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Variable Offset Method Based on Five-finger Pressure to Enhance Weight Perception in Virtual Reality

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In virtual reality, virtual weight perception allows users to perform tasks more precisely and enhances immersion. In this paper, we propose a variable offset (VO) method based on a five-finger pressure input technique and combines it with visual and haptic feedbacks to enhance virtual weight perception. The VO method integrates a haptic controller that can capture forces applied by five fingers with a control/display ratio control scheme. When a user grabs a virtual object using all five fingers, a semitransparent duplicate of the object appears below the original, and VO between the two is adjusted dynamically on the basis of the object's weight and force applied by the user. To reinforce this perception, visual cues, e.g., dynamic lines and outline changes, and vibrotactile feedback are incorporated during the object manipulation task. In an experiment, participants were asked to arrange four cubes by increasing weight. Two comparative experiments were designed to evaluate differences in the visual and haptic feedback techniques based on the proposed VO method. Quantitative measures, i.e., task completion time and accuracy, were collected, and questionnaire-based qualitative assessments were performed. Results showed that connecting lines between objects improved performance over outline emphasis and other conditions. For haptics, continuous vibration based on force and weight outperformed single vibration based on weight alone and received higher immersion ratings.

1. Introduction

In virtual reality (VR) environments, higher levels of immersion allow users to perceive the virtual environments as more realistic, and realistic experiences can enhance the users' comfort and enjoyment.(1) Immersion is determined by the degree of congruence between sensory feedback, e.g., visual, auditory, and haptic cues provided by the interface, and the user's physical movements. Accordingly, numerous recent studies have investigated ways to improve immersion. In particular, previous studies have focused on combining multiple sensory modalities to make interactions in virtual environments feel more realistic. When sensory

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feedback is integrated successfully, it induces perceptual illusions that enhance immersion. Among such illusions, the perception of weight plays an important role because it enables users to manipulate virtual objects in a more stable and efficient manner. However, in conventional VR systems, most virtual objects can be lifted with equal minimal effort, frequently requiring little to no noticeable physical strain. If weight perception can be simulated in VR applications, the users will be required to exert more effort to lift a heavy virtual object than a light virtual object, and they would be able to distinguish between containers with identical appearance on the basis of their internal weight. In addition, by combining visual cues with haptic feedback while manipulating virtual objects, users can experience physical properties that resemble those in the real world. This combination can induce the illusion of weight for virtual objects that have no physical mass, thereby enhancing the users' sense of realism and immersion in virtual environments.

Humans primarily perceive the weight of objects through haptic feedback and proprioception, which is a sensory system responsible for detecting the position and movement of one's body. Weight perception is dynamically constructed from the pressure sensed in the hands and from muscle contractions and joint movements. This sensory information is transmitted through peripheral mechanoreceptors to the central nervous system, where it provides information about joint position, movement, vibration, and pressure.(2) However, in virtual environments, the users do not grasp physical objects with their hands (beyond holding a controller), which makes it difficult to simulate precise physical interactions that are similar to those that occur in the real world. Unless special equipment is used, e.g., devices that physically attach solid or liquid materials to the controller, it is challenging to deliver authentic weight sensations to the user's body. Thus, many VR systems rely on perceptual illusion techniques that leverage the human sensory system.(3,4) For example, if a virtual object is shown to move more slowly when lifted, users may perceive it as heavier. In addition, when lifting two objects with the same weight and material, users frequently perceive the smaller object as heavier owing to the size–weight illusion.(5) Similarly, with objects of the same size and weight, the material–weight illusion may cause users to perceive a plastic object as heavier than a metallic one based on visual cues.(6) Weight perception can also be conveyed indirectly by providing tactile feedback, e.g., vibration or electrical stimulation, of varying intensity to the hands or arms, or by applying resistance to the fingers through haptic interfaces. Previous studies have attempted to enhance weight perception using offset-based visual feedback methods, in which the virtual hand and object are visually lowered together to represent increased weight. While these techniques offer a simple way to convey the sensation of heaviness, they often result in a spatial discrepancy between the user's real and virtual hands. This mismatch can lead to a reduced sense of embodiment and detachment during interaction. If only the visual state of a virtual object responds dynamically to the amount of force applied by the user, this form of real-time visual feedback can help users perceive differences in the weights of virtual objects. Furthermore, if visual or tactile feedback clearly indicates whether the applied force is sufficient or insufficient, users will be able to perceive the weight more accurately.

In this study, the Bstick haptic controller was employed to enable users to interact with virtual objects using all five fingers, closely mimicking real-world hand interactions.(7) When a user grabs an object, the controller measures the pressure exerted by each finger, and these pressure data are used to design a virtual hand model and interaction module that facilitates realistic object manipulation. To enhance weight perception during the interaction, a variable offset (VO) method that combines visual and haptic feedback is proposed. The proposed VO method generates a semitransparent duplicate of the grasped object below the original object, separated by a vertical offset. This offset changes dynamically depending on the weight of the object and the user's finger pressure. When the applied pressure is insufficient to lift the object, visual feedback and haptic feedback are provided to reinforce the perception of heaviness. The visual feedback includes either a dynamic connecting line or an outline that changes according to the offset distance, which reflects the degree of insufficient force. The haptic feedback delivers vibrations to the hand, which increase in intensity with both object's weight and offset distance.

To examine the effects of the visual and haptic VO enhancements on weight perception, an experiment was conducted in which the participants were asked to arrange four virtual objects in order to increase weight. A quantitative evaluation was conducted by measuring both task accuracy and completion time, and a qualitative evaluation was performed using questionnaires about the perceived weight, immersion, and task load. Through these analyses, we assessed the effectiveness of the proposed VO method in conveying virtual weight.

2. Related Work

Well-implemented physical interactions of virtual objects in VR applications can positively affect both task performance and user immersion, and such physical interactions include the perception of weight.(8,9) In VR environments, objects follow the laws of physics through the game engine; however, the users cannot feel reaction forces or friction through their muscles, skin, or mechanoreceptors; thus, it is difficult to replicate the sensation of real weight.(10,11) As a result, most previous studies have focused on indirect methods to enable users to perceive weight in virtual environments. In VR environments, the indirect rendering of weight can be realized through either device- or software-based approaches.

