterfaces (VR), Shanghai, China, 2023, pp. 243-253, doi: 10.1109/VR55154.2023.00040.

[4] M. S. Moosavi, P. Raimbaud, C. Guillet, J. Plouzeau and F. Merienne. “Weight perception analysis using pseudo-haptic feedback based on physical work evaluation”, Front. Virtual Real., 13 February 2023 Sec. Technologies for VR Volume 4 - 2023 https://doi.org/10.3389/frvir.2023.973083

[5] X. Ye and J. Long, "Real-Time Adjustment of Tracking Offsets Through a Brain-Computer Interface for Weight Perception in Virtual Reality," in IEEE Transactions on Human-Machine Systems, vol. 52, no. 5, pp. 855-866, Oct. 2022, doi: 10.1109/THMS.2022.3182910.

[6] Y. Ujitoko, S. Kaneko, T. Yokosaka and T. Kawabe “Falling and heaviness: Heaviness judgment for a visual object which users lift up is influenced by the presentation of the object’s falling or staying still”, Front. Psychol., 28 March 2023 Sec. Human-Media Interaction Volume 14 - 2023 | https://doi.org/10.3389/fpsyg.2023.1042188

[7] R. Kovacs , E. Ofek, M. G. Franco, A. F. Siu , S. Marwecki, C. Holz, M. Sinclair

Shengyi Gong, Goldsmiths, University of London

“Haptic PIVOT: On-Demand Handhelds in VR”, Session 15A: ForceFeedback and Haptics in VR UIST '20, October 20–23, 2020, UIST '20: Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology
Pages 1046 - 1059 https://doi.org/10.1145/3379337.3415854
[8] Butler, A. A., Héroux, M. E., & Gandevia, S. C. (2015). How weight affects the perceived spacing between the thumb and fingers during grasping. PLoS ONE, 10(5), Article e0127983. https://doi.org/10.1371/journal.pone.0127983
[9] I. J. R. Martínez, A. Mannini, F. Clemente and C. Cipriani, "Online Grasp Force Estimation From the Transient EMG," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 28, no. 10, pp. 2333-2341, Oct. 2020, doi: 10.1109/TNSRE.2020.3022587.
[10] Bonnefoy A, Louis N, Gorce P. Muscle activation during a reach-to-grasp movement in sitting position: influence of the distance. J Electromyogr Kinesiol. 2009 Apr;19(2):269-75. doi: 10.1016/j.jelekin.2008.04.010. Epub 2008 Jun 27. PMID: 18585929.
[11] Proske U, Tsay A, Allen T. Muscle thixotropy as a tool in the study of proprioception. Exp Brain Res. 2014 Nov;232(11):3397-412. doi: 10.1007/s00221-014-4088-5. Epub 2014 Sep 9. PMID: 25200179.
[12] Maehigashi, A., Sasada, A., Matsumuro, M., Shibata, F., Kimura, A., & Niida, S. (2021). Virtual Weight Illusion: Weight Perception of Virtual Objects Using Weight Illusions. Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3411763.345184
[13] Moosavi, M.S., Raimbaud, P., Guillet, C. et al. Enhancing weight perception in virtual reality: an analysis of kinematic features. Virtual Reality 28, 72 (2024). https://doi.org/10.1007/s10055-024-00948-7
[14] Mahdiyeh S.M., Pierre Raimbaud, Christophe G., Jeremy P. and Frederic M. et al“Weight perception analysis using pseudo-haptic feedback based on physical work evaluation” Front. Virtual Real., 13 February 2023 Sec. Technologies for VR Volume 4 - 2023 | https://doi.org/10.3389/frvir.2023.973083
[15] L. Dominjon, A. Lecuyer, J. . -M. Burkhardt, P. Richard and S. Richir, "Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments," IEEE Proceedings. VR 2005. Virtual Reality, 2005., Bonn, Germany, 2005, pp. 19-25, doi: 10.1109/VR.2005.1492749.
[16] E. H. Weber, E. H. Weber: The Sense of Touch, London, U.K.:Academic, 1978.
[17] Y. Tanaka, A. Horie and X. A. Chen, "DualVib: Simulating haptic sensation of dynamic mass by combining pseudo-force and texture feedback", Proc. ACM Symp. Virtual Real. Softw. Technol. (VRST), pp. 1-10, 2020.
[18] J. Lee, J.-I. Kim and H. Kim, "Force arrow 2: A novel pseudo-haptic interface for weight perception in lifting virtual objects", Proc. IEEE Int. Conf. Big Data Smart Comput. (BigComp), pp. 1-8, Feb. 2019.
[19] J. M. Suchoski, S. Martinez and A. M. Okamura, "Scaling inertial forces to alter weight perception in virtual reality", Proc. IEEE Int. Conf. Robot. Automat. (ICRA), pp. 484-489, May 2018.

[20] F. E. van Beek, R. J. King, C. Brown, M. D. Luca and S. Keller, "Static weight perception through skin stretch and kinesthetic information: Detection thresholds JNDs and PSEs", IEEE Trans. Haptics, vol. 14, no. 1, pp. 20-31, Jan. 2021.
[21] M. Rietzler, F. Geiselhart, J. Gugenheimer and E. Rukzio, "Breaking the tracking: Enabling weight perception using perceivable tracking offsets", Proc. CHI Conf. Hum. Factors Comput. Syst., pp. 1-12, Apr. 2018.
[22] C. D. Giachritsis, P. Garcia-Robledo, J. Barrio, A. M. Wing and M. Ferre, "Unimanual bimanual and bilateral weight perception of virtual objects in the master finger 2 environment", Proc. 19th Int. Symp. Robot Hum. Interact. Commun., pp. 513-519, Sep. 2010.
[23] J. Hummel, J. Dodiya, R. Wolff, A. Gerndt and T. Kuhlen, "An evaluation of two simple methods for representing heaviness in immersive virtual environments", Proc. IEEE Symp. 3D User Interfaces (3DUI), pp. 87-94, Mar. 2013.
[24] Kothe, C. A. (2014). Lab streaming layer (LSL). GitHub repository https://github.com/sccn/labstreaminglayer
[25] Makowski, D., Pham, T., Lau, Z.J. et al. NeuroKit2: A Python toolbox for neurophysiological signal processing. Behav Res 53, 1689–1696 (2021). https://doi.org/10.3758/s13428-020-01516-y
[26] Ross, H. E., & Brodie, E. E. (1987). Weber Fractions for Weight and Mass as a Function of Stimulus Intensity. The Quarterly Journal of Experimental Psychology Section A, 39(1), 77-88. https://doi.org/10.1080/02724988743000042
[27] Lee KA, Hicks G, Nino-Murcia G. Validity and reliability of a scale to assess fatigue. Psychiatry Res. 1991 Mar;36(3):291-8. doi: 10.1016/0165-1781(91)90027-m. PMID: 2062970.
[28] John Brooke et al., "Sus-a quick and dirty usability scale", Usability evaluation in industry, vol. 189, no. 194, pp. 4-7, 1996.
[29] Samad M, Gatti E, Hermes A, et al.: Pseudo-haptic weight: changing the perceived weight of virtual objects by manipulating control-display ratio. Proc 2019 CHI Conf Hum Factors Comput Syst. 2019, 320:1-13. 10.1145/3290605.3300550