IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 14, 2021, accepted November 8, 2021, date of publication November 30, 2021,
date of current version December 17, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3131525

A Systematic Review of Weight Perception in Virtual Reality: Techniques, Challenges, and Road Ahead

WOAN NING LIM[1], (Senior Member, IEEE), KIAN MENG YAP[1], (Senior Member, IEEE), YUNLI LEE[1], (Senior Member, IEEE), CHYANNA WEE[1], AND CHING CHIUAN YEN[2]
[1]Research Centre for Human-Machine Collaboration (HUMAC), Department of Computing and Information Systems, Sunway University,
Petaling Jaya 47500, Malaysia
[2]Division of Industrial Design (DID), National University of Singapore (NUS), Singapore 117356

Corresponding author: Woan Ning Lim (woanningl@sunway.edu.my)

This work was supported by the Sunway University Individual Research Grant (IRG) 2021 (GRTIN-IRG-52-2021).

ABSTRACT Weight is perceived through the combination of multiple sensory systems, and a wide range of factors – including touch, visual, and force senses – can influence the perception of heaviness. There have been remarkable advancements in the development of haptic interfaces throughout the years. However, a number of challenges limit the progression to enable humans to sense the weight in virtual reality (VR). This article presents an overview of the factors that influence how weight is perceived and the phenomenon that contributes to various types of weight illusions. A systematic review has been undertaken to assess the development of weight perception in VR, underlying haptic technology that renders the mass of a virtual object, and the creation of weight perception through pseudo-haptic. We summarize the approaches from the perspective of haptic and pseudo-haptic cues that exhibit the sense of weight such as force, skin deformation, vibration, inertia, control–display ratio, velocity, body gestures, and audio–visual representation. The design challenges are underlined, and research gaps are discussed, including accuracy and precision, weight discrimination, heavyweight rendering, and absolute weight simulation. This article is anticipated to aid in the development of more realistic weight perception in VR and stimulated new research interest in this topic.

INDEX TERMS Weight perception, virtual reality, pseudo-haptic, haptic interfaces, human–computer interaction.

I. INTRODUCTION

Since the conception of the first head-mounted display in 1968 [1], advancements in virtual reality (VR) technology have come a long way. Today, with companies like Oculus, HTC, Sony, Google, Valve, and Windows – all having released their version of a VR device – commercialized headsets are more accessible to the public. Typically, apart from a head-mounted display, commercialized VR devices come with a pair of handheld controllers. While the controllers allow users to interact with the environment in VR, it is only capable of providing basic input capabilities and simple haptic feedback [2]. To support the overwhelming needs for realistic haptic interfaces for VR, a number of studies have been dedicated to simulating object properties such as shape, size, weight, compliance, temperature, and texture.

According to Lederman and Klatzky [3], humans perceive object properties through a range of exploratory procedures (EP). For instance, lateral motions are associated with texture, pressure with hardness, static contact with temperature, unsupported holding with weight, and enclosure or contour following with shape. It can be deduced that most object properties can be simulated with direct cutaneous simulation on a single finger. However, owing to the human need to lift an object to discriminate between weights of different mass, muscular exertion is usually of focus when developing interfaces for weight perception [4]. Undoubtedly, this requires interfaces with more complex designs, which can be challenging to researchers. Since force can also vary in terms of magnitudes and directions, this further adds to the existing challenge.

The associate editor coordinating the review of this manuscript and approving it for publication was Giuseppe Desolda.

The needs for weight perception in VR are most apparent in the training field, where precision in manual tasks are crucial. For instance, in a micro-surgery training simulation, a surgeon may need precise feedback to perceive the weight of his/her tool to ascertain how to adjust the force applied onto an affected area [5]. This applies to assembly line simulations where fragile objects are produced [5], [6]. Employees should be able to perceive the weight of the product so they can successfully transfer their skills onto the real world. VR gaming has garnered massive popularity by providing the players with a truly immersive, first-person perspective of game action. Without the weight feedback, all game objects have the same equivalent weight as a remote controller. Having different weight perspectives can further enhance the gaming realism experience. Players can feel the different weights of the ball in bowling [7] or feel the weight of the falcon standing on the hand in the falconry training [8].

A. CONTRIBUTIONS

This review addresses some of the limitations of recent surveys on haptic interfaces for VR [9]–[11]. While the literature generally reviewed multimodal, commercialized, and non-commercialized haptic interfaces, this paper solely focuses on weight perception simulation. It is a challenge to render weight sensation in virtual form owing to the complex nature of humans in determining the heaviness sensation. Our contribution is to provide a systematic review on the aspect of weight perception development in VR, with a special emphasis on recent works, to identify the challenges and open research opportunities. To facilitate the understanding of this topic, critical factors that influence how humans perceive weight and an overview of weight illusions are presented. This paper complements the earlier survey on weight perception simulation [12] with a comprehensive view of the weight simulation development from the perspective of haptic and pseudo-haptic cues through a systematic review. This paper is anticipated to aid in the development of more realistic weight perception in VR and to spark new research interest in this topic.

B. ORGANIZATION OF THIS PAPER

The rest of this paper is organized as follows. Section II and III present background on how humans perceive weight and the illusions that influence weight perception. Section IV presents the methodology of the systematic review and discusses the development of weight perception in VR. Section V and Section VI focus on the haptic interfaces and pseudo-haptic techniques in weight perception. Section VII and VIII discuss the challenges and some possible future directions and opportunities. Section IX concludes this paper.

II. HOW DO HUMANS PERCEIVE WEIGHT?

The study of how humans perceive the weight of an object has been investigated since 1834 [13]. Human beings perceive objects encountered in daily life by using their sense organs and transmitting the stimulus information to their brain. Weight is perceived through the combination of multiple sensory systems by sensing the physical properties of an object. Weight perceiving involves the subprocesses of sensory, perceptual, and decisional [14], [15]. Somatosensory information is processed to form a percept of weight, followed by a decision on how to transform this internal percept into an outward report of heaviness.

The sensory mechanisms underlying weight perception can be traced back to the early psychological experiments of Ernst Weber [13], who asserted that the main factor that influences the perception of heaviness is the sense of force. Weight discrimination is more effective if the object is lifted rather than placed on a hand passively resting on a table. When considering the physics behind lifting an object in a simplified way, there are two forces that work against each other. The first is gravity, which pulls the object toward the ground. The second is the force that a person applies to lift the object. When lifting a heavier object, one must increase the force and strain the muscles to a greater degree. If one lifts the object with a small lifting force and proves to be unsuccessful, it could be increased repeatedly until an effective force is found that can help lift the object [16].

The weight of an object is mainly perceived by the two main sensations involved when lifting an object, first by the touch-sense in the skin and seconded by the special sense of the voluntary muscles [13]. During touching and grasping an object, the skin pressure and grip force constitute the outer information perceived by the mechanoreceptors, known as cutaneous force sensation [17]. The internal information involving muscle force or joint position during lifting is perceived by the proprioceptors in muscle spindles or tendon organs, and is known as the proprioceptive force sensation [18]. Davis and Roberts [19] stated that the observer's knowledge of the weight of objects is mainly dependent on proprioceptors within the muscle, which by their nature respond both to weights lifted and the muscular force of the lift. These changes could serve as "heaviness" input, since afferents have been shown to project to sensory-motor cortex [20]. The weight discrimination by these two forces has been measured, and it has been concluded that pure cutaneous forces discrimination is more than twice as precise with the addition of proprioceptive forces [13].

Since the introduction of these experiments and their validated efficacy, weight perception has been continued to be investigated [21]–[25], and findings have demonstrated that discrimination of an object's weight is not a distinct somatosensory task. Besides the touch and sense of forces, visual information provides another important cue to identify an object's weight [26]–[28]. The vision can provide information such as size, color, and material for one to relate to an object's weight. Objects with a bigger size are presumed to be heavier than smaller objects. On the other hand, objects with a brighter color are assumed to be lighter than a darker object. In addition, our conceptual understanding of materials tells us that the object made of polystyrene should be lighter than an object made of aluminum [29].

Amongst the sensory information contributing to the weight perception, research has revealed that compared with vision, information regarding an object's weight is processed most directly by the somatosensory system via the proprioceptors in the muscles [17], [30]. Vision can be used to extract an object's weight by observing the characteristics of the object but is conceivably a more demanding cognitive process [27], [31]. It is usually treated as a secondary input. In contrast to vision, the somatosensory system is designed to calculate the object's weight more directly through the haptic feedback [16] and is thus arguably better and more efficient in weight perception than the visual.

III. WEIGHT ILLUSION

Theoretically, the perception of an object's weight is determined by its mass. With the gravitational constant, the force applied should directly relate to the mass and thus the weight. However, in the real world, objects with the same mass could result in different sense of weight, thereby painting a complex picture of weight perception. This line of studies reveals that various factors can influence the weight perception process. However, despite years of research, there is little consensus about the mechanisms underpinning these perceptual theories. Some phenomena have been claimed as a sensorimotor mismatch, known as weight illusion [24], [32].

The perceived weight of an object is highly dependent on force perception. Any distortion of haptic or tactile force feedback can impact how heavy an object feels, such as muscle fatigue [33]–[35], tactile sensitivity [36], the way of gripping [37], and sensorimotor memory [38], [39].

Weight perception is also affected by the object properties, such as object size [21], [40]–[43], the material [28], [44]–[47], distribution of mass [48]–[50], shape [51], [52], temperature [13], [53], [54], and color or brightness [26], [55], [56]. Cognitive factors such as conceptual expectancy [57], [58] and social cues [59] are other important factors that cannot be excluded in weight perception study. In the following sections we will examine the factors that contribute to the illusions.

A. FORCE PERCEPTION

When lifting an object, first the brain uses visual cues and the external object representation to predict its weight and scales fingertip forces accordingly. When the hand grasps and lifts the object, tactile and haptic information is rapidly integrated to update the weight prediction and refine the internal object representation. In the scenario where the visual cues are omitted, weight perception is derived from the perception of the forces. A few peripheral effects (e.g., muscle fatigue, flexor sensitivity, gripping configuration and style) can influence an individual's somatosensory feedback, thus giving a different perception of force and impacting how heavy an object feels.

Previous research relating muscle and flexor reaction to the force perception pointed to the perception of a sense of weight. In research [33], [34], subjects were asked to maintain a constant isometric force with one arm as a reference and compared the force electromyography (EMG) signal retrieved from the fatigued and non-fatigued arm. The experiment suggested that during fatigue, subjects are unable to accurately estimate the force of contraction, and the over-estimation of force was observed owing to the increase in the excitatory input to the fatiguing muscle. Jones [35] stated that all subjects reported a distinct increase in effort when lifting an object as fatigue developed. The increase of effort and over-estimation of force led to the increase in the perceived heaviness. The experimental studies presented in [36] proposed that the flexor sensitivity can impact the judgment of weight; objects lifted by the thumb appear heavier when the skin and joint of the thumb is anesthetized. When the facilitatory input from sensory nerves in the skin and joint of the thumb to the thumb flexor is abolished by anesthesia, a greater voluntary motor command is required to compensate for the loss to lift the object. Thus, the lifted object feels heavier than usual.

Research [37], [45], [46] showed that the changes in grasp configuration could affect perceived heaviness in a weight discrimination task. The studies suggested that the effort involved in lifting the object and in applying grip forces to stabilize the object in hand can influence the perceived heaviness. The increase in either of the efforts led to an increase in perceived weight. A slippery object is perceived to be heavier with the additional grip force applied [46]. The object is perceived to be lighter when lifting with five fingers in comparison to two, a wide grip in comparison with a narrow grip, and a large contact area in comparison with a small contact area [37].

Another perceptual influence on force estimation is sensorimotor memory. The perception of weight is claimed to be biased according to the previous lifting experience [38]. The implicit knowledge acquired from prior lifting experience can result in force scaling during object lifting. The research [39] demonstrated that the force perception is affected by trial history in an opposite way. If predictive force and actual object weight do not match, the forces will be corrected and downscaled rapidly, causing lower weight estimation in a proportional manner. The weights were estimated lighter after a heavy lift, and the effects were correlated with the length of prior lifting experience. However, the weight estimates were negatively correlated with the magnitude of planned force parameters and the bias was noticed only if the current lift was light but not heavy. The effect of previous sensory experience was only found in active lifting, and no effect was experienced when weights are passively applied on the hand. The weight expectation in this experiment is an implicit phenomenon resulting from the sensorimotor memory-driven changes in force scaling. It is in contrast with explicit expectations that lead to different weight perception as demonstrated in [60], where a higher needed grip force is associated with a higher perceptual estimate [37], [44].

B. OBJECT PROPERTIES

1) SIZE

The most well-known studied weight illusion is the size–weight illusion (SWI), first documented by Charpentier [40]. It states that the perceived weight of an object depends not only on its physical weight but also its size. He demonstrated that when two objects of identical mass with different volumes are lifted, the smaller object is generally perceived to be heavier than the larger object. The experiments were carried out using two identical weight spheres but with different sizes (40 mm and 100 mm diameter, respectively) and had the observers lifted each with their hands. The SWI can decrease the perceived heaviness of more than 50% of stimuli that increase in size without a change in mass [41]. Koseleff [61] agreed with the SWI phenomenon and used optically distorting lenses and Müller–Lyer patterns to demonstrate that when an object appears larger, it feels lighter; when it appears smaller, it feels heavier. The illusion is claimed to be cognitively impenetrable supported by Flournoy's study [42], and the illusion is preserved even when the observers were told that all the objects have the same physical weight. Studies showed that the greater the difference in volume, the stronger the illusion [62]. The SWI is experienced by adults as well as young children [63]. Gordon *et al.* [64] examined the visual size influences on the grip force in 30 children (1–7 years old) and 10 adults and concluded that the size did not influence the force before the age of 3 years. The magnitude of the illusion appears to diminish throughout childhood; however, the SWI does not diminish with repeated experiences or interactions with the objects.