2.1 Device-based approaches

Device-based methods simulate weight by applying physical feedback, e.g., force or pressure, directly to the user's hand. For example, HapSticks is a chopstick-shaped haptic device that allows fine force control using the thumb, index, and middle fingers. The HapSticks device enables users to distinguish between small virtual objects with different perceived weights through precise grip manipulation.(12) In addition, the Aero-plane handheld controller is equipped with miniature propellers that can generate up to 14 N of force feedback using airflow to convey the sensation of a rolling ball's weight on a virtual surface.(13) Drag:on, which is a device with fan-like surfaces attached to the controller, alters the surface shape to simulate varying air resistance based on object's weight, thereby allowing users to perceive different weights through resistance-based force feedback when lifting objects.(14) Separate from the controller itself, Tasbi is a wrist-worn device that utilizes vibration and a tightening mechanism to convey weight perception. Here, as the perceived weight increases during interaction, the device tightens around the user's wrist to simulate heaviness.(15) Triggermuscle is a modified version of a commercial VR controller's trigger button, where the resistance of the trigger increases in proportion to the virtual object's weight, which provides a sense of heaviness through finger force.(16) In addition, Grabity is a wearable device equipped with force and vibration feedback pads on the thumb and index finger, which delivers force or vibration as the object's weight increases to simulate variable weights for virtual cubes.(17) Vibration feedback also plays a significant role in enhancing weight perception. A previous study employed a haptic glove with vibration feedback to allow users to distinguish between the weights of virtual cubes and complete a brick-moving task, relying solely on vibration cues without any force feedback.(18) The DualVib device is a compact handheld controller equipped with vibration actuators positioned at the thumb, index finger, and palm. Here, when manipulating objects with dynamic behavior, e.g., a sloshing water bottle, the controller adjusts the location of the vibration to convey the sensation of shifting weight.(19)

2.2 Software-based approaches

Software-based approaches simulate weight perception without requiring expensive or specialized hardware, relying instead on commercially available controllers. These methods frequently employ pseudohaptic techniques that leverage visual cues to create a sensation of weight in the absence of actual tactile feedback. Among these methods, the control/display (C/D) ratio method, which manipulates the discrepancy between the user input (control) and the system response (display) to produce sensory illusions is the most commonly used. For example, Samad *et al.* proposed a method based on the assumption that lighter objects should be easier to move.(20) In this method, the vertical position of the virtual hand model is adjusted according to the perceived weight of the object, i.e., raising and lowering it for lighter and heavier objects, respectively, and by providing visual cues to support the perception of weight.(20) Similarly, Stellmacher *et al.* simulated a scenario in which the user held a virtual cup and filled it with water.(21) Here, as more water was added, the hand and cup were visually lowered, and when the water was removed from the cup, they returned to a higher position, thereby simulating changes in weight.(21) Rietzler *et al.* applied a weight-dependent offset in a virtual bowling environment, where heavier bowling balls required the users to lift their arm higher.(22) Participants reported experiencing distinct weight differences, which contributed to increased presence and immersion.(22) In another study, Yu and Bowman manipulated the rotation speed of a virtual object based on its weight by adjusting the C/D ratio, and they demonstrated that heavier virtual cubes rotated more slowly, thereby allowing participants to distinguish between two cubes of different virtual weights.(23)

2.3 Combined device- and software-based approaches

Combining device- and software-based approaches can enhance immersion in virtual environments. For example, Kim *et al.* investigated the integration of a C/D ratio-based offset method with an electrical muscle stimulation system to identify the threshold at which weight perception becomes effective.(24) They demonstrated that combining multisensory feedback is effective in conveying the weight of virtual objects.(24) Force Arrow is a pseudohaptic interface that integrates conventional VR equipment with electromyography sensors to detect hand gestures and motion. Here, by extending the user's input range through the measured physical force, the system dynamically changes the shape of an arrow user interface to indicate whether the applied force is insufficient or excessive, which guides the user to apply the appropriate amount of force based on the weight of the virtual object and enhances the sense of presence.(25) In addition, Lim *et al.* proposed a virtual haptic model to study weight illusion by combining a VR controller with an Arduino-based force sensing resistor sensor.(26) The displacement of the virtual object being lifted was determined on the basis of the passively measured force, thereby allowing users to perceive different weights through visual displacement.(26)

Building on these previous studies, in the current study, we attempted to enhance users' perception of virtual weight by integrating hardware and software approaches, i.e., a device that can measure the applied force and deliver haptic feedback is integrated with a software-based system that presents different visual cues according to the weight of the object.

3. Proposed VO Method Based on Five-finger Pressure

When grasping an object, humans naturally apply greater force to maintain grip as the object's weight increases, and objects are typically dropped when insufficient force is applied. However, standard VR controllers employed in virtual environments typically rely on trigger buttons for object manipulation, making it difficult to input the forces of the user's fingers, which limits the ability to simulate realistic weight sensations. To address this issue, previous studies introduced offset-based visual methods to convey weight perception by lowering the virtual hand and object together.(21,22) However, such approaches can lead to spatial misalignment, reducing the sense of embodiment during interaction. To mitigate this, in this paper, we propose a method in which the virtual hand remains aligned with the position of the user's hand, and a semitransparent duplicate (or shadow) of the object is rendered below the object, and the vertical distance between the object and its shadow functions as a visual cue for weight perception. In addition, if the system can measure the user's gripping force, it can determine whether the user is exerting sufficient force to lift and hold the object. By combining these elements, we introduced the VO method in which the shadow shifts dynamically on the basis of the weight of the object and the user's finger pressure. When the user attempts to lift a heavy object with insufficient force, the shadow descends further from the original object, indicating inadequate grip force. Once the applied pressure becomes sufficient, the shadow returns to the original position of the object. Through this dynamic feedback, the users can intuitively perceive the difference between the object's weight and the exerted force. In addition, by integrating visual and haptic feedback to emphasize insufficient force, the system can further enhance the user's sense of realism and immersion. In this section, we describe in detail the design of an interaction system that allows users to manipulate virtual objects on the basis of the pressure exerted by all five fingers, and we explain the implementation of the VO method using this system.

3.1 Virtual hand model and five-finger interaction system

A virtual hand model that can interact with objects was designed using the Bstick controller, which is a lightweight handheld device that can measure the pressure from all five fingers.(7) As shown in Fig. 1(a), the Bstick controller is worn on one hand, and the corresponding virtual hand model is shown in Fig. 1(b). The fingers of the virtual hand bend in response to how much force the user applies to the buttons using their fingers. The pressure values are measured in real time by sensors located at the points where the fingers contact the controller's buttons. In addition, haptic feedback is delivered during interactions via vibration actuators in the controller. Each fingertip of the virtual hand is equipped with a capsule collider to detect contact with an object and determine the conditions of the interaction. A physical collider encompassing the entire virtual hand is also implemented to facilitate physical interactions with virtual objects in the environment.

A five-finger region-based interaction system is applied to allow the users to grab and release the virtual objects using their fingers, and the pressure values applied by each finger are utilized.(27) Here, a detection area is defined at the tip of each finger, and this area becomes a detected area when it contacts a virtual object, as shown in Fig. 2. At least two detected areas are required, including the thumb as a mandatory finger, to grab an object successfully. The object is considered to be grabbed successfully when the sum of the pressure values from the detected areas is greater than the minimum force required to lift the object.

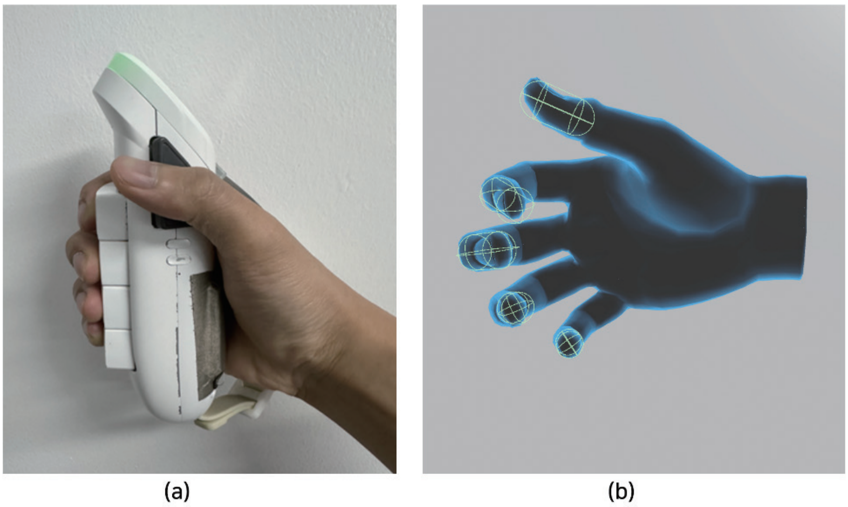
(a)
(b)

Fig. 1. (Color online) (a) Bstick controller and (b) virtual hand model.

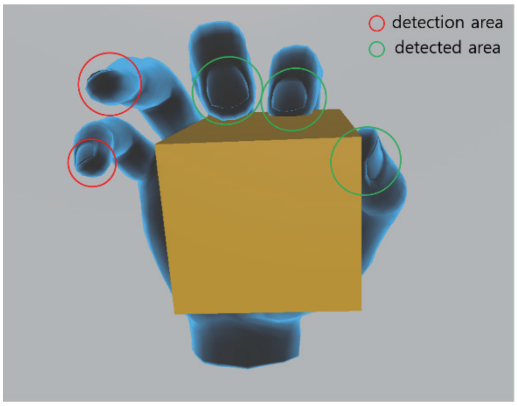

Fig. 2. (Color online) Detection and detected areas.

The grab state of an object is classified into three categories on the basis of the user's measured force, as shown in Fig. 3. Here, the stable grab state refers to the condition where the user applies sufficient force to hold the object securely. The unstable grab state occurs when the user is holding the object with slightly insufficient force, thereby making the grab unstable. In the object release state, the user's force is completely insufficient, resulting in the object being dropped. Here, the user's pressure P_{user} is the real-time pressure measured when the user presses the controller button with their fingers, the stable pressure P_{stable} is the threshold required to hold the object in a stable manner, and the unstable pressure $P_{unstable}$ is the threshold below which the object is considered to be released. On the basis of an average adult male, $P_{standard}$ is defined as the amount of pressure that can be applied and maintained stably for over 30 s while gripping the controller tightly. Note that P_{stable} is calculated by multiplying $P_{standard}$ by the object's weight and a predefined weight coefficient that differs for each object. $P_{unstable}$ is set to 30% of the corresponding P_{stable} value. As the object's weight increases, P_{stable} and $P_{unstable}$ increase linearly; thus, the user must apply a proportionally appropriate force to manipulate heavier objects. If P_{user} is greater than or equal to P_{stable} at the moment of grabbing, the object enters the stable grab state. If P_{user} is less than P_{stable}, the system grants a 3 s grace period. If P_{user} does not reach P_{stable} within that time, the object is released. In addition, if P_{user} becomes less than $\mathrm{P}_{\mathrm{unstable}}$, the object is released immediately because the force applied by the user is insufficient to lift the object.

3.2 Weight-based object offset

The proposed VO method was designed to induce a sense of virtual weight when manipulating objects using the five-finger interaction system. As shown in Fig. 4, when an object is grabbed, the VO method generates a semitransparent shadow of the object below its original position. This shadow is placed at a vertical distance, referred to as the offset distance, that changes dynamically on the basis of the weight of the object and the user's pressure. This varying offset distance allows the user to visually assess how much additional force is required to lift the object. Here, as P_{user} approaches P_{stable}, the offset distance decreases gradually toward zero, and when P_{user} exceeds P_{stable}, the offset becomes zero, which indicates that the force

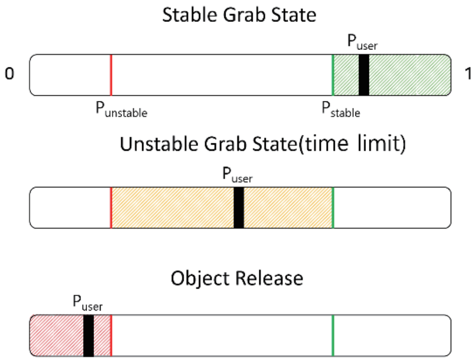

Fig. 3. (Color online) Object manipulation states: stable grab, unstable grab, and object release, defined by user pressure values.