The strength of the illusion varies with the modality used to derive the size of the object. In most of the traditional SWI experiments, the observers received volumetric information both visually and haptically. Ellis and Lederman [16] studied the contributions of visual and haptic size information to the SWI. In their first experiment, participants were asked to lift the object while blindfolded and could only assess the object's size through haptic information. In their second experiment, participants could see the objects but with haptic information removed, and they could only lift the objects using strings. In their third experiment, participants were permitted to see the objects, providing them with information of the volume cues via both haptic and visual channels. Comparisons between the three conditions indicated that the illusion is the strongest when an object's volume is assessed haptically and visually and the weakest when it is sensed using visual alone. The same pattern was also observed in the experiment described in [65], where the availability of visual information about size made no difference to illusion strength when haptic feedback was also available. Another study [66] found that the visual size cue, if not available when the object is lifted, yields no effect on the SWI. However, without visual cues, observers' percepts of weight were influenced by the size of the object they had just viewed by being told that the object is the same as they have lifted before [60]. The findings concluded that the haptic information is sufficient to produce a robust SWI without the visual information. Amazeen [67] extended the study and found that visual input appeared to improve mass discrimination compared with haptic touch alone. The effects of vision were not limited to the influence of volume on perceived heaviness but increased the sensitivity in mass when the participant was able to view the object in his or her hand.

Much research has been done to explain the SWI phenomenon; however, none can account for all relevant findings [24], [68], [69]. The earlier explanation involves expectation theories [70], which stated that a mismatch between predicted and actual sensory feedback is the cause of SWI. Prior experience with objects leads observers to expect that a larger object will generally carry a larger weight than a smaller object. The correlation assumed between large volumes and heavy weights can affect an overestimate of the force required for lifting a larger object [71]. The larger object with identical mass being lifted with higher force will result in greater acceleration and velocity than the smaller one [19], causing contrasting mismatches between efference and afference and lead to the percept that the smaller object outweighs the large object. Some coined it as sensorimotor mismatch [24].

However, Flanagan and Beltzner [72] argued that the SWI is unlikely to be sensorimotor origin, and thus, the expectation theories cannot adequately explain the illusion. Their study showed that over multiple lifts, individuals adapted and scaled their fingertip forces precisely to the actual object weights and exhibited accurate sensorimotor feedback, but the perceptual illusion persisted. The results demonstrated that the illusion could be caused by perceptual factors and sensorimotor system independently. This is further supported by the study of Grandy and Westwood [73], who stated that sensorimotor and perceptual systems utilize different mechanisms for determining object mass.

In contrast to the expectation theories, a number of SWI studies [41], [74], [75] had examined how weight perception changes with density, suggesting that subjects perceiving an object's density but erroneously reporting the same as its weight is one of the causes of SWI. Furthermore, neuroimaging research [76] used functional magnetic resonance imaging (fMRI) adaptation techniques, which suggested that the object size and weight are computed by the neural sensory and primary motor (M1) areas, respectively. However, the object's density, which leads to the SWI is computed by ventral premotor area in the frontal cortex, a higher-order area that integrates the sensory information of size and weight.

2) MATERIAL

The density of an object, which plays a dominant role in determining the perceived heaviness and contributes to SWI, is related to the mass and volume of the object. Objects with the same mass and volume are judged differently in their heaviness, a concept first described by Wolfe [43] and known as material–weight illusion (MWI). Objects with identical weight and size made from heavy-looking material (e.g., metal, brass), would appear lighter than objects made from a less dense material (e.g., wood, polystyrene) [20], [47].

Ellis and Lederman [77] indicated that the MWI is principally a haptically derived phenomenon. Visual cues of the material could only generate moderate MWIs, whereas haptically accessed material cues were sufficient and necessary for full-strength illusions. Vision-only illusions were conspicuously weaker than either haptics + vision or haptics-only illusions. The results also demonstrated that the magnitude of MWI is mass-dependent. In the experiment, the illusions generated at a low-mass level were stronger. There was no effect of material on perceived heaviness for higher masses (e.g., 357 g) [77]. The decreased level of cutaneous feedback signals from the finger pads, which presumably reduced material surface cues, could be the possible cause when higher grip forces were applied to lift the heavier masses.

Further research [44]–[46] suggested that the texture and surface of different materials are important haptic cues that can influence the perceived heaviness of an object during lifting. Flanagan and his co-worker [44], [45], and Rinkenauer *et al.* [46] found that the smoother the surface texture, the greater the perceived weight. A smooth object was judged heavier because the grip force required to prevent it from slipping was larger [45]. Further analysis revealed that this hypothesis was applicable for vertical object lifting with the thumb and index finger holding the sides of the object. There was no effect of surface texture on weight perception when the object was lifted horizontally with the thumb supporting the weight from underneath and index finger on top of the object [44]. The findings helped the researchers conclude that the influence of surface texture in perceived heaviness was highly dependent on the grip force exerted against the shear force causing the object to slide from the grasp.

Saccone *et al.* [32] conducted a meta-analytic review of the SWI and MWI and provided preliminary evidence that variations in physical size resulted in larger differences in perceived weight than apparent material and hence concluded that SWI has a significantly stronger effect than the MWI in weight illusion paradigms.

3) DISTRIBUTION OF MASS

Research studies have shown that the perceived heaviness of wielded objects is influenced by the objects' rotational inertia – the objects' resistance to rotational acceleration. Amazeen and Turvey [48] attached weights to different locations on a long hammer-like rod to create rotational inertia when held and manipulated by the participants. The experiment showed that altering the mass distribution had a much larger effect on the perceived heaviness than altering the mass itself. Streit *et al.* [49] demonstrated that perceived heaviness was positively related to rotational inertia and inversely related to rotational gain. When virtual objects rotated faster than the actual wielded objects (rotational gain was applied to virtual objects), the wielded objects were perceived as lighter. The results further suggested that the detection of rotational inertia is based on the relation between applied torque and the object's responsiveness.

4) SHAPE

The perception of weight has been found to be influenced by the shape of the object. The shape–weight illusion was first described by Dresslar [51] as early as 1894. Changes in shape without changes in volume would produce an illusion in the judgment of weight. In the experiments, the subjects were instructed to explore and perceive the weight of eight objects made of sheet lead with identical area, thickness, and mass. The objects were shaped in various two-dimensional figures, such as circles, squares, and irregularly angled figures. Results showed that objects with more compact shapes were perceived heavier than less compact shapes.

Further research by Kahrimanovic *et al.* [52] extended the findings by exploring the effect of three-dimensional shapes on the perceived weight of objects. In one of the experiments, sets of brass objects with the shapes of tetrahedrons, cubes, and spheres ranging from 16.8 g to 117.6 g were compared in pairs by the blindfolded subjects, and the volumes and weights were discriminated. The results showed that tetrahedron was perceived to be the largest in size amongst the shapes of the same physical volume, and the sphere was perceived smaller than the cube. In the weight discrimination tasks, the weight of tetrahedron was found to be consistently underestimated compared to the cube with the same physical mass and volume. The tetrahedron was perceived as being significantly lighter than the cube. The phenomenon was supported by Vicovaro *et al.* [56] in their recent study. Their experiments revealed a significant effect of shape on weight perception, although the direction and the magnitude of the biases were subject-dependent. The result of the larger object (tetrahedron) being perceived as lighter is congruent with the findings from Dresslar's study [51]. However, the results showed that the shape–weight illusion could not be explained by only the influence of haptically perceived size on perceived weight without any visual information.

5) TEMPERATURE

Another factor that has been observed to influence the perception of weight is objects' temperature. This phenomenon is known as a temperature–weight illusion. It was first reported by Weber [78], who experimented with objects placed on the forehead and observed that cold objects were perceived heavier compared to the warm objects. Stevens and Hooper [54], [79] extended the research by placing the cold and warm stimulators on the forearm at three different skin temperatures, and weight illusion was found to be affected by both cold and warm objects. The former felt considerably heavier than neutral objects, whereas the latter felt heavier, but the effect was noted to be somewhat insignificant. Further research on the intensity of temperature on the touch modality [80] showed that cooling effects greatly intensify touch magnitude at the forearm and forehead, however the warming effects had little effect via the forehead.

A recent study [53] investigated the effect of temperature on the perception of heaviness and the grasp and lift forces. Psychophysical experiments were performed by using cold (18°C), neutral (32°C), and warm (41°C) test objects with two different masses: 350 g (light) and 700 g (heavy). Cold objects were felt 20% heavier than thermally neutral objects when placed on the palm of the subjects. A 10% increase in grip force was observed when the cold objects were lifted. The effect was found more prominent in heavy objects and less pronounced in lighter or warm objects. These findings can be considered congruent with the temperature–weight illusion phenomenon, according to which cooling of an object increases its heaviness perception and influences scaling of the forces during grasping and lifting. Furthermore, the results of force perception experiment from Galie and Jones [81] indicated that the thermal cues did not have any influence on the perceived weight when haptic cues of the forces generated by muscles were available. This finding suggests that temperature–weight illusion is a tactile-oriented phenomenon as opposed to haptic.

6) COLOR AND BRIGHTNESS

The color–weight illusion is a less well-known weight illusion and has remained relatively underexplored than SWI or MWI. It was first described by De Camp [55] that light-colored objects were felt slightly heavier than darker objects. Experiments had been performed to examine how the variations in hue, tint, and chroma affect the perception of heaviness. Cubical blocks with nine different colors: red, orange, yellow, green, blue, violet, purple, black, and white were deployed in the test. In one of the experiments, red and black were judged heavier than yellow and blue, and white was judged lighter than red, yellow, and blue. It was argued that white objects appear larger than darker color objects and thus have the tendency to be judged heavier as discussed in the SWI. However, this was not consistently observed in other color pairs such as red (lighter) and blue (darker). Hence, it led to the conclusion that apparent size is inadequate as a basic explanation of the results obtained. Certain factors other than the apparent size of the blocks are likely to be involved.

The research findings [55] summarized and suggested that dark-colored objects are generally judged heavier than their light-colored counterparts; however, the impact of color of an object upon its weight perception is inconsistent and relatively slight compared to the other illusions. There is no simple correlation between the effect of color and its influence upon the apparent weight. Studies have suggested that the influence of the colors is not because of their tint value alone but also because of the hue factor. Further research supported this hypothesis and proposed the association between surface lightness and weight and termed it as brightness–weight illusion [26]. However, the experimental results obtained by Vicovaro *et al.* [56] are inconsistent with the findings and demonstrated a lower probability 0.49 compared to 0.8 (in [26]) for a white object to be judged as heavier than a black object. The researchers argued that the discrepancy might be due to the differences in test objects' weight (220 g versus 129 g) and the mode of lifting (using a string versus holding in the hand) during the experiments, which reduced the subjects' sensitivity to subtle differences in weight. They concluded that the existence of the brightness–weight illusion was restricted to a specific weight range and a specific mode of lifting. Therefore, the brightness–weight illusion is less robust and generalizable than the size–weight, material–weight, and shape–weight illusions [56].

C. COGNITIVE FACTORS

Much research on weight illusion leans quite strongly toward the sensory-based interpretation model. Undoubtedly, the perception of an object's heaviness is strongly influenced by its properties and the visual or somatosensory feedback. However, cognitive factors cannot be entirely excluded from the weight perception research, as demonstrated by the well-cited "golf-ball illusion" [57]. The practice golf balls and real golf balls were presented to the golfers and non-golfers to percept the weight. Both kinds of balls were altered so that they had the same weight (practice golf balls are known to weigh much less than real balls by golfers). The results showed that the experienced golfers judged the practice golf balls to be heavier than real golf balls, whereas the non-golfers judged them to weigh the same. Conceptual expectancy is accounted for this phenomenon, i.e., golfers having the background knowledge of the weight differences between the practice and real golf balls estimated lighter weight of the practice golf ball. This expectation-based illusion had led to the misjudgment when the practice golf balls were altered to the same weight as real golf balls.

In order to make perceptual decisions about properties in our environment, we couple sensory information with expectations in accordance with prior experience [82]. As discussed in SWI research, prior experience and knowledge about an object's size can affect the perceived weight even if the object is shown only prior to lifting [58], [60]. The perception of heaviness was found to be influenced by social cues. This was demonstrated by Dijker [59], who conducted experiments using multiple dolls representing human individuals of different age, sex, and somatotype as test objects. These dolls were given the same physical weight by inserting small pieces of lead and foam–rubber through openings made in their back and head. The results showed that female dolls were felt heavier in comparison with larger male dolls. However, this effect disappeared when the dolls were lifted with participants' eyes closed. The illusion reflected the subjects' expectations that females weigh less than males; the social cues stimuli motivated the subjects to lift the small and cute female dolls more carefully than the larger and physically stronger male dolls.

IV. DEVELOPMENT OF WEIGHT PERCEPTION IN VR

The advantage of VR lies in its capability to create a sense of presence and immersion. With the advancement in haptic technology, humans are able to feel the properties of virtual objects such as shape, texture, temperature, and stiffness. However, to simulate the real sense of weight in a virtual environment is still a big challenge in view of the complex nature of humans in determining the heaviness of an object.

A systematic approach has been adopted in searching and screening (Figure 1) in the process of reviewing the weight perception development in VR. The term ‘‘virtual reality’’ refers to simulated experience in virtual form, including platform with or without head-mounted-display (HMD) unit. The keywords ‘‘weight’’ and ‘‘virtual reality’’ were used to search the literature studies with the result of initial 2035 papers extracted from various sources, including ACM, IEEE, EBSCOhost, Open Access, ScienceDirect, etc. A total of 245 papers were selected after the removal of duplication and first-level filtration by title. Further exclusion was done on the basis of paper abstract, and any studies in the literature such as research papers on haptic interfaces but without discussion or analysis on weight perception were excluded. The final number of studies included in this review after the filtration process was 65.

Amongst the research papers, 10 out of 65 are research work carried out before year 2010. The papers were not eliminated from the review with the aim to provide an overview of the progression and evolution of the weight perception research in VR. By analyzing the type of platform used in the experiment as shown in Figure 2, the last 15 years of research works were seen to be mainly conducted in the VR platform without the HMD. These included the non-immersive Desktop VR, where a computer monitor is used as a display to provide a graphical interface [83], [84], the semi-immersive workstation, where the graphics reflect from an LCD monitor in a mirror over the workspace [85], and the full-immersive Cave Automatic Virtual Environment (CAVE), where projectors are used to project the image between three to six of the walls of a room-sized cube [86]. From the statistics (Figure 2), the interest in the weight perception research in VR seemed to be slow-moving prior to 2015 owing to the technical complexity and costly setup of the full-immersive VR experimental platform. The research interest started to grow with the advancement of technology since the launch of the first consumer VR headset (e.g., Oculus Rift and HTC Vive) in 2016. The result shows a growth in the weight perception research using a full-immersive VR environment setup with HMD in recent years.

Direct haptic is the major stream of weight perception research focusing on the innovation of haptic devices that can generate the gravitational forces or direct proprioceptive force sensations when grasping, holding, or lifting a physical object. A device capable of generating real forces can normally provide the user with a more realistic feeling. However, the trade-off is that such devices often need to be externally grounded, and as such, many of them are quite bulky and thus lack in mobility. On the other hand, indirect haptic focuses on simulating the feeling of weight by generating non-gravitational haptic forces through tactile sensation. The other category is pseudo-haptic, which does not involve any haptic devices but primarily relies on visual stimuli to create weight illusion. The summary is encapsulated in Table 1.

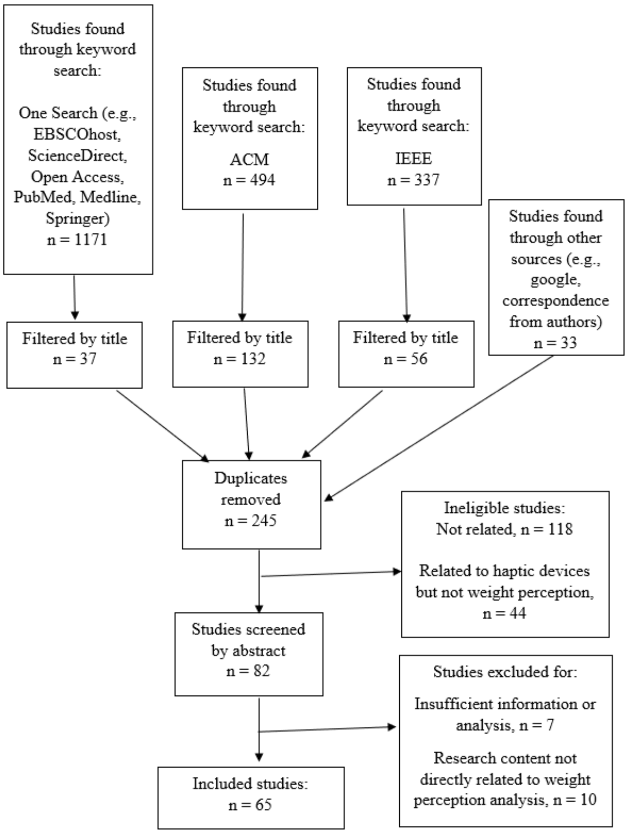


FIGURE 1. Search and screening processes.

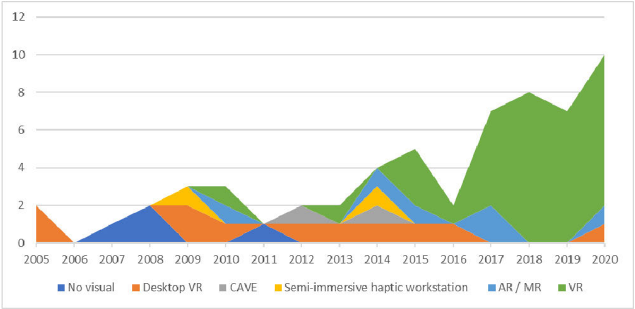


FIGURE 2. Number of literature studies in different experimental platforms.

TABLE 1. Weight perception research categories.

Category		Description	Characteristic
Haptic	Direct Haptic	Actual mass rendering through kinesthetic feedback	Typical large actuators, bulky and encumbering
	Indirect Haptic	Weight rendering through tactile feedback	Smaller actuators, freer movement (e.g., skin deformation, vibration, pin stimulation)
Pseudo-Haptic		Uses the visual feedback and verges on sensory illusion to generate weight sensation	High mobility, easy to setup

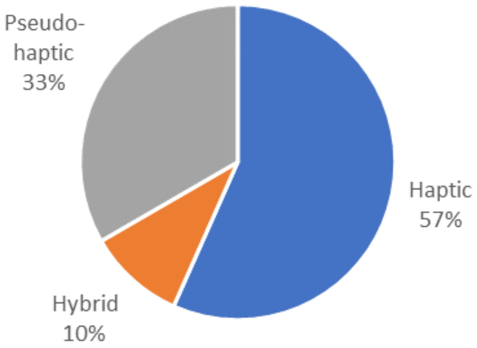


FIGURE 3. Summary of weight perception techniques in the literature.

Further analysis was done by categorizing the techniques used in the literature in this review (see Figure 3). The results show that almost two-third of the studies focus on haptic (57%), followed by pseudo-haptic (33%) and hybrid (10%). Hybrid category refers to the studies adopted the combination of haptic and pseudo-haptic techniques in their weight perception experiments.

V. WEIGHT PERCEPTION WITH HAPTIC INTERFACES

This section discusses the works that focus on creating the weight perception in VR by using haptic interfaces. In the review process, each of the techniques developed and deployed in the literature was studied. The findings are enumerated in Table 5 (in Appendix), and the derived results are used to support the discussion in this review.

A. TYPE OF INTERFACES

Analysis on the type of haptic interfaces as shown in Figure 4 shows that the focus of the literature on weight perception in VR is more on handheld [87]–[90] and wearable [91]–[94] interfaces compared to ground-based [95]–[97]. Wearing the device at the fingertips [98]–[100] were favored over other body parts, followed with wrist [93], [101] and palm [91], and last is the head [102], body [103], and arm [104]. The encountered type of interface such as quadcopters/drones [105], [106] and ultrasonic mid-air haptics [107], [108], mainly used in providing tactile feedback during touch sensations, were less seen in the review of weight perception research works. This could be because of the limitation of the strength and range of effect to generate the quantum of force, which is sensible for human in weight discrimination.

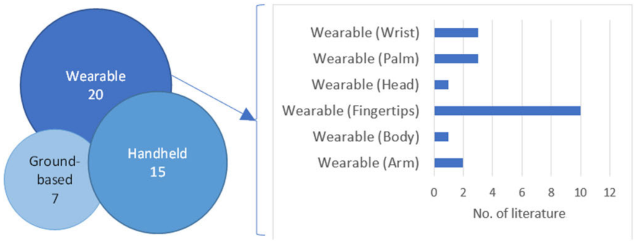


FIGURE 4. Type of haptic interfaces deployed in the literature.

B. HAPTIC CUES

This section highlights the haptic techniques and actuation methods in delivering haptic feedback to create the weight sensation in the virtual environment. The two primary sources of haptic feedback are kinesthetic and tactile feedback. Kinesthetic force feedback usually provides realistic physical interactions with virtual objects, giving a direct haptic cue to the weight sensation. In contrast, tactile force feedback provides an indirect haptic cue to create weight illusion through the skin sensation. The primary interest of this review is to investigate the haptic cue that can be generated by the haptic devices to create a sense of weight in a virtual environment.

Four main categories of haptic cues concluded from the literature reviews are force, skin deformation, vibration, and weight shifting, the other less investigated haptic cues are grouped into other categories as shown in Figure 5. The following discussions are arranged into individual sections according to the criteria as summarized in Table 2. The visual representation of the main haptic interfaces discussed in this section is shown in Figure 6, grouped by the haptic cues.

1) FORCE

Force is one of the important haptic cues to create weight sensation in a VR environment. As discussed earlier, humans sense weight by the information received from the proprioceptive and cutaneous force feedback. Traditional ground-based kinesthetic feedback devices can provide realistic physical proprioceptive force feedback, but they require large actuators and are usually bulky and constrained by restricted workspace. Examples of commercially available ground-based haptic devices include Omega 3 [84], [95], PHANToM [85], and SPIDAR [10], [109]. Alternatively, a wearable haptic device that is usually lightweight and has high mobility can create soft kinesthetic and tactile

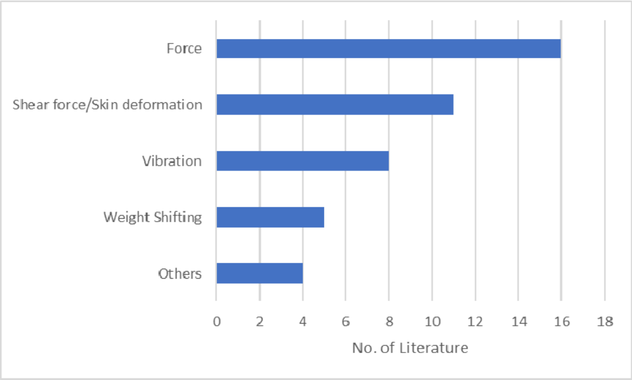


FIGURE 5. Haptic cue that enables weight perception.

TABLE 2. Haptic cue and the inclusion approach.

Haptic Cue	Inclusions
Force	Includes approaches that generate various force feedback as a haptic cue to weight sensation, such as proprioceptive force, contact force at palm and wrist, grip force, inertia force, etc.
Shear force/ Skin deformation	Includes approaches that apply lateral or shear forces on the fingers or fingertips resulted in the skin deformation as the haptic cue for weight perception.
Vibration	Includes approaches that use the vibration actuators to create the vibrotactile sensation as the haptic cue to generate weight perception
Weight Shifting	Includes approaches that move the physical weight prop, or using the virtual force to create the weight shifting effect as a haptic cue of weight perception.
Others	Includes approaches that generate other haptic cues that do not belong to the above four categories, such as liquid inertia, muscle tension, and head motion rotation, which give a hint of weight perception

sensations to simulate the sense of force, stiffness, and friction. It is usually in the form of exoskeleton commercially available haptic gloves, including CyberTouch, CyberGrasp, and Dexmo [109], [110]. Despite the high price tag, the challenge for all ungrounded haptic devices is realistically conveying the sense of object weight and inertia. It is impossible to render the downward force of weight or gravitational forces without connecting to the physical world. In the following subsections, we discuss the various forces deployed in the literature to render the weight sensation.

a: PROPRIOCEPTIVE FORCES

Giachritsis *et al.* [5], [111] designed a MasterFinger-2 ground-based haptic device equipped with two three-DoF finger modules, each actuated by three electric motors to generate forces in all translation directions. FlexiForce sensors by Tekscan were used to measure contact force during the experiment. The study showed that users were able to discriminate between both the real and virtual weights, but the Weber fraction (WF) results obtained revealed that the users seemed to be five times less sensitive to virtual compared to real weights. The study also confirmed that with the same simulated weight, unimanually lifted virtual objects feel heavier than bimanually lifted virtual objects, and both kinesthetic and tactile feedbacks are equally important in weight perception. This is supported in the later research by Van Beek *et al.* [95] with experiments using the customized Omega 3.0 device from Gurari and Baud-Bovy [112]. The results confirmed that integrating the tactile and kinesthetic information leads to better weight detection thresholds than unisensory cues. However, it was found that kinesthetic feedback was less reliable for lighter weights, whereas both kinesthetic and tactile feedback were equally reliable for heavier weights up to 300 g.

Aside from a ground-based device, Günther *et al.* [103] proposed the PneumAct jacket, which can create the kinesthetic movements of arm joints using the pneumatically actuated mechanism. It integrated a contraction and an extension actuator inflated through compressed air to contract the biceps and triceps resulting in a motion of the forearm toward the upper arm or move away from the upper arm. Experiments were conducted where 32 participants were asked to lift a weight by performing barbell curls and pulling down the handle of a cable pull while wearing the jacket. HTC VIVE controller was mounted to both sides of a physical pole to resemble the barbells and cable pull handle. The results showed that pneumatic kinesthetic actuation was able to let the participants feel the weight of the virtual barbell and increased the immersion experience in VR compared to no-haptics and controller-based vibrotactile feedback.