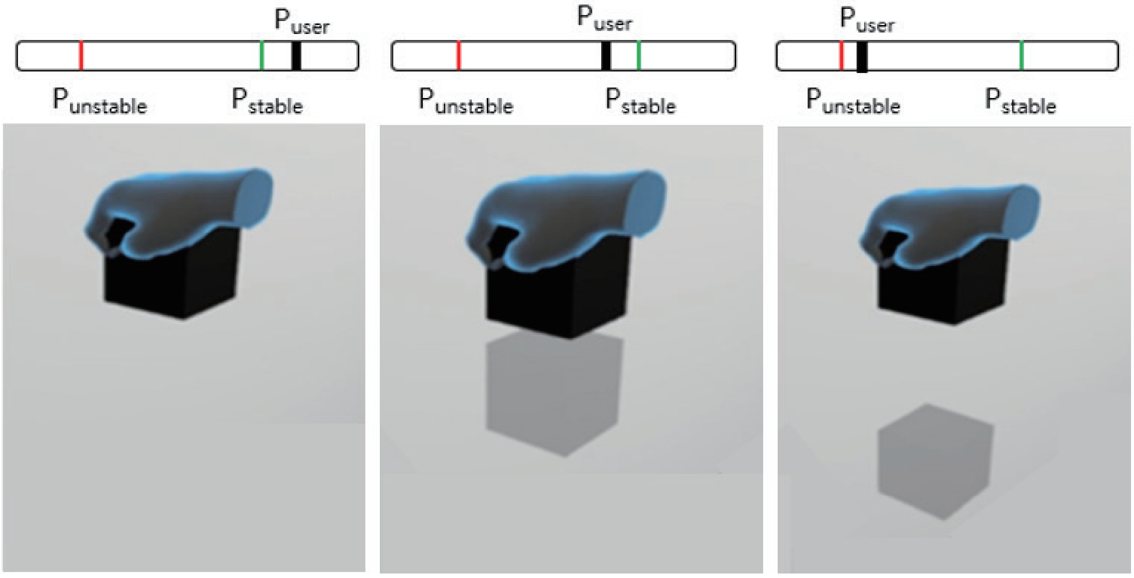

Fig. 4. (Color online) Proposed VO method.

applied by the user is sufficient to lift the object; thus, the shadow is no longer rendered. In contrast, as P_{user} approaches $P_{unstable}$, the offset distance reaches its maximum, positioning the shadow farther below the original object. To reflect the differences in the weight of the object, the maximum offset distance is set to increase with the object's weight. If P_{user} becomes less than $P_{unstable}$, the object is released, and the shadow disappears.

3.3 VO method with visual feedback

When manipulating objects using the proposed VO method, the offset between the object and its shadow increases if the applied pressure is insufficient to maintain a stable grip. To enhance the visual salience of this offset and intuitively convey a sense of weight, two visual feedback variations were developed, i.e., the rope-rendering VO (RVO) and the outline blink VO (OBVO).

In the RVO method (Fig. 5), a dynamic rope is rendered between the original object and its shadow. Here, the rope's length and thickness vary according to the offset distance and the pressure applied by the user. Through these visual cues, the user can intuitively perceive the insufficient grip force. The maximum rope length corresponds to the maximum offset distance, which is determined by the object's weight. The thickness of the rope decreases as P_{user} approaches $P_{unstable}$, and the object is released when P_{user} becomes less than $P_{unstable}$. At that moment, the rope appears to snap, visually stimulating the object falling due to the loss of grip.

In the OBVO method, the outline rendered around the shadow becomes increasingly prominent as the offset increases owing to insufficient pressure. Here, the outline blinks at a higher rate and changes color as the user's grip weakens. This combination of color changing and blinking is designed to draw the user's attention and prompt a quicker response.(28) The OBVO method emphasizes the urgency of a potentially unstable grip, making the offset visually more salient. As shown in Fig. 6, when P_{user} approaches P_{stable}, the outline color shifts toward yellow, and the blinking interval is set to 0.5 s. As P_{user} approaches $P_{unstable}$, the color changes to

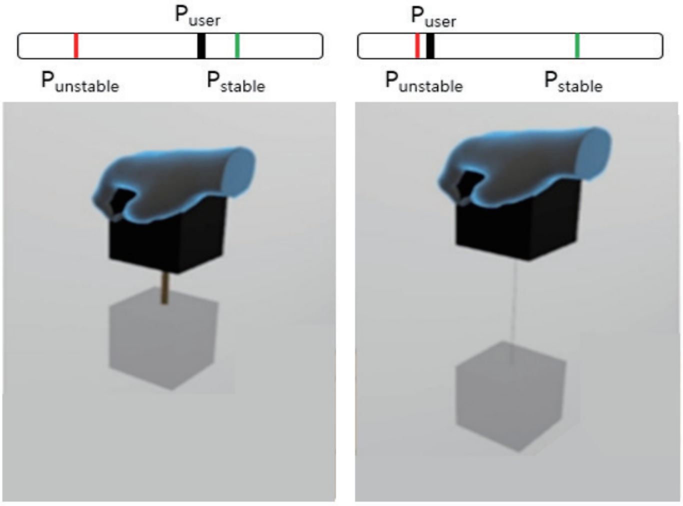

Fig. 5. (Color online) RVO method.

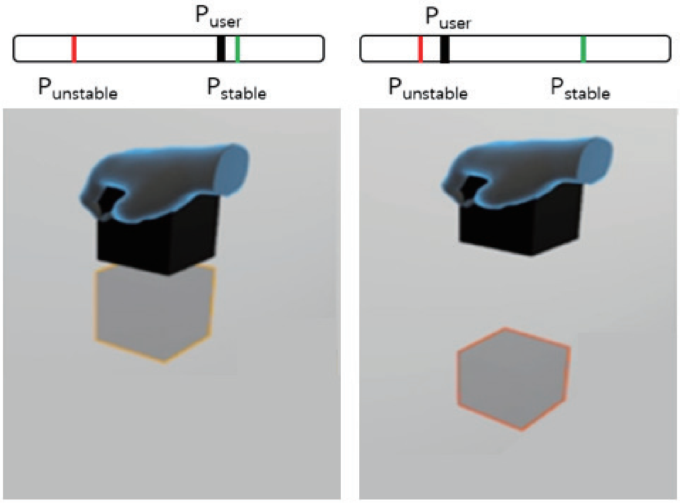

Fig. 6. (Color online) OBVO method.

red, and the blinking interval is reduced to 0.1 s. This dynamic variations in color and blink rate reinforce the perception of instability and communicate the need for a greater force to maintain a sufficient grip on the object.

3.4 VO method with haptic feedback

Continuous vibration feedback reflecting the weight of the object and the user interaction can enhance the VR experience.(29) To convey a sense of virtual weight through haptic feedback, two vibration-based extensions of the VO method are developed, i.e., the variable vibration VO (VVVO) and fixed vibration variable offset (FVVO) methods.

In the VVVO method, the vibrations change dynamically on the basis of the object's weight and the force applied by the user during manipulation. Similar to how a larger offset appears when the pressure is insufficient, the vibration intensity increases as P_{user} approaches $P_{unstable}$, and it decreases as P_{user} approaches P_{stable}. When P_{user} exceeds P_{stable}, which indicates a sufficiently stable grip, the offset and vibration disappear. The maximum vibration strength is determined by the weight of the object. On a device scale of 0–10, the heaviest object is assigned a maximum vibration intensity of 10, and the lightest object is assigned a value of 4. By combining the dynamically changing visual element (VO) with direct tactile feedback to the hand (vibration), the users can perceive the weight of the object effectively during interaction.