Faure *et al.* [96] proposed another innovative approach to render the weight of a virtual crate and any collisions with the virtual environment constraints by using a cable-driven parallel architecture. Eight cable-driven robots were connected to an end-effector within a fixed workspace to simulate the crate mass and the mechanical stops in the vertical and horizontal directions. The setup was able to generate 5 N of horizontal force and 15 N of vertical force to render up to 2-kg crate mass. This setup is capable of simulating heavier weight objects compared to other devices that usually manage to render lighter weight (< 1 kg).

b: FORCES ON PALM

Contact force at the palm is another haptic cue that was studied in weight perception research. Trinitatova and Tsetserukou [91], [113] designed DeltaTouch, a novel haptic interface to be wear at the palm, which can deliver tactile forces to simulate the sense of weight. The device has a lightweight (30 g) and compact structure, which comprises a base with three revolute joints of lower arms actuated by servo motors and connected to an end-effector that can deliver forces at any point of the palm. It can produce up to 4.2-N force in the normal direction to present the tactile sensation of weight. Three different force magnitudes (0.7 N, 1.5 N, and 2.5N) were simulated during the

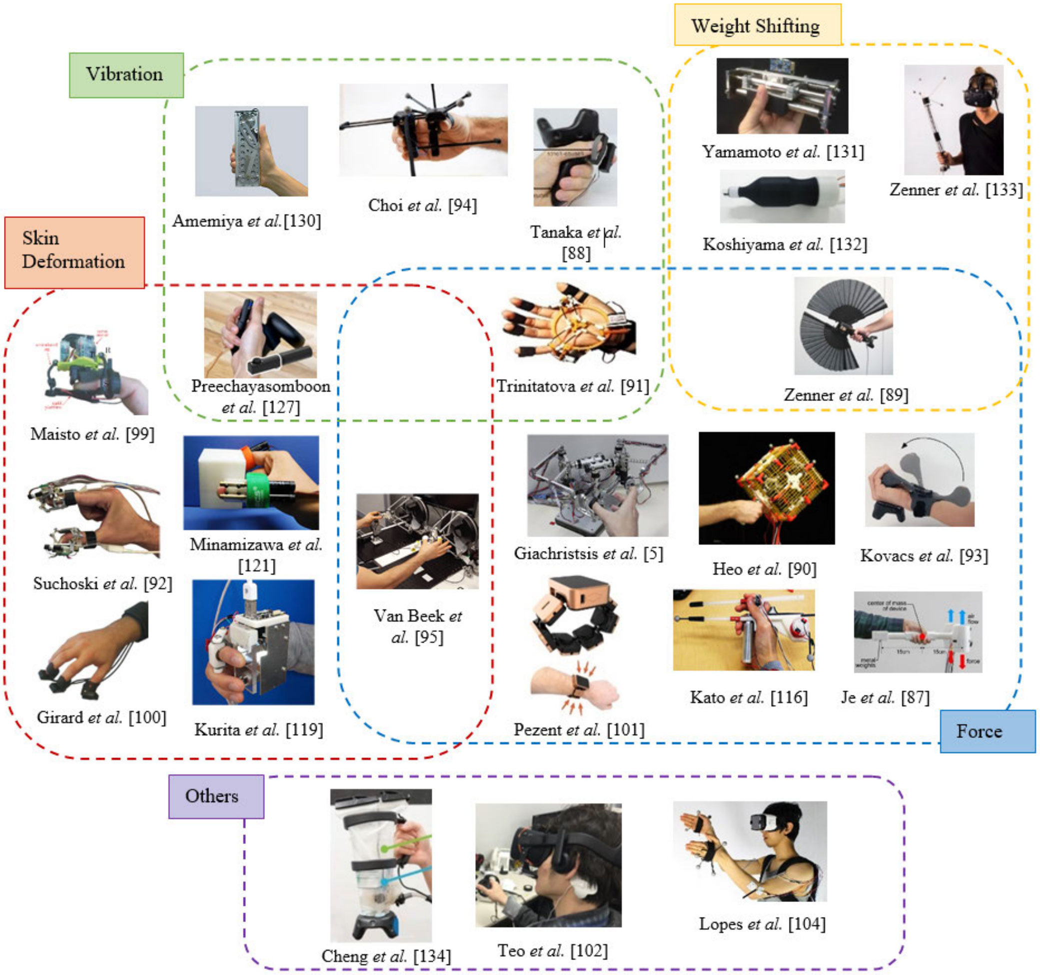


FIGURE 6. Visual representative of weight perception haptic interfaces.

experiment, and the results helped the researchers deduce that users could discriminate between objects with different weights; light and heavy objects were recognized more significantly than the medium. The device was only tested with users holding the virtual object on the palm. It would be interesting to see if the same sense of weight can be simulated in the lifting position.

Kovacs *et al.* [93] presented a wrist-worn haptic device PIVOT, which renders the weight of a virtual object by applying the push–pull force on user's palm. The design comprises an actuated joint that pivots a haptic handle into and out of the user's palm on demand. The dynamic forces were produced to render the weight sensations of grasping and lifting an object. The PIVOT – weighing 188 g – is capable to produce maximum 3.5-N force, which is equivalent to 350-g rendered weight on the palm. Participants were asked to grab three different virtual balls and select the heaviest and lightest ball they perceived, and 83% and 91% accuracies were achieved for the heaviest and lightest ball, respectively. The full weight sensation was felt when the palm was facing upward or downward and proportionally less in the horizontal position, because of the mechanism of the device that rendered the gravitational force of the perpendicular component to the plane of the palm.

c: FORCES ON WRIST

Aside from forces on the palm, research has shown that the weight and inertia of the objects could be rendered through squeezing at a wrist. Pezent *et al.* [101], [114] created a compact bracelet device Tasbi, capable of rendering the squeeze force at the wrist to render the sense of weight. The bracelet incorporated the vibration and squeezed haptic modalities, actuated by six linear resonant actuators and a dorsally located tensioning mechanism. Users were asked to pick up the tennis ball and wave the tennis racket, and the squeezing level was proportional to the weight of the ball and the tilt angle of the racket, conveying the inertia moment arm torque it would impact to the wrist to create the weight perception. Likewise, Hannig and Deml [115] applied pressure around the wrist by using another actuation method – a pneumatic actuated pressure sleeve. The pressure sleeve was filled with air compressing the wrapped wrist and the pressure level was controlled in proportion to the weight to be rendered in a virtual environment.

d: FORCES ON FINGERS

HapSticks [116], developed by Kato *et al.*, is a chopstick-like haptic device that mimics the sensation of manipulating objects with chopsticks to render the virtual weight by applying forces on the fingers. When users grasp or lift an object using a chopstick, the vertical force at the tip causes the force sensations on the middle finger, thumb, and the oblique arch of the index finger to create a sense of weight. HapSticks used the rotation and thread winding mechanism to create the vertical force at the tip of the long tool and by pressing a small plate against the finger to generate the pressure force. The distance from the tool tip and the rotation center is large, and thus, when a small vertical force magnitude is applied at the tool tip, it produces large forces to the fingers that are close to the rotation center. Weight discrimination tasks were carried out by using real and virtual weight ranging from 2 g to 55g. The results suggested that the device was able to render a reliable illusion of sensed weight, but the discrimination ability was still lacking compared to the real weights.

e: AIR RESISTANCE AND INERTIA

The impact forces and inertia rendered by airflow is another type of force that has garnered the interest of some researchers working on weight perception studies. Heo *et al.* [90] designed an ungrounded air-based haptic feedback device called Thor's Hammer. The device is a hammer-like in shape and consists of a cube-shaped structure connected to a handle. The cube was installed with six motors and propellers to provide three-DoF force feedback in six directions, i.e., each face of the cube. It is actuated by the propeller propulsion force to create force feedback simulating different weights. In the experiment, the device exerted up to a maximum 4-N force in each direction, allowing the user to experience different gravitational forces and feel the weight up to 816 g.

Similarly, Aero-plane designed by Je *et al.* [87] is an ungrounded handheld haptic device actuated by two small jet-propellers attached to the left and right of a handle to create the sense of dynamic weight. The device not only renders the weight of an object but also creates the illusion of a weighted object moving on a virtual plane by modulating the speed of the propellers. Users can perceive the weight of a mass located at the x position from the hand through the total forces created by the two propellers. Experiments were carried out with application using virtual ball freely rolling on a wooden board and application to exploit the weights of different cooking utensils (e.g., frying pans, pots, and rolling bat). The device is able to generate a maximum of 14 N of force, with 7 N by each propeller, but a noteworthy drawback is the heavy weight of the device that is close to 1 kg. Wind-Blaster [117] and LevioPole [118] applied the same mechanism by delivering the mid-air forces with drones-propellers and quadrotors to generate linear and rotational forces. However, testing has not been done to analyze the efficiency of the devices in rendering weight perception.

In contrast to the active forces generated with propellers, Drag: On [89] is based on the passive haptic feedback from air resistance to enable the sense of weight. It is a dynamic passive haptic device that dynamically resizes its folding fan surface area to leverage the airflow during interaction to create the drag and rotational inertia felt by the user. Participants were asked to differentiate the weight when interacted with a virtual shovel and moving a virtual wagon right to left by swinging or rotating the device. The results indicated that lightweight objects were associated with a closed fan, and heavy weight was felt when the fan was fully opened. The limitation is the fixed orientation of the fan plane, as the resistance effect would vanish when the controller moves parallelly to the fan plane and thus requires manual rotations of the device to coincide with the translation direction.

2) SHEAR FORCE/SKIN DEFORMATION

Skin deformation is the second most research haptic cue in rendering weight perception and relies on the tactile feedback, which potentially substitutes the kinesthetic force feedback to enhance the sensory in weight perception. Human perception of weight via kinesthetic feedback and skin stretch cues in a virtual environment were compared in a number of studies [84], [95], [97]. Suchoski *et al.* [84] recorded WF of 11% for kinesthetic force feedback and 35% for skin deformation feedback, and the results ranged from 22% to 44% in Van Beek *et al.*'s [95] experiments. Both studies showed that humans can discriminate the virtual object weight with either of the haptic cues but are less sensitive to skin deformation than kinesthetic feedback. Kurita *et al.* [119] studied the effect of slip condition on a fingertip on the weight display. A prototype that controls the eccentricity (a slip condition of a contact area) of the contact surface on fingertips was developed. It consists of a movable transparent acrylic plate actuated by a DC motor and a camera to capture the contact surface. The experimental findings suggested that sensing a slip condition at a fingertip plays an important role in estimating the weight properties of an object, and controlling the contact condition could create weight illusions.

High friction tactors are usually used to apply shear and lateral forces to the finger pad of the user to simulate the natural skin deformation, to create an illusion of downward forces, which mimic the gravitational sensation during object interactions, particularly in grasping and lifting. Gravity Grabber, a haptic device that presented the virtual mass sensation by applying the skin deformation, was first developed by Minamizawa *et al.* [120]–[122]. The weight sensation in this device is rendered by stretching fingertips with fabric belts controlled by pulley with two DC motors. By wearing this device on the thumb and index finger, users can feel the augmented weight by holding a light-weight

Styrofoam cube and the inertia of the water in an empty glass. The experiments confirmed that the deformation at finger pads could generate the reliable gravity sensation even in the absence of the proprioceptive sensation on the wrist or arm. The experiment has been extended to render the shape and weight of virtual objects in an augmented reality (AR) environment by Scheggi *et al.* [123].

Schorr and Okamura [98] developed a fingertip tactile device with a delta mechanism to create three-DoF translational motion of the end-effector at the finger pad. The device weighed approximately 32 g and was capable of producing 7.5 N of normal force and 2 N of lateral force. The device was able to convey the virtual object weight by evaluating the increasing grasp forces of participants when lifting virtual objects with the rendered mass increased. The device has been further tested [92] to ascertain the impact of scaled inertial forces on virtual weight perception with skin deformation feedback, where the end-effector of each device was commanded to move 2.1 mm/N of virtual force. The results demonstrated that virtual block (200-g reference weight) was perceived lighter, with point of subjective equality (PSE) of 171 g and 151 g, respectively when the scaling factor is greater than 1.

A similar mechanism was applied in three-RRS (Revolute–Revolute–Spherical) [124] with a rigid platform driven by three servo motors to provide contact deformation stimuli at the user fingertip and hRing [125] device to be worn on the finger proximal phalanx with a moving belt, driven by two servo motors to provide skin stretch to the finger skin. Both the devices were tested by Maisto *et al.* [99] to differentiate the weight of the virtual objects through pick and place tasks. The users preferred the hRing as it allows the freedom of the finger movement, and both devices outperformed the visual only stimuli (color change) in the weight discrimination task.

Haptip [100] rendered the lateral force by a plastic housing fixed above a parallelogram structure actuated by two DC motors to move a plastic cap to create the shear force feedback on the fingertips when the user positioned the pulp of the finger on the device. The device weighing 22 g can simulate maximum 3.4 N force on the fingertip with a displacement range of ±2 mm. Another device, Chasm [126], [127], is a compact screw-based actuator that can augment the user experience with pseudo weight sensation by rendering the corresponding force as the skin stretch on the thumb when the user prods the virtual object with the device. It can render 4.8 N maximum force through a single tactor of low-frequency skin-stretch and 170 Hz high-frequency vibrations, both simultaneously and independently.

3) VIBRATION

The commercial VR systems are usually equipped with off-the-shelf handheld controllers that provide vibrotactile feedback for contact and notification to provide a physical sensation to the user when they touch or interact with a virtual object. Vibration haptic feedback has been intensely investigated in weight perception simulation because of the availability of low-cost and compact vibration actuators, such as voice coil actuators, linear resonant actuators, and piezo-electric actuators. Vibration can be used as a substitution of force feedback in the experiments to judge the weight of cubes [83]. A CyberTouch data glove was used to supply the vibrotactile feedback through six stimulators, one on each finger and the palm in the experiment. Different vibration magnitudes were applied when the users picked up different cubes and judged the weight of each cube relative to each other. Results showed that faster vibration was associated with stronger force, and the cubes were judged heavier. However, users commented that the vibrotactile feedback was unnatural as it was applied to the back of the finger instead of the fingertips. A similar experiment was conducted by Rosa *et al.* [128] to establish the relation between the vibration intensity and the weight sensation. Generally, the vibration is expected to be more intense when a heavier object is dropped on the shoulders. The research suggested that in VR systems, the vibration intensities need to be exaggerated to achieve certain weight effects. This was further supported by Mizuno *et al.* [129], who investigated weight perception affected by vibrotactile stimulation by using a customized handheld vision–tactile–force display device. The experimental results concluded that when strong vibration stimulations were given in the direction of weight movement, the weight seemed heavier.

Besides the studies relating the vibration intensity with the weight of the objects, the connection between the vibration pattern and an object's perceived heaviness was investigated [130]. Amemiya *et al.* developed a vibration box with asymmetric oscillation actuated by two crown gears engaged on a DC motor that rotates in opposite directions in each layer. Two objects with identical physical appearance but different oscillation patterns (vibrating vertically at different frequencies, with symmetric and asymmetric acceleration patterns, at gravity or antigravity directions) were tested in a lift-up and hold experiment. The results revealed that the heaviness perception of an object increased when vibrating with asymmetric acceleration compared to symmetric acceleration. The perceived weight increases when the oscillation amplitude increases in the gravity direction but cannot decrease through antigravity direction vibration. Findings of another research corroborated this and suggested that physical weight or mass cannot be offset by an upward virtual force [94].

Choi *et al.* [94] developed a wearable device called Grabity for rendering the mass of a virtual object with a brake mechanism and two vibration actuators. With a weight of 65 g, the device is light enough to be worn on the thumb and gripped with the thumb and index finger. During virtual object manipulation, this device can provide the grasping force feedback simulated by a unidirectional brake system, the contact force with the vibrations by two voice coil actuators, and the perceived gravitational forces with asymmetrically stretched on user's fingers resulting from the horizontal movements of magnet present in the voice coil actuator. The limitation is the asymmetric vibration that can only generate one-DoF virtual forces in the axis of voice coils. The study demonstrated that Grabity could convey various magnitudes of weight and force sensations by adjusting the amplitude of the vibrations. Users were able to discriminate the weights of virtual blocks with different masses; however, they faced difficulties in identifying the heaviest block, likely because they were confounded by the stronger vibration cues, which overshadowed the weight cues.

DualVib [88] is another handheld haptic device designed to render the sensation of dynamic mass through asymmetric vibration using voice coil actuators. The device was equipped with two vibration actuators: Haptuator Mark II and HAPTIC Reactor attached to the VIVE Tracker. User studies were conducted with 12 participants to identify nine types of dynamic masses by shaking a virtual container containing three different materials such as water, yogurt, and marble chocolates with various sizes (small, medium, large). Results indicated that the accuracy achieved was not high, and the best average was 43.6%. The complexity of the tasks may have contributed to the low performance.

4) WEIGHT SHIFTING

Weight shifting or changing the center of mass is another technique to render the sense of weight by equipping the devices with one or several moving dummy weights. Mizuno *et al.* [129] mounted a 222-g weight on a cylindrical shaft and attached the same to the back of the display device. The weight component can move to the left or right from the center of the device to evoke the perception of the weight of the visual object displayed on the screen. A vibration motor was attached to both sides of the device to further augment the perception.

Yamamoto and Hirota [131] investigated the discrimination of content weight through shaking interaction by shifting the gravity center of a box-shaped device. The device consists of a 360-g frame holding a 400-g weight linearly actuated by the shaft motor, which accelerates correspondence to the shaking gesture. The inertial force resulting from the movement of weight enables weight perception. The weight discrimination experiments were conducted for solid and liquid content using real and virtual models. Results suggested that the device successfully presented the weight of the solid content but not the liquid content.

On the other hand, VolRec [132] enables the perception of the inner volume of a virtual object by angular shaking interaction. It is a bottle-shaped haptic device with a total mass of 268 g with the center gravity simulated by a linear motion inner weight (146 g) actuated by DC motors. The center of gravity within the device is rendered higher when the object's volume increases during the angular shaking moment. A total of 14 participants were engaged in the experiment and were able to discriminate the bottles with different volumes of water. However, the device cannot reproduce volume below 300 ml because of the restriction of the slider position, which cannot move the weight (center of gravity) beyond the lower limit of the grasping position.

Shifty [133] and Drag: On [89] are dynamic passive haptic feedback devices that provide compelling passive haptic sensations, which enhance the perception of weight by changing its weight distribution using a proxy. The former enables the user to feel the weight when picking up a virtual object by continuously shifting the internal weight between the grip and the top end of the proxy. The pole-shaped device weighing 440 g houses a movable weight of 127 g controlled by a pulley actuated by a stepper motor. In the experiments, the participants were asked to pick up a light, medium, and heavy virtual object by holding the Shifty. The results showed that the participants were able to discriminate between the different weights, and the realism increased when interacting with the virtual objects. Drag: On, as discussed in the earlier section, provides the weight-shifting effect by adjusting the shape of the surface area, creating different sensation of inertia leverages on the airflow when the user drags or rotates the devices. The device successfully renders different weight sensation when manipulating materials such as plastic, wood, or metal.

5) OTHERS

Muscle Tension: Another approach to give a sense of weight when handling virtual objects is to stimulate the user's muscles with electrical impulses. When the user grabs and lifts an object, the object's weight is expected to create tension in the biceps and pectoralis muscles, giving a sense of gravity force. Lopes *et al.* [104] used electrical muscle stimulation (EMS) to elicit the opposite muscle contractions (e.g., triceps and shoulder muscle) to create the desired tension in the biceps and pectoralis muscle, thereby creating a sensation of weight. In the experiments, users were asked to lift the virtual cube and push the virtual wall with eight electrode pairs placed at their wrist extensors, biceps, triceps, and shoulder external rotators. Different magnitudes of pulses were applied to create the effect of repulsion of a wall or gravity sensation when picking up an object. The findings suggested that the magnitude of the EMS signal is to be adjusted so it is not arbitrarily strong and draw the user's attention away to the pulling of the muscle instead of the hint of the haptic cues.

Head Motion Rotation: Teo *et al.* [102] conducted a novel investigation to transform virtual object information such as mass into head rotation signals using galvanic vestibular stimulation and servo motors. Two electrode pads actuated with low current < 2.5 mA were attached at both sides of the vestibular sensory area behind the ears to trigger the visual motion caused by ocular torsion and resulted in the head rotation toward the stimulation direction. The mass of the virtual object was represented with different strengths of stimulation by adjusting the current magnitude. Two servo motors coated with a haptic pad were attached to the VR HMD and placed on both sides of the users' face to push the skin vertically upward or downward. The servo motors moved in the opposite direction to guide the user to bend their head toward left or right. The system has successfully transformed the mass information into sensations through virtual embodiment technique, but at time of writing, no user testing was done yet to determine the system's feasibility in weight discrimination.

Liquid Inertia: GravityCup [134] is a haptic device that uses the inertia of liquid to simulate dynamic weights in VR. This 1500-g device mimics a physical mug comprised of a handheld device (365 g) attached to the HTC VIVE tracker, a wearable device (374g), and two water bags that can store up to 760 ml of water. The water bags are connected to the electric pump, which can pump up to 330 g of water in 16.8 seconds. In the experiments, users were tested with a few scenarios, such as filling a cup with coffee, watering a plant with a can, holding a container to scoop up dog food, and holding an empty cup. The system showed that rendering the dynamic weight with the simulation of liquid inertia can enhance the user's immersive experience in a virtual environment. Further analysis was yet to be carried out by the author to evaluate the effectiveness of the system by the time of this writing.

VI. WEIGHT PERCEPTION WITH PSEUDO-HAPTIC

Although weight representations by using haptic devices enable the perception of weight and provide more realistic feedback in VR, such methods have limitations in the device weight and wearing comfort, constrain the user's movement and interaction, and likely involve mechanical complexity. An alternative that has attracted the interest of researchers is to simulate haptic sensations without the actual matching haptic stimulus, using other sensory modalities such as visual feedbacks to create the weight perception, known as pseudo-haptics or visuo-haptic illusions [135]. Pseudo-haptics employ visual feedback instead of active haptic devices to generate haptic perception in virtual environments by exploiting a cross-modal effect in the brain between visual and haptic sensations [136].

Pseudo-haptic feedback has been used to simulate various haptic properties such as shape, stiffness, texture, or mass of a virtual object [137]. It is less expensive and allows a wider range of user motion compared to other haptic approaches. It uses the software-oriented approach relying on the overall dominance of the visual system verging on haptic illusions to evoke the perception of weight. As it requires relatively simple or no hardware except HMDs, it faces less hardware problems of weak motor output, heavy device weight, or low spatio-temporal resolution.

The objective of pseudo-haptic feedback is to simulate haptic sensations with minimal sensing and actuation. The following sections discuss the scholarly works that applied the pseudo-haptic techniques in rendering the weight perception in VR.

A. PSEUDO-HAPTIC CUES

The pseudo-haptic cues applied in the literature were reviewed and summarized (Figure 7). Two primary types of pseudo-haptic cues broadly used to create the illusion of weight are control–display (C/D) ratio and velocity. The other less investigated cues are passive force, audio feedback, visual information such as color and size, liquid movement, and body gestures.

The following discussions are arranged into individual sections according to each pseudo-haptic cue and the inclusions criteria as summarized in Table 3. The visual representation of the pseudo-haptic techniques discussed in this section is illustrated in Figure 8, grouped by the pseudo-haptic cues.

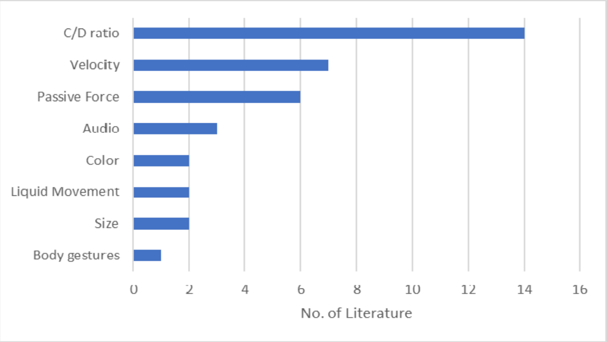


FIGURE 7. Pseudo-haptic cue that enables weight perception.

TABLE 3. Pseudo-haptic cue and the inclusion approaches.

Pseudo-Haptic Cue	Literature	Inclusions
C/D ratio	[7], [115], [126] [137]–[145]	Includes approaches that adjust the translation and rotation displacement of the object or the movement offset between virtual hand and actual hand to create an illusion of weight perception
Velocity	[128], [140], [144], [146]–[149]	Includes approaches that alter the moving speed of the object/hand to create the illusion of weight
Passive force	[86], [137], [150]–[152]	Includes approaches that trigger the user to generate and control the force feedback himself or herself by increasing or decreasing the force exerted on the static interface to give an impression of weight
Audio–Visual	[83], [146], [148], [149], [153]–[155]	Includes approaches that change the audio–visual representation of the object and others such as manipulating the avatar posture or body gesture, or displaying the liquid movement to create an illusion of weight

1) CONTROL–DISPLAY RATIO

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, by changing the amount of movement between virtual and actual hand or the displacement of the object to generate different weight illusion. The technique

FIGURE 8. **Visual representative of pseudo-haptic cues in weight perception.**

was applied in the research works of Dominjon *et al.* [142], Rietzler *et al.* [7], Samad *et al.* [143], Taima *et al.* [141], Hirao *et al.* [140], and Issartel *et al.* [138].

Dominjon *et al.* [142] adjusted the translational C/D ratio to generate the perception of mass. The adequacy concept was appraised by attaching a physical foam ball to a PHANToM device. The participants were asked to compare the weight of the virtual balls on screen while lifting the physical ball. When the visual motion of the ball was amplified compared to the user's actual hand motion (with C/D ratio less than 1), the weight was perceived to be less. The results helped the researchers conclude that the increasing or decreasing of the visual motion tends to influence the haptic perception of the mass of the manipulated object. This was supported by Samad *et al.* [143], in whose experiments, participants were asked to lift and discriminate the weight of the physical wooden blocks while wearing custom motion capture gloves with the HMD on. In accordance with the fact that lighter objects are easier to move and heavier object vice versa, the visual position of users' hands were manipulated by increasing or decreasing their displayed movements to induce an illusory perception of weight. The findings proposed an equation model to quantify the range of C/D ratio that can be used to simulate weight in VR and suggested that a reference mass of 185 g can be modulated by ±5 g by inducing hand displacement of 5–10 cm. The reference mass of 185 g was used in the experiment to mimic the mass of the consumer VR handheld controllers.

Likewise, Rietzler *et al.* [7] used deliberate tracking offsets as a metaphor for weight. When the force of weight pulls an object toward the ground, a spring-like force as a vector equal to the offset was applied. The force vector was defined as the offset between real tracking and visually displayed positions. The testing was done with a fully immersive VR bowling game. The tracking offsets successfully nudged the users to lift their arm higher when the tracking offset increased, which resulted in an illusion of haptic perception of the bowling ball's weight. The participants reported the ability to feel the weight and improvement in presence, immersion, as well as enjoyment. However, the results showed that a large variance of offset was associated with the weights when the participants were asked to guess the weights of the objects. Hence, they suggested that this offset metaphor works better on relative weight differences (e.g., comparing the weight of two objects) than determining an object's absolute weight.