In contrast, the FVVO method delivers a single vibration when the object is initially grabbed, and the vibration intensity is based solely on the object's weight. As in VVVO, heavier objects trigger stronger vibrations (set to 10), and lighter objects produce weaker vibrations (set to 4).

4. Experiments and Results

4.1 Experimental overview

To analyze whether the proposed VO method, which is based on the object's weight and the user-applied force, positively affects the perceived weight during virtual object manipulation tasks, the following two hypotheses were proposed and tested through two comparative experiments.

H1: Providing visual feedback to the object's offset, which changes according to the weight and user force, will enhance the user's ability to perceive the virtual weight.

H2: Providing vibrotactile feedback to the object's offset, which changes according to the weight and user force, will enhance the user's ability to perceive the virtual weight.

To test the differences in visual feedback and haptic feedback, two independent experiments (Experiments A and B) were designed. In Experiment A, which was designed to verify H1, the RVO method (which renders a dynamic rope between the object and its shadow) and the OBVO method (which applies color and blinking effects to the shadow's outline) were compared. In Experiment B, which was designed to verify H2, the VVVO method (which delivers dynamic vibration based on object's weight and user force) and the FVVO method (which delivers a single vibration based on object's weight) were compared. The experimental environment was implemented using Unity 2021.3.24f1 with an HTC Vive Pro Eye and the Bstick controller. Before conducting the main experiments, the participants completed a short training session to mitigate the potential impact of unfamiliarity with the controller on task performance. In this training phase, the participants practiced lifting and releasing a simple cube object without the visual or haptic feedback using the VO method for approximately 1 min. At the end of each experiment, the task time and accuracy were recorded automatically, and the participants completed a post-experiment questionnaire. Prior to beginning the experiments, the participants were informed of the procedures and safety precautions, and they were made aware that they can withdraw from the study at any time. A total of 26 participants (16 males and 10 females; average age: 25.7 years) were included in the study. Among them, seven participants had no prior experience with VR, 12 had 1–5 prior experiences, and seven were experienced users with greater than six VR sessions.

4.2 Experimental method

In the experiments, the participants were asked to manipulate cubes and arrange them in order of increasing weight. As shown in Fig. 7, four cubes with different weights were placed on a table, and participants were required to reposition them into the designated answer slots from left to right, with the lightest cube placed on the far left and the heaviest on the far right. Each experiment involved two difficulty levels, i.e., easy and hard. With the easy difficulty level, the cube weights were set to 1, 3, 5, and 7 weight units, resulting in a weight gap of 2 units between the adjacent cubes. In the hard difficulty level, the weights were set to 1, 2, 3, and 4 weight units, resulting in a gap of 1 unit. All conditions across Experiments A and B used the same task structure, and the task completion time and accuracy scores were recorded. Here, the accuracy was scored using a five-point scale ranging from 0 to 4 points, where a base score of 1 point was awarded for each cube correctly placed in its designated weight slot. To further differentiate the participants' ability to perceive weight, an additional point was awarded when exactly two cubes were placed incorrectly but those incorrect placements occurred in adjacent answer slots.

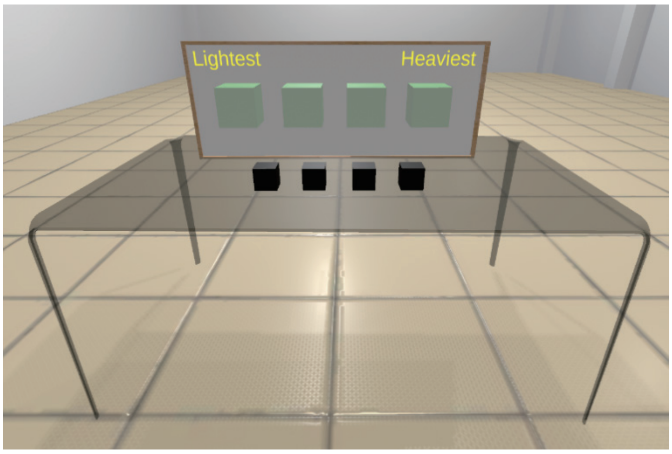

Fig. 7. (Color online) Experimental virtual environment.

Sample sets that would qualify include (1, 2, 4, 3), (1, 3, 2, 4), and (2, 1, 3, 4). In contrast, sets with incorrectly placed cubes in nonadjacent positions, e.g., (1, 4, 3, 2) and (4, 2, 3, 1), were considered to reflect poorer weight discrimination and did not receive bonus points.

4.3 Questionnaires

Four questionnaires, i.e., the weight perception questionnaire,(30) the Borg CR10 scale,(31) the presence questionnaire (PQ),(32) and the NASA task load index (NASA-TLX),(33) were used in this study. The weight perception questionnaire is an extended version of the questionnaire used in Samad *et al.*'s study and comprises nine items related to the perception of weight during virtual object manipulation rated on a seven-point scale.(20) The Borg CR10 scale evaluates the participant's subjective arm fatigue on a scale from 0 to 10, and the PQ questionnaire measures the sense of presence in VR using a seven-point scale and is divided into four key categories, i.e., involvement, sensory fidelity, adaptation/immersion, and interface quality. Here, involvement evaluates the psychological state experienced due to sustained attention and mental energy focused on consistent stimuli or meaningful events, and sensory fidelity examines the sensory accuracy and realism experienced in the virtual environment. In addition, adaptation/immersion indicates how well the users adapt to and become immersed in the virtual environment, and the interface quality relates to the quality of the interface used for interaction in the virtual space. The NASA-TLX is a 21-point scale questionnaire to evaluate task load that includes six categories measuring mental and physical strain during a task. Here, the mental demand, physical demand, and temporal demand categories measure the cognitive, physical, and time-related burdens experienced during the task, and the effort, frustration, and performance categories evaluate the level of effort required to complete the task, the level of irritation or dissatisfaction experienced, and the perceived success in completing the task, respectively.