Issartel *et al.* [138] applied a similar spring constraint decoupling technique to enhance the mass perception in a mixed reality interface by attaching the virtual clone object to the real object with a virtual spring. A six-DoF spring constraint model, with consists of springs on translation and rotation axes, was applied. Each spring had a stiffness parameter. The technique was controlled by the parameters of the linear spring stiffness, the torsional spring stiffness, the mass of the object, and its inertia tensor. Participants were asked to push the virtual object by holding a physical prop, and the virtual clone displacement was rendered and displayed on the screen. To further improve the realism of the perception, the research suggested to apply dynamic deformation when the decoupling becomes too high and display the spring constraint explicitly (e.g., representation by using a virtual rubber band).

Besides translational motion, rotational kinematics can influence the perception of heaviness as suggested by Streit *et al.* [49], [156]. Yu and Bowman [139] complemented the works and implemented a technique to display an object's mass by scaling its rotational motion relative to its mass. Empirical studies were carried out to evaluate the efficiency of two pseudo-haptic approaches in displaying the object's mass distribution. One involved in manipulating the pivot point of the rotation, while the other involved in adjusting the rotational motion based on the real-time dynamics of the moving object. The VIVE tracker was chosen as the proxy to manipulate the virtual cubes during the experiment in a VR environment. Seventeen participants were asked to discriminate the relative mass between two virtual objects represented with different rotational C/D ratio. The results showed that both techniques can influence the perception of mass distribution with the second technique being noticeably more effective, with an average accuracy greater than 80%. However, the study did not cover the testing to determine the just noticeable threshold in distinguishing the mass difference.

Besides applying only the pseudo-haptic technique, some research works [115], [126], [145] adopted a hybrid approach by combining the use of haptic devices, to augment the sensation of the weight of the haptic forces feedback with visual cues. Hannig and Deml [115] applied the bimodal approach by using a pneumatic haptic device and C/D feedback. The former substituted the proprioceptive weight perception by exerting pressure to the user's wrist with an air-compressed sleeve. The latter encoded the weight by visually altering the motion of the virtual hand. The survey results indicated that participants preferred the use of pneumatic feedback to display lighter objects and C/D feedback for heavy objects.

2) VELOCITY

Provided with constant force, an object's mass is proportional to its velocity. Humans always relate the moving speed of an object to its perceived weight, and the faster an object moves, the lighter it seems. Earlier studies [128], [146] have been observed to use the visually represented speed of an object in combination with other stimuli to influence the perception of weight in VR. In Rosa *et al.*'s [128] experiments, with the HMD on, the participants were shown with an avatar sitting on a chair with the arm on the table while wearing a vibrotactile sleeve. The simulated falling speed of a virtual object onto the arm altered the perceived weight of the object and the intensity of the vibration felt on the skin.

By using a delay parameter, Hirao and Kawai [146], [157] incorporated the delaying speed of the object into the cross-modality testing during the lifting of a virtual object in VR. The more the delay, the heavier the sense of weight by the participant. The findings confirmed that the delay parameter compared to the changing of C/D ratio could present a higher level of sense of weight. Further research was conducted by Hirao *et al.* to compare the weight sensation in VR by using a motion-based versus controller-based method [140] while dragging the object. In the experiments, participants were required to pull the handle of a virtual box by motion-based manipulation (i.e., extending the hand to grab the handle and pulling it toward their body), and by controller-based manipulation (i.e., tilting the controller's analog stick to control the virtual hand movement without moving the actual hand). Seven delay parameters ranging from 0 to 1 were used to represent the different virtual weights of the box. The delay parameter was applied in the equation of motion to determine the target position by frame. When the distance between the virtual object and target position is small, the object moves slower and move faster when the distance is large. The results showed that the virtual weight sensations were successfully represented by adjusting the velocity of the object in both the controller- and motion-based manipulations.

Aside from visually stimulating the virtual object motion, the speed of the physical hand movement can create a sense of weight. In the dumbbell-lifting experiments [148], the magnitude of lifting forces was calculated from the velocity by tracking the users' hand position. An arrow indicator was used to guide the user to increase or decrease the speed. User was guided to move their hand slower on a heavier dumbbell, and vice versa. The survey results showed that the change in the velocity successfully created a sense of weight and enhanced the immersive user experience in the dumbbell-lifting exercise. The results helped researchers deduce that the average success rate of distinguishing the weights of the virtual dumbbells increased by 16.87%. Bäckström [147] applied the same technique where the velocity of the hand movement was measured to compare against the virtual weight, and the object dropped when the velocity exceeded the limit of the intended weight (heavy object moved slower).

3) PASSIVE FORCE

Another pseudo-haptic approach is to create the illusion of haptic sensation from the voluntary force feedback exerted and controlled by the users, and this is typically performed with a passive isometric device. For example, when a user moves a virtual object through a narrow passage and the velocity of the visual object is artificially reduced, the user responds with the increasing force exerted to make the object move through the passage. The combination of the manipulated visual effect and the voluntary force feedback reaction gives the user a sense of resistance without the use of active haptic devices. In a previous research, Leìcuyer [137], [158] asked the users to push a piston connected to an isometric Spaceball$^{\text{TM}}$device while displaying the virtual spring compressing on the screen to test the perception of stiffness. The sense of spring stiffness was inherent to the reaction force exerted on the Spaceball and the sensory cues presented.

Keller and Blanch [150] showed that the illusion of weight could be simulated by applying a similar technique in the experiment of dragging a virtual object with the fingers pressing on the DiamondTouch tabletop. The fingers' force exerted during the interaction was measured and the object was virtually moved when the force exceeded its weight, thereby resulting in the perception that heavy objects are hard to move compared to light objects. Four squares with light to heavy weights were sorted during the experiments, and an average of 68.52% success rate was recorded.

According to Ponto *et al.* [151] and Chen *et al.* [86], the exertion force scales linearly with objects' mass, and a minimum exertion force value can be associated with the effort required to grasp and lift an object. The researchers utilized the biofeedback from EMG with the combination of visual effects to simulate the weight perception when manipulating virtual objects in a CAVE environment. In the experiments, surface EMG was affixed to the four muscle groups (extensor carpi radialis [ECR], flexor carpi radialis [FCR], triceps, and biceps) of the participants, and objects with weights 1.36 kg, 2.27 kg, and 4.54 kg were lifted and held. The real-time EMG signals were compared to the predefined threshold to determine the movement of the object (lifted or dropped). Although the results showed that participants produced more effort in a virtual environment than necessarily needed for physical exertion, the muscle activity trends for varying weights were not significant. The research demonstrated that perceived exertion levels and muscle activity patterns correspond to the assigned virtual loads, and the method can be used to evoke weight perception.

Hummel *et al.* [152] related the distance between fingers to the grasping force required for lifting a virtual object. In the experiment, participants grasped the virtual object by wearing finger tracking devices on both their thumb and index finger to evaluate the penetration caused by the tracked finger position. The grasping force was calculated in proportion to the distance between the positions of tracked fingers and the virtual fingers, which stay on the object's surface. To lift a heavier object, the fingers must grasp deeper into the object to create a stronger grasping force. The result validated that the method can create the perception of heaviness and allow relative weight discrimination. However, the proposed method does not simulate any realistic kinesthetic or cutaneous force senses corresponding to the actual weight.

4) AUDIO–VISUAL

Besides the haptic cues discussed, audio and visual effects are always incorporated to create multimodal illusions of weight perception. In Lee *et al.*'s research [148], the dumbbells were virtually present in different sizes in addition to the measurement of lifting speed to reflect various weights. Color intensity and audio pitch were mapped to the object's weight in Herbst and Stark's [83] research; darker color and lower pitch were associated with heavier weight and vice versa. Sikstsrom *et al.* [153] conducted experiments to investigate whether the full-body avatar's weight in VR can be influenced by different audio effects of the footsteps. They applied three different audio filter settings, and their results indicated that the weight of the avatar was estimated as heavier when the audio filters amplified the lower center frequencies compared with the higher center frequency.

In another cross-modality research [146], various audio–visual stimuli were added to the interaction in VR to represent the physiological responses and the knowledge of haptic experiences when gripping and lifting a heavy object. Visual expressions such as skin color of the hand model turning red were applied to represent strong gripping conditions. Audio expressions such as louder and faster heartbeat were simulated to represent an increase in force magnitude. The lateral vibration effect to render the hand tremor sensation and delaying of the speed of the visually represented object were also added to the testing.

Body Gesture: Jauregui *et al.* [144] investigated how the animation of the virtual avatar can be altered to create different haptic perceptions in weight-lifting exercises. When lifting objects, the acceleration and the posture of the avatar, such as the angle of upper-body inclination, varies depending on the weight of the object lifted. In the experiments, the real data of motion speed, lifting posture, and gestures were recorded for various weights, and these motion profiles were used to compute the avatar animation. The participants were asked to perceive the effort delivered and discriminate between the weights by monitoring the physical movement and gestures of the avatar. The results suggested that the participants preferred the combination of all the proposed visual effects and achieved better results than isolated effects.

Liquid Movement: Research has shown that the sense of weight could be affected by the MR (mixed reality) visual stimulation by changing the appearance of a real object by superimposing a dynamically changeable virtual object onto it [155]. This psychophysical influence is known as "R–V Dynamics Illusion." Experiments were conducted to analyze the influence of this illusion on the threshold of the weight perceived upon the object of fix mass (750 g) [155] and various masses (500 g, 700 g, and 1 kg) [154]. Participants were requested to hold the handle and swing an acrylic case with weights enclosed while different liquid visual stimulation was superimposed on the acrylic surface. The results showed that the object is perceived lighter when the virtual liquid state is moving compared to when it is not moving.

On the other hand, under the same moving liquid visual stimulation, the threshold of perceived weight was found to have no significant difference by the changes in real objects' mass, which contradicts the real-world scenarios, where the threshold of weight increases as mass increases. The research did not quantify the change of perceived weight caused by R–V dynamics illusion.

VII. CHALLENGES

So far, this paper has presented a systematic review of the recent works on weight perception in VR. As per the research presented in Sections V and VI, eight challenges are delineated in this section.

A. ACCURACY AND PRECISION

Weight perception has been scientifically studied in the field of psychophysics [13]. The precision of weight perception is usually measured with accuracy [88], [148] expressed in PSE [92], [95] or just noticeable difference (JND), and WF [7], [111], [152]. 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):

$$WF = \frac{JND}{m_r} \tag{1}$$

The experiments carried out by numerous researchers are involve the task of weight discrimination with a two-alternative forced-choice method and the sorting task. In such a task, the participants are usually asked to compare the weight of the tested object with the reference object by either identifying the heavier object or adjusting the weight to match with the reference object. In the sorting task, the participants were presented with an array of objects and required to sort it according to the weight sequence. Literature reported higher precision (lower JNDs) for weight discrimination with real objects than with virtual objects, with JND as low as 10 g predicted by WF [5], [13], [95]. Giachritsis *et al.* [111] reported nearly five times higher JND (48 g) with WF of 16.1% in handling virtual objects compared to real objects with JND of 8 g and WF of 3.3%. Van Beek *et al.* [95] reported similar JND of 32g and WF of 22%–44% in the experiment of holding a static virtual object.

Combining tactile and proprioceptive information led to better weight discrimination thresholds than unisensory cues. Studies showed lower WF ranged from 9% to 12% with the availability of kinesthetic force feedback reported by Ross and Reschke [159], and WF of 7% with combined cues of kinesthetic and touch, whereas 33% for touch only as reported by Brodie and Ross [22]. Similar findings by Minazawa *et al.* [120] reported WF of 6.95% with proprioception force and 11.8% without proprioception force for reference weight of 200 g. The findings were supported in later research by Jacob *et al.* [84] recorded WF of 11% for kinesthetic cue and 35% for skin deformation cue.

As evidenced in Table 4, the average WF of weight discrimination in a virtual environment regardless of the reference stimulus ranged between 11% to 49%, whereas WF can be as low as 3.3% for real-object manipulation. Achieving high accuracy in perceiving an object's weight in VR is a challenge mainly because of the absence of a rich set of force feedback such as proprioceptive and tactile sensation that can be felt when handling a real object. The pseudo-haptic approach alone demonstrated weaker precision with WF of 18% or above [7] compared to experiments using the haptic approach. Future research should focus on reducing the JND to improve the accuracy of mass perception.

B. WEIGHT DISCRIMINATION

Weber's law asserts that the magnitude needed to detect physical change in a stimulus is proportional to the absolute magnitude of that stimulus. Thus, the more intense the stimulus, the greater the increment needed for a change to be detectable [13]. Therefore, it is a challenge to discriminate heavyweight objects in VR, which require bigger increment for the observer to detect the change, and it is difficult to generate heavy stimulation in VR (discussed in Section C).

On the other hand, according to Weber's law, the size of the WF in most cases tends to be a constant within a specific stimulus condition and sense modalities [160]. However, most of the results from the weight discrimination experiments in VR showed that the JND indeed decreases with the reference stimulus, but both do not seem to be proportional (Table 4). The performance of weight discrimination in VR deteriorates when the reference weight decreases, which can be seen from the increases in the WF results. As reported by Minazawa *et al.* [121], the WF increased 1.5 times from 11.8% to 18.6% when the reference weight decreased by four times from 200 g to 50 g. Issartel *et al.* [138] reported similar deterioration where WF increased threefold from 12.98% to 36.75% when the reference weight decreased four times from 800 g to 200 g. By experimenting with two different weight perception methods, Hummel *et al.* [152] showed different increments of WF from 12.67% to 26.75%, and 13.92% to 17.25% when the reference stimulus tripled. It is difficult to rank the thresholds across experiments because of different subjects and experimental setups using different reference stimulus units. However, in general, the literature showed that differentiating variation of less than 10% for lightweight reference (< 200 g) is challenging.

When rendering the very lightweight stimulus, the lack of either visual or haptic feedback makes differences between light masses unperceivable. Issartel *et al.* [137] reported that participants could barely sense the change of weight of 15-g reference object. The reaction force exerted on the virtual effector was small and hence resulted in no conspicuous decoupling effect. Kinesthetic information was reported as less precise for lighter weights compared to tactile information [95]. A wearable device that relies on skin stretch or shear forces is normally deployed to render a lightweight sensation [98], [119].

TABLE 4. Summary results of accuracy, JND and WF from the literature studies.

Author (Year)	Type*	Experiment	Reference Stimulus	Accuracy	JND and WF
Tanaka *et al.* (2020) [88]	H	Shake the device to feel the volume of the dynamic mass inside a virtual jar	20 g, 50 g, 80 g	16.8% (force only) 15% (texture only) 43.6% (both)	
Issartel *et al.* (2015) [138]	P	Push virtual object by holding physical props to differentiate the mass of two virtual objects	15 g, 200 g, 800 g		Stimulus = 15 g, 200 g, 800 g JND = 157.3 g, 71.5 g, 103.8 g WF = 1048.67%, 35.75%, 12.98%
Yu *et al.* (2020) [139]	P	Use HTC VIVE tracker to rotate the virtual cube to discriminate the weight of two virtual cubes	Rotational C/D scale from 0.2 to 1.8	80%	
Chantal Keller *et al.* (2012) [150]	P	Drag a virtual object by pressing on the tabletop surface to identify the heavier object	Virtual weight of 80 g, 95 g, 110 g	68.52%	
Minamizawa *et al.* (2007)[120], [121] (2008) [122]	H	Hold the physical cube with index finger and thumb to compare the objects' weight	50g, 100g and 200g		Tactile only: WF = 18.6% (50g stimulus) WF = 16.5% (100g stimulus) WF = 11.8% (200g stimulus) Tactile + Proprioceptive: WF = 16.2% (50g stimulus) WF = 9.3% (100g stimulus) WF = 6.95% (200g stimulus)
Hummel *et al.* (2013) [152]	H+P	Lift two virtual cubes (reference and comparison) to determine which cube is heavier	Virtual weight with arbitrary unit of 4 kg, 8 kg, and 12 kg and four variations of comparison (5%, 10%, 20%, and 30%).		Finger distance-based: Stimulus = 4 kg, 8 kg, 12 kg JND = 0.69 kg, 1.46 kg, 1.67 kg WF = 17.25%, 18.25%, 13.92% Average WF = 16.25% Pinch strength-based: Stimulus = 4 kg, 8 kg, 12 kg JND = 1.07 kg, 1.02 kg, 1.52 kg WF = 26.75%, 12.75%, 12.67% Average WF = 15.48%
Rietzler *et al.* (2018) [7]	P	Lift the virtual sphere with a remote controller to compare their weight	Offset of 8 cm and 20 cm, with additional comparison offset from 0.8 cm to 4 cm (in 0.8-mm steps)		8-cm stimulus: JND = 2.5 cm WF = 31.25% 20-cm stimulus: JND = 3.6 cm WF = 18%
Suchoski *et al.* (2016) [84]	H	Lift a virtual block and adjust the mass of the block to be equivalent to the standard stimulus block	35 g, 70 g, 105 g, and 140 g (with a comparison variation of 30 g)		WF = 35% (skin deformation) WF = 11% (kinesthetic)
Kato *et al.* (2017) [116]	H	Use a chopstick-liked device to grasp and lift the virtual object to compare the perceived weights	Standard stimuli: 29.5 g comparison stimuli: 0 g, 16.8 g, 23.2 g, 29.5 g, 35.9 g, 42.2 g, and 54.9g		WF = 12.3% (real object) WF = 18.5% (virtual object) WF = 49.5% (virtual object, incl. non-sensitive participants)
Giachritsis *et al.* (2009) [5] (2010) [111]	H	Lift the virtual object and compare the weights	Seven weights ranging from 75 g to 525 g with step size of 75 g		Real weight: JND = 8 g, WF = 3.3% Virtual weight: JND = 48 g, WF = 16.1%
Suchoski *et al.* (2018) [92]	H	Lift and compare the weight of two virtual cubes	Reference weight of 200g with comparison weight of 50 g, 125 g, 200 g, 275 g, and 350 g		Scaling factor 2: PSE = 171 g, JND = 25.2 g, WF = 12.6% Scaling factor 3: PSE = 150.5 g, JND = 23.2 g, WF = 11.6%
Lee *et al.* (2019) [148]	P	Lift and differentiate the weight of three virtual dumbbells	Virtual weight of 2 kg, 6 kg, and 8 kg	65.83 % (size only) 82.7% (size + force indicator)	
Kovacs *et al.* (2020) [93]	H	Grab and lift the virtual balls to identify the heaviest and lightest ball	90 g, 200 g, and 300 g	83% (heaviest ball) 91% (lightest ball)	
Van Beek *et al.* (2021) [95]	H	Hold haptic devices with thumb and index finger and compare the rendered weight	100 g, 200 g, and 300 g		JND = 32g WF = 22%–44%

*H = Haptic, P = Pseudo-haptic

C. HEAVYWEIGHT RENDERING

Simulating heavy weight in VR is a challenge; to render weight greater than 1 kg generally requires a fixed setup (ground-based) and constrained workspace. It is a limitation to augment such quantum of force effect in most haptic devices [88], [94], [116]. The wearable device was normally not able to render heavy weight because of weak motor output. Small actuators are usually used to preserve mobility and wearability. The device's maximum amplitude was reached easily [100], which resulted in force saturation [92]. As shown in Table 5 (in Appendix), the maximum force for most actuators adopted in the haptic devices range from 2 N to 8 N, and the devices weigh from 20 g to 500 g. HapSticks (196 g) are able to render 55-g weight with 1.23-N wind string force [116]. Haptic PIVOT (188 g) rendered 350-g weight on the palm with maximum 3.5-N force [93]. Thor's Hammer [90] can exert up to 4 N of force in each direction of the cube, and a user can feel weight changes up to 816 g.

The range of force output could be increased with larger gearboxes, but the device weight would increase as well. It is a challenge to strive for the balance between the device weight and the rendered force to achieve the desired weight simulation effect. Bulky devices reduced the immersive experience and deteriorated the effectiveness of weight perception. As remarked by Al-Hathal and Fetais [8], it was very exhausting for the player in falconry sport to prolong stimulation if the haptic glove was heavy. The weight of the device (∼1 kg) was raised as the main issue in the Aero-plane [87], which is capable of rendering up to 14-N force with two jet-propellers (200 g each). To reduce the weight by half (to 476 g), the jet-propellers were recommended to be substituted to a lighter version (56 g each) and traded-off the force to 5.2 N. Furthermore, haptic devices that rely on tactile feedback should be lightweight for the skin stretch to be perceived as a weight owing to the low virtual forces (usually < 30 g) [94]. The increases in total device weight resulted in the decrease in the weight perception acuity [160].

Weight rendering in pseudo-haptic also experienced the challenge of maximum amplitude as haptic. The more intense the pseudo effect is, the heavier the weight can be sensed by the participants; however, the effect of delay or displacement cannot increase over the human acceptance level, which creates strong unnaturalness. Participants declared that the strongest unnaturalness when experimented with the heaviest delay parameter of 0.005 [146] and displacement of 42 cm [7]. Interestingly, the result showed that participants could accept up to 24-cm displacement offset comfortably as a weight metaphor, associated with around 3-kg absolute weight in the bowling game [7]. It may be too early to conclude if pseudo-haptic has the potential to render heavier weight as it does not have the physical limitation as haptic devices. Further studies are required to confirm this as the results also indicated a large variation in the weight-association tasks.

D. ABSOLUTE OR RELATIVE WEIGHT

Relative or virtual units are commonly used to represent mass in weight perception experiments that do not render the direct gravitation or kinesthetic forces. The virtual weight can be associated to the intensity of actuation, such as applied voltage [116], vibration strength [88], the distance of displacement [7], or movement speed [148]. Relative weight instead of absolute weight has been commonly used to evaluate the effectiveness in weight perception studies. Research experiments mainly compare two or more objects to identify which one is heavier instead of determining the actual weight of one object. The different magnitude of haptic or pseudo-haptic cues could lead to the perception of an object being heavier than the other but does not evaluate the perception of the absolute value of the object's mass or the actual mass ratio between two objects. For example, a C/D ratio of 1:0.5 could not lead to the conclusion that an object is weighs 2 kg or two times heavier than the 1 kg object. It only gives the perception if the one with a C/D ratio of 1:0.5 feels heavier than the reference with 1:1 [139].

Only a few studies have been conducted in mapping the perception of weight to the actual weight. Rietzler *et al.* [7] suggested that working in actual weight is not recommended in view of the big variations recorded from the weight association experiments. Samad *et al.* [143] worked on a predictive model to quantify the weight illusory to the actual weight reported that pseudo-haptic feedback can lead to overestimation or underestimation of real weight. Future research can investigate how the parameters used in the weight perception techniques can connect to the perceived absolute values of mass and mass difference.

E. DOUBLE HAND MANIPULATION

As stated in this review, most interfaces for weight perception are single-handed. While weight perception can be carried out with just one hand, two hands are often used in real life. This is especially true if we are trying to perceive the weight of a heavy and large object. Hence, to better achieve a sense of realism of immersion, more interfaces should be developed. According to Giachritsis and Wing [161], when lifting a weight with both hands, the load feels lighter than when lifted with either hand. This effect is caused by the decrease in total grip force needed to lift the object when two hands are used [162], [163]. Consequently, bimanual weight perception is less labor-intensive compared to unimanual weight perception because of the effect of lateralization that reduces some sensory weight information [164].

With that said, bimanual interaction may be necessary for some scenarios. Thus, from a design perspective, the challenge is to develop frameworks to ensure that both interfaces can work synchronically to efficiently imitate double-handed interactions, incorporated with the weight distribution model and double hand grasping behavior to create a realistic weight perception experience.

F. SYNCHRONICITY

The need for synchronicity between real-life events and events happening in the virtual environment is necessary to effectively simulate weight perception. Latency in VR can be caused by delays originating from the sensors, delays incurred during processing, delays incurred during data transmission, delays incurred from the process of data smoothing, delays incurred from the rendering process, and delays caused by frame rate drops [165]. This issue was noted in [151] and [87], where latency caused a distortion effect (e.g., objects appeared to be stuck in the hand), which ultimately may have decreased the sense of immersion and realism.

While it is difficult to provide an acceptable value for delays, some researchers have managed to come up with an estimate. For instance, Jerald [166] concluded that this number may vary among different individuals. Some may not notice a delay of 100 ms, while some may even notice a delay of 3–4 ms. Consequently, Carmack [167] proposed that delays should not be over 20 ms. However, no methodical tests have been performed to corroborate this proposition. Davis *et al.* [168] briefly mentioned that delay might cause motion sickness in their article. However, the authors did not quantify the amount of delay that might cause these symptoms.

According to Boger [165], predictive tracking can be used to potentially reduce latency. This technique reduces ''motion-to-photon'' latency, which refers to the time between the actual movement and when that movement is reflected on a display. Essentially, predictive tracking utilizes information about the behavior of a targeted body to extrapolate its position in the near future. In the context of haptic interfaces for weight perception, predictive tracking can be achieved by collecting information on head and hand movements and use the collected information to predict users' actions.

G. HAPTIC INTERFACES DESIGN CHALLENGES

1) ADAPTABILITY

Haptic interfaces for weight perception can come in many forms, and some are worn, held, grasped, or entirely grounded to a surface. Typically, adaptability should be of concern when it comes to interfaces that depend on direct cutaneous simulation to deliver haptic sensations. For instance, this issue was seen in [94], [150], where capacitance varies depending on anthropometric factors such as the size of a user's finger and skin humidity. This means that sensors should be designed and developed with anthropometric factors in mind.

As for interfaces worn on the user's body, the device should be able to adapt to the different body or hand sizes. Depending on the type of interface, this can be achieved with adjustable straps made out of Velcro as seen in [103], or even adjustable hinges.

Other than that, the interface should also be able to predict and accommodate unwarranted movements or situations that may arise from use. For instance, this issue was seen in [116] where participants were instructed not to invert or tilt the device. While it is generally fine to impose rules on how the device should be handled, it should not however, directly affect the ability of users to perceive weight.

For interfaces that utilize props to simulate weight perception in the virtual environment, the most notable challenge stems from the need to develop more dynamic props. This issue was noted in [89], where the fan prop is unable to simulate drag effects when the fan is oriented a certain way. Essentially, props for weight perception should be designed in such a way that they can simulate forces of varying magnitudes and directions in an on-demand manner.

2) COMFORT

When designing haptic interfaces for weight perception, comfort should also be of priority. This issue was seen in [8], [93], where prolonged wear of the device resulted in numbing sensations felt in the arm of users due to the heavy weight of the developed interface. This is mainly caused by the type of material used to build or house the device, commonly made from metal. Hence, to mitigate this issue, other lightweight materials (e.g., plastic) could be used instead.