4.4 Experimental results

4.4.1 Comparison of visual feedback in VO

In Experiment A, the RVO and OBVO methods were compared in terms of task completion time and accuracy, and the corresponding results are shown in Fig. 8 and are summarized as follows. In the first round (1R), the average task completion times were 59.3 ± 15.5 s for the RVO method and 78.1 ± 7.8 s for the OBVO method. In the second round (2R), the task completion times for the RVO and OBVO methods were 72.5 ± 19.7 s and 85.6 ± 13.8 s, respectively. On average, the RVO method was faster than the OBVO method by 18.8 s in 1R and 13.1 s in 2R. In terms of the accuracy scores, in 1R, the RVO method scored 3.7 ± 0.5 points and the OBVO method scored 3.4 ± 0.5 points. In 2R, the RVO method scored 3.3 ± 0.9 points and the OBVO method scored 2.6 ± 1.3 points. These results indicate that the RVO method outperformed the OBVO method by averages of 0.3 and 0.7 points in 1R and 2R, respectively.

The questionnaire results are shown in Fig. 9. For the arm fatigue level reported during the task (based on the Borg CR10 scale), the RVO method scored 3.7 ± 1.6 and the OBVO method

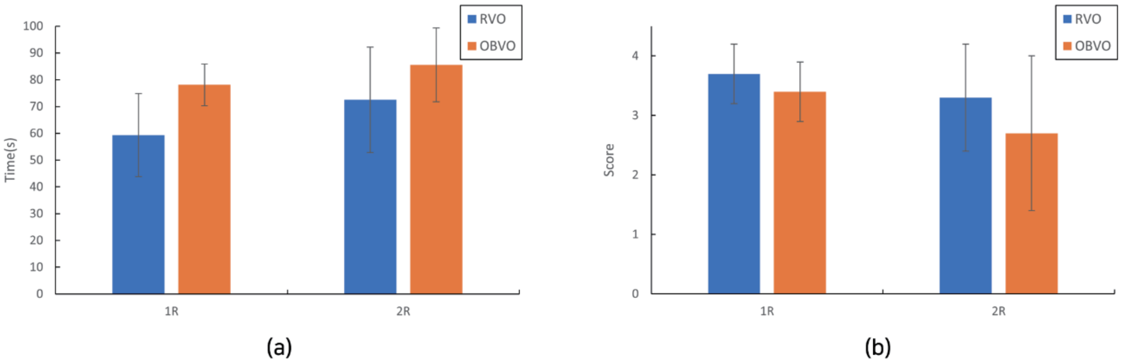

Fig. 8. (Color online) Results of Experiment A: (a) task completion time and (b) accuracy scores.

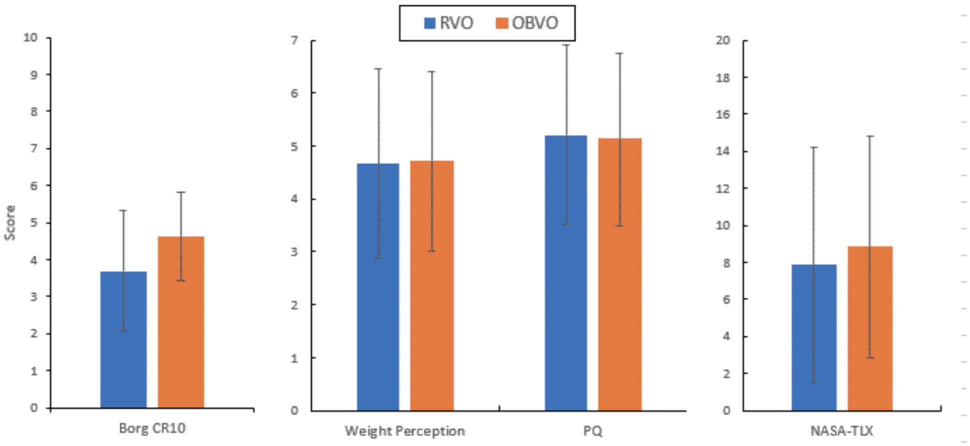

Fig. 9. (Color online) Questionnaire results of Experiment A by category.

scored 4.6 ± 1.2. However, this difference was not statistically significant. For the weight perception questionnaire, the average scores and standard deviations were 4.6 ± 0.93 and 4.6 ± 0.94 for the RVO and OBVO methods, respectively. As shown in Table 1, the individual item scores in the weight perception questionnaire were generally similar. The largest difference between the conditions was observed in the Time of Weight Illusion item, which asks when the user first perceived the object's weight. Here, a score of 1 indicates that the user felt the weight upon initial contact, and a score of 7 indicates that the weight was perceived only after fully lifting the object. The OBVO method obtained a lower average score of 4.2 ± 1.9 compared with the RVO method's 5.2 ± 1.2, which suggests that the OBVO users sensed the weight slightly earlier; however, the result was not statistically significant ($p = 0.130$). For the PQ, the RVO method scored 5.2 ± 1.7 and the OBVO method scored 5.1 ± 1.6. The scores for the corresponding subcategories are shown in Table 2. The NASA-TLX workload scores were 7.8 ± 6.4 for the RVO method and 8.8 ± 6.0 for the OBVO method. Note that no statistically significant differences were found in the subcategories, as shown in Table 3.

Table 1
Subscale scores of the weight perception questionnaire in Experiment A.

Weight Perception	RVO	OBVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Effectiveness	5.3 (1.5)	5.2 (1.5)	−0.256	0.800
Efficiency	4.5 (1.8)	4.8 (1.7)	0.570	0.574
Haptic realism	3.8 (1.9)	4.2 (1.6)	0.676	0.505
Grasping effort	5.9 (1.0)	5.9 (0.9)	0.000	1.000
Lifting effort	5.9 (0.9)	6.0 (0.9)	0.221	0.827
Time weight perc.	5.2 (1.2)	4.2 (1.9)	−1.578	0.130
Unintuitiveness	4.2 (1.7)	4.4 (1.4)	0.370	0.715
Limb ownership	4.2 (1.9)	4.7 (1.3)	0.865	0.396
Surfaces	3.1 (2.1)	3.0 (2.0)	−0.098	0.923

Table 2
Subscale scores of the PQ in Experiment A.

PQ	RVO	OBVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Involvement	5.8 (0.7)	5.6 (0.9)	−0.481	0.635
Sensory fidelity	4.9 (1.1)	4.8 (1.1)	−0.059	0.954
Adaptation/immersion	5.6 (0.6)	5.5 (0.8)	−0.382	0.706
Interface quality	2.5 (1.6)	2.5 (0.9)	0.102	0.920

Table 3
Subscale scores of the NASA-TLX in Experiment A.

NASA-TLX	RVO	OBVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Mental demand	5.5 (3.9)	5.2 (4.7)	−0.136	0.893
Physical demand	8.7 (6.2)	11.1 (4.2)	1.153	0.262
Temporal demand	3.5 (4.0)	5.4 (4.7)	1.070	0.295
Effort	16.1 (4.4)	15.9 (2.9)	−0.105	0.918
Frustration	5.0 (4.9)	6.2 (5.5)	0.606	0.550
Performance	8.3 (6.3)	9.2 (6.0)	0.384	0.704

The results demonstrate that the RVO method outperformed the OBVO method in terms of both task completion time and accuracy. Here, we note that participants may have required a longer time to understand the mechanism of the OBVO method, i.e., using color changes and blinking effects to represent offset magnitude and insufficient user force. In contrast, the RVO method employs a visual representation of a rope that stretches and thins as the offset increases, which likely provides a more universally intuitive cue. This familiar visual metaphor, i.e., suggesting that the rope may break when overly extended, may have enabled the participants to grasp the interaction mechanism more quickly, thereby leading to faster task performance. Given that the RVO method resulted in both shorter task times and higher accuracy, it can be considered to have had a more positive effect on the users' perceptions of the virtual weight. In addition, the RVO method exhibited lower arm fatigue scores than the OBVO method, and the physical demand subscale in the NASA-TLX also indicated lower physical load for the RVO method. This reduced physical fatigue may be related to the shortened task duration. The arm fatigue score for the RVO method (3.7 ± 1.6) was similar to the scores recorded in real-world tasks involving holding a physical bottle (3.65 ± 2.6),(34) which suggests that the act of grasping virtual objects with variable force based on weight may simulate the sensation of handling a real-world object.

4.4.2 Comparison of haptic feedback in VO

The second experiment compared the differences in how the vibration feedback was delivered. The task completion times and accuracy scores for the VVVO and FVVO methods are shown in Fig. 10. In 1R, the task completion times were 66.6 ± 16.6 s and 65.6 ± 11.6 s for the VVVO and FVVO methods, respectively. In 2R, the VVVO method had a task completion time of 73.8 ± 19.5 s and the FVVO method had a task completion time of 71.5 ± 13.9 s. On average, the FVVO method was slightly faster than the VVVO method, i.e., 1.0 s in 1R and 2.3 s in 2R. In terms of accuracy, in 1R, the VVVO method obtained 3.4 ± 1.1 points and the FVVO method obtained 2.8 ± 1.4 points. In 2R, the VVVO method obtained 3.2 ± 0.8 points and the FVVO method obtained 2.5 ± 1.4 points. On average, the VVVO method achieved 0.6 (1R) and 0.7 (2R) points higher accuracy than the FVVO in each round.

The questionnaire results are shown in Fig. 11. For arm fatigue, the VVVO method obtained a score of 3.0 ± 1.4 and the FVVO method scored 4.4 ± 1.2, revealing a statistically significant

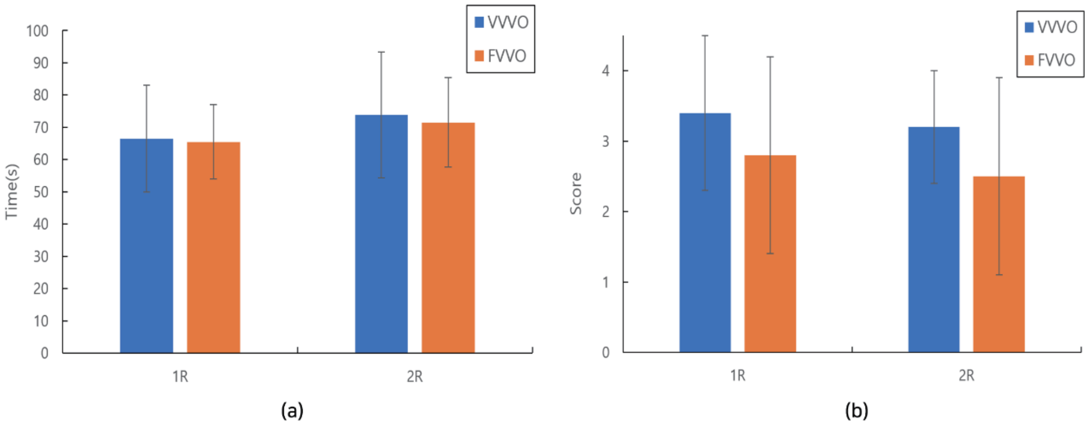

Fig. 10. (Color online) Results of Experiment B: (a) task completion time and (b) accuracy scores.

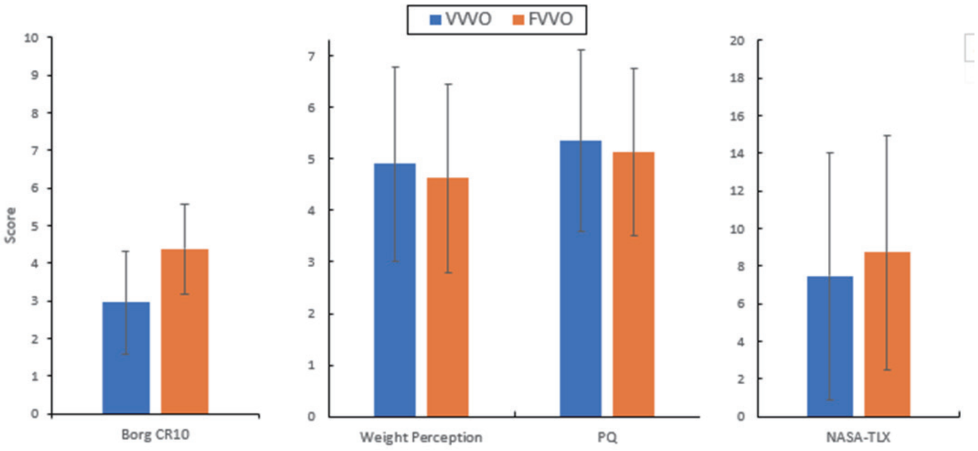

Fig. 11. (Color online) Questionnaire results of Experiment B by category.

difference (p = 0.009). In terms of the weight perception questionnaire, the VVVO method obtained an average score of 4.9 ± 1.9 and the FVVO method scored 4.6 ± 1.8. Among the subscales listed in Table 4, the Lifting Effort item, which asked whether the participants had to apply more force to the arm when perceiving one object as heavier than another, obtained scores of 6.3 ± 0.8 and 5.2 ± 1.6 for the VVVO and FVVO methods, respectively, indicating a significant difference of 1.1 points (p = 0.041). For the PQ, the VVVO method scored 5.4 ± 1.8 and the FVVO method scored 5.1 ± 1.6. Among the subscales shown in Table 5, the Adaptation/Immersion category exhibited differences of 6.0 ± 0.6 and 5.5 ± 0.9 for the VVVO and FVVO methods, respectively, which was marginally significant at the 90% confidence level (p = 0.078). The NASA-TLX workload scores were 7.5 ± 6.6 for the VVVO method and 8.7 ± 6.2 for the FVVO method. The subscale scores of the NASA-TLX (Table 6) did not show any statistically significant differences.

The task completion times for the VVVO and FVVO methods were found to be similar; however, the VVVO method obtained a higher accuracy than the FVVO method. The VVVO method delivers continuous vibration feedback proportional to the user's insufficient force; thus,

Table 4
Subscale scores of the weight perception questionnaire in Experiment B.

Weight Perception	VVVO	FVVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Effectiveness	5.5 (1.6)	5.1 (1.6)	−0.756	0.457
Efficiency	5.2 (1.7)	4.2 (2.3)	−1.153	0.260
Haptic realism	4.5 (1.8)	4.3 (1.8)	−0.322	0.750
Grasping effort	6.0 (0.8)	5.8 (1.1)	−0.395	0.696
Lifting effort	6.3 (0.8)	5.2 (1.6)	−2.209	0.041
Time weight perc.	4.2 (2.4)	3.9 (2.0)	−0.355	0.726
Unintuitiveness	4.2 (1.9)	4.5 (2.1)	0.390	0.700
Limb ownership	4.9 (1.7)	5.1 (1.4)	0.253	0.803
Surfaces	3.3 (2.2)	3.5 (1.5)	0.314	0.756

Table 5
Subscale scores of the PQ in Experiment B.

PQ	VVVO	FVVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Involvement	5.9 (0.7)	5.5 (1.0)	−1.093	0.285
Sensory fidelity	5.0 (1.2)	5.2 (0.9)	0.468	0.644
Adaptation/immersion	6.0 (0.6)	5.5 (0.9)	−1.839	0.078
Interface quality	1.9 (1.0)	2.5 (1.1)	1.293	0.208

Table 6
Subscale scores of the NASA-TLX in Experiment B.

NASA-TLX	VVVO	FVVO		
	Mean (*SD*)	*Mean* (*SD*)	*t*-value	*p*-value
Mental demand	4.0 (3.5)	7.1 (5.8)	1.634	0.118
Physical demand	8.5 (5.8)	9.8 (5.2)	0.605	0.551
Temporal demand	3.8 (4.1)	5.8 (4.8)	1.189	0.246
Effort	17.2 (4.3)	16.0 (4.8)	−0.647	0.524
Frustration	4.8 (5.2)	6.1 (5.9)	0.563	0.579
Performance	6.5 (5.6)	7.0 (5.1)	0.220	0.828

the participants may have been able to perceive weight more effectively by sensing changes in vibration intensity. In the weight perception questionnaire, the Lifting Effort item exhibited a statistically significant difference at the 95% confidence level. Unlike single-event vibration or purely visual cues, the VVVO method provides more intuitive and sustained tactile feedback, which likely encouraged the participants to apply greater arm force more naturally. In the PQ questionnaire, the Adaptation/Immersion item showed a marginally significant difference at the 90% confidence level. This suggests that the VVVO method helped the participants perceive virtual weight more effectively, thereby enhancing their sense of immersion within the virtual environment. Although no statistically significant differences were observed in the NASA-TLX workload results, the VVVO method obtained lower scores in the items measuring time pressure and stress. It is possible that the vibration feedback, which was generated in real time according to the applied force, helped the participants more easily recognize how much effort was required to lift the object, potentially reducing the cognitive burden.

5. Conclusion

In this paper, we proposed the VO method to provide VR users with a sense of weight during virtual object manipulation. The proposed method generates a VO between a virtual object and its semitransparent duplicate (shadow), which appears when the object is grasped using a virtual hand that can measure the pressure from all five fingers. The VO is adjusted dynamically on the basis of the object's weight and the pressure applied by the user's fingers. A greater offset appears when the applied force is insufficient, and the maximum offset range increases with the object's weight. As a result, users can perceive varying levels of virtual weight through the dynamic offset changes based on the difference between weight and pressure. To enhance the VO method, visual feedback was implemented using two techniques, i.e., connecting a virtual rope with variable length and thickness between the object and its shadow, and applying color and blinking effects to the shadow's outline. In addition, haptic feedback was implemented by generating continuous vibrations based on the weight and pressure differences or by delivering a single vibration based on only weight.

An experiment was conducted in which the participants were asked to distinguish the weights of different virtual objects and arrange them in order of weight using the proposed VO method with both the visual and haptic feedback techniques. Here, objective performance metrics were collected, and questionnaire data were used to evaluate the impact of each method on the participants' perception of the weight. The experimental results demonstrated that the RVO method, which incorporates the rope-based visual feedback, yielded the highest accuracy among all VO variations in the weight-sorting task. However, the subjective questionnaire results exhibited minimal difference between the RVO and OBVO methods. In contrast, the participants demonstrated greater accuracy when using the VVVO method, which provided dynamic vibration feedback, compared with the FVVO method. In addition, the participants reported exerting more physical effort when the objects felt heavier and described higher levels of immersion with the VVVO method. The FVVO method obtained the lowest accuracy among all VO conditions. These results suggest that the RVO and VVVO methods, which combine the VO method with visual and haptic feedback, can enhance VR users' ability to perceive and discriminate virtual weights more precisely. However, no statistically significant differences were observed in the immersion scores between the feedback methods. Thus, further research is required to develop advanced VO techniques that can simultaneously improve both task performance and user immersion in VR environments.

In future research, we plan to conduct a follow-up experiment to analyze the effects of combining RVO and VVVO, both of which demonstrated superior performance. The integration of these two feedback conditions is expected to enhance weight perception rather than induce sensory conflict. Notably, VVVO already integrates visual information based on the VO method and tactile information based on vibration, and it recorded higher average scores than visual-only feedback conditions in the subcategories of sensory fidelity and immersion in the presence questionnaire. A study by Kim *et al.* reported that combining visual offset with electrical stimulation improved users' weight perception.(24) This finding suggests that the integration of multisensory feedback can enhance perceptual coherence and contribute to improved weight discrimination ability. In addition, this study did not account for individual differences in tactile sensitivity when setting the vibration intensity. By incorporating a preliminary step in the experimental design to measure each participant's sensitivity range and providing more segmented vibration levels accordingly, it is expected that individual sensory characteristics can be more effectively accommodated, thereby contributing to improved weight perception accuracy and a heightened sense of presence.

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