These days, multimodality is often prioritized when designing haptic interfaces. This may also be prevalent for interfaces specifically designed for weight perception as force can come from different directions and in varying magnitudes. To cater to this requirement, it is often the case that one must fit as many actuators as possible into a single device or interface. It is thus inevitable that weight must be sacrificed.

3) NOISE

Haptic interfaces for weight perception are often complex and have a number of moving parts. Hence, one common by-product that may come out because of this is noise, which may decrease the sense of immersion, realism, and the ability to accurately perceive weight. This issue was observed in [123], where noise is produced because of slight vibrations when weight is shifted from one end to the other end of the spherical-shaped device. Noise caused by vibrations was also reported in [116] and [89]. Additionally, both wind and noise should be matters of concern when developing interfaces that feature propellers like [87].

According to Renninger [169], vibrotactile noise can be mitigated with structural damping and the isolation of vibrations. The damping treatment consists of materials that are applied to a component to dissipate mechanical energy. Common damping materials include polymers [170], metal, and rubber [171]. As for vibration isolation, materials such as bellows, steel springs, and rubber pads are used to reduce the transmission of vibrational energy from one structure to another [169]. For haptic interfaces that employ the use of drones to transmit sensations, propeller noise can be silenced with the use of a Q-tip style propeller, increasing the number of blades on a single propeller, or a ducted propeller [172].

H. PSEUDO-HAPTIC DESIGN CHALLENGES

1) FOCUS LIFESPAN

Lack of sensitivity to the pseudo-haptic cue and short focus lifespan are the most common challenges encountered in pseudo-haptic rendering of weight perception. Pseudo-haptic relies on purely virtual sensations as opposed to real physical changes. All pseudo-haptic effects require sight and are no longer present when the focus of attention shifts. Kato *et al.* [116] reported that the discrimination precision worsened from 18.5% to 49.5% with the inclusion of the non-sensitive participants. A wide array of activities and nudging the participants intermittently can be implemented to keep the participant engaged [7].

2) FEEDBACK INDICATOR

Another challenge faced by the pseudo-haptic is the lack of feedback indicator to guide or limit the participant's actions to achieve the desired weight-perception effect. One of the examples is to limit the speed when the object is lifted to render the perception of heaviness. The exploratory study [147] suggested that even though the interaction method showed potential regarding the perception of heaviness, the results did not show clear signs to limit the lift velocity for the participants. This can be overcome by introducing a virtual indicator to guide the participants on the speed of lifting [148], or to combine with other interfaces or sensors that can provide biofeedback to be used as the indicator to provide a more accurate weight perception.

3) ACCURATE TRACKING

Accurate tracking is essential in the experiments using C/D ratio offsets as weight representation. Slight tracking errors could lead to unpredictable perception, thereby affecting the weight discrimination precision and a plausible decrease in the sense of presence. Tracking must be very accurate, and the body parts visually displayed may vary from the actual position, but the relative precision of motions needs to be maintained. Additional hardware [173] or improved tracking algorithm can be deployed to improve the VR tracking [174].

VIII. FUTURE WORKS AND OPPORTUNITIES

In line with the works and challenges discussed, five possible future works and research opportunities are presented in this section.

A. HYBRID FRAMEWORKS OR MODELS

Haptic interfaces could create a real sense of weight by rendering tactile and proprioceptive sensations. However, they suffer from physical limitations in weight perception rendering to balance the maximum throughput over the size and weight of the actuators. Pseudo-haptic techniques relying on human cognitive characteristics could be deployed to overcome the weakness by enhancing and augmenting weight perception. The design of modularized hybrid haptic frameworks for weight perception needs to be further investigated. The development process can be simplified with adaptable models and frameworks by looking at challenges that "hapticians" are generally confronted with when building haptic interfaces. According to Sutherland [1], these challenges can range from interdisciplinary requirements, the vertically integrated nature of haptic experiences, and the need to establish a comprehensive understanding of human behavior.

Owing to the vertically integrated nature of haptic experiences, any alterations or changes made to a particular haptic component would require major overhauls to the whole system. Typically, a haptic system comprises actuators in constant contact with other components that are also present in the system. It is integral that all components should be fully functioning as they are often tightly coupled and highly dependent on each other. A potential solution to the aforementioned problems is to develop frameworks that support modularity, which would mean that all components in the system would have a certain degree of separation between them. In other words, when there are any changes made to a single component or when one component fails to function, modules can be interchanged or replaced without any further consideration. Frameworks that support modularity can be especially useful when simulating weight perception in hybrid settings, as these interfaces are often complex, involving many moving parts, and need to be smoothly integrated with the visual effects.

Furthermore, the need for interdisciplinary collaborations is at the core of weight perception development. Often, experts and professionals from computer science, engineering, psychology, and physiology must collaborate to combine their knowledge. For instance, when building an efficient haptic interface to render weight perception, engineers are needed to build mechanical prototypes, physiologists are needed to identify how to simulate weight perception properly, computer scientists are needed to program the interface, and phycologists are needed to carry out usability testing once the prototype has been developed. Additionally, if one decides to market and commercialize the product, a salesperson who is well versed in matters regarding haptic or perceptual interfaces, in general, would be needed as demos can be quite complicated to carry out. Thus, there is a need for the development of frameworks or tools that can streamline interdisciplinary collaborations.

B. MULTIMODALITY

Weight is perceived through a combination of object properties information obtained from sensory feedbacks through vision, hearing, touch, and proprioception information from muscles and joints. Incorporating multimodality in designing interfaces for rendering weight perception is prevalent. As of now, the development of multimodal haptic interfaces remains a challenging task. Ideally, a true multimodal haptic experience should be able to support features such as being able to simulate various shapes and forms, surface types and textures, temperatures and thermal sensations, all types of contact forces, ranging from air resistance, applied forces, frictional forces, gravitational forces, shear forces, spring forces, and tension. However, inevitable challenges that cannot be ignored in the multimodal weight perception are the conflict of senses that render the weight cues [142], [175], [176] and the conflict in the mechanical design of the device. Attaching multiple sensors or actuators to the same body part may dampen the transmission of desire haptic feedback and limit the weight sensations [94].

Studies by Rossignac *et al.* [177] and Stanley and Okamura [178] have shown that multimodality can be achieved to a certain extent by developing deformable surfaces. However, both studies were limited to simulating changes in object properties including size and shape, much like clay. These works can be used as a basis to develop more multimodal interfaces, possibly by introducing mechanisms that can simulate texture, compliance, and temperature. With that said, the challenge of developing multimodal haptic interfaces for weight perception is to incorporate all the aforementioned features without incurring much cost, functionality, and complexity. Hence, it is hoped that this paper can serve as a basis for weight perception to aid the future development of multimodal interfaces.

C. REALISM ANALYSIS

Owing to the different characteristics and features of weight perception techniques proposed in the literature, as well as the underlying experiment settings, there is a lack of study on a qualitative comparison of the realism in weight perception among the studies. The evaluation of realism is especially crucial in the pseudo-haptic approach with the absence of physical sensations. As commented by Rietzler *et al.* [7], pseudo-haptic effects are useful to communicate different weights, which increases the respective perception, but still will never be able to create a true and natural perception of weight.

The evaluations were mostly done through questionnaire surveys on subjective experiences in isolated application scenarios. Further research could be pursued to conduct a qualitative comparison to assess the level of presence, immersion, and realism of the experience among the individual and combination of techniques under a comprehensive set of weight cues and settings, and to identify measurable benefits on broad user experience from the addition of weight sensations. The user evaluation process on haptic interfaces often lacks real-world testing, and the failure to properly carry out evaluation would impede the progress of the haptics field in general. Thus, this calls for frameworks to produce surveys or evaluation methodologies that can be adapted and used by researchers. The benefit of this is twofold, where this can potentially expedite the evaluation process and provide consistent data in published studies.

D. ENCOUNTERED-TYPE HAPTICS

Encountered-type haptic display is a device capable of placing a part of itself or in its entirety in an encountered location, which allows the user to have the sensation of voluntarily eliciting haptic feedback with that environment at a proper time and location. Encounter-type haptic was first conceptualized with a robotic system as a haptic rendering part of a VR simulation. Robotic arm is a grounded encountered-type haptic display that position the end-effector in a particular position of the workspace for rendering different type of haptic sensation and feedback. Robotic arms could be placed at movable platform and exert forces when encountered by users to simulate the weight sensation. The possible shortcomings worth noting are the workspace restriction by the robotic arm spans and height limitation imposed by a mobile robot on wheels.

These shortcomings could be overcome with the ungrounded encountered-type display, which is not constrained to an anchor position. It is more feasible to develop an encountered-type interface with the mobility of unmanned aerial vehicles (UAV). Recent research in this area focused on the use of drones to provide haptic feedbacks and render tactile sensations. A drone is capable of actively generating kinetic energy which could create directional force feedback to simulate the sense of stiffness and weight. Alternatively, drone could be used to carry the physical props to simulate haptic user interaction with the objects.

The potential of encountered-type haptics display in the weight simulation remains to be explored and exploited. Weight sensation could be rendered with presenting of physical surface to users through dynamic positioning of passive haptics or animating passive props. However, development of end-effectors and haptic displays that could properly render the surfaces to be touched and the limitations in current technology are the challenges to be overcome.

E. MID-AIR HAPTICS

Mid-air interfaces aim to eliminate the need to wear, hold, or set up external props and devices to receive haptic feedback. Such interfaces are capable of creating the sensation of touch where there is nothing but thin air. Ultrasonic actuation is one of the methods that have attracted much interest from researchers in recent years. Feedback is transmitted through a device that features a panel of ultrasonic transducers. The phase delay between the actuators creates interference patterns in the sound waves that propagated into the air [179]. Aside from ultrasonic, other possible contactless haptic feedback are electromagnetic-based actuation [180], air-pressured actuation, and electrostatic forces [181]. These methods typically require a wearable prop on a finger or hand. Ultrasonic typically have frequencies and wavelength limitations [107]. The strength of the effect of mid-air haptics possibly is an issue that may require to be overcome in order to render weight sensation, as the mid-air tactile force thresholds are usually small. Using a large number of ultrasonic transducers can strengthen the effect but can make the device bigger, heavier, and more costly [182]. To our best knowledge, there is no study and research in simulating weight perception through mid-air technology in the extant literature. It might seem impracticable to render weight with ultrasound and air pressure in view of current technology limitations. However, given the nature of mid-air haptics in providing contactless haptic feedback, it certainly has the potential to create a flexible weight perception rendering with high adaptability if the limitations can be overcome in the future.

TABLE 5. Systematic review summary–weight perception with haptics.

Literature	Environment *	Device Type	Actuation Method	Device Weight	Haptic Cue **					Maximum force	Experiment
					F	S	V	W	O		
[84]	DVR	Ground-based	DC motors	-	✓	✓				-	Lift a virtual object
[98]	VR	Wearable (Fingertips)	DC Motors	32 g		✓				7.5 N (normal force) and 2 N (lateral force)	Lift a virtual cube by index finger and thumb
[92]	VR	Wearable (Fingertips)	DC Motors	-		✓				End-effector move 2.1 mm per Newton of virtual force	Lift the virtual object
[91], [113]	VR	Wearable (Palm)	Servo motor + vibration motor	30 g	✓		✓			4.2 N (normal force)	Hold the virtual object on the palm
[123]	AR	Wearable (Fingertips)	Pulley with two motors (Maxon Motor Corp. RE10)	-		✓				-	Hold the virtual object
[120]–[122]	NV	Wearable (Fingertips)	Pulley with two motors (Maxon Motor Corp. RE10)	-		✓				-	Hold a light-weight Styrofoam cube
[5], [111]	DVR	Ground-based	3 motors per finger	79.62 g	✓					-	Lift the virtual object
[99]	AR	Wearable (Fingertips)	Servo motor 3-RRS: PWM-controlled HS-5035HD hRing: PWM-controlled HS-40	3-RRS: 25 g (35x50x48 mm) hRing: 38 g (30x43x25 mm)		✓				-	Pick and place the virtual object
[95]	VR	Ground-based	Force-torque sensors (Nano17, ATI) + high fidelity haptic device	-	✓	✓				-	Hold the virtual object
[101]	MR	Wearable (Wrist)	A brushed DC motor coupled to a strain-wave gear unit from Harmonic Drive	< 200 g	✓					-	Pick up the tennis ball and wave the tennis racket
[83]	DVR	Wearable (Fingertips and Palm)	Vibrotactile feedback from CyberTouch data glove	-			✓			-	Pick up, push and pull the virtual object
[130]	NV	Handheld	Coreless DC motor	400 g	✓		✓			-	Hold and lift the haptic device (NV)
[85]	SVR	Ground-based	High fidelity haptic device	-	✓					-	Push down the pan of a virtual two-pan balance
[115]	VR	Wearable (Wrist)	Pneumatics	-	✓					-	Lift a virtual cylinder
[119]	NV	Handheld	Electric motor to actuate the plate (Portescap Corp.:16G88-208E)	-		✓				-	Lift the device (close the eyes)
[152]	VR	Wearable (Fingertips)	Finger-tracking device extended with pinch intensity sensor	-	✓					-	Lift the object
[129]	DVR	Handheld	Vibration motors + linear motor	-			✓	✓		-	Hold the haptic device with both hands
[128]	VR	Wearable (Arm)	Vibrations through Elitac tactile display	-			✓			-	Drop the virtual object on the shoulder
[131]	VR	Handheld	Shaft motor	The frame is 360 g, the weight 400 g				✓		Stroke 57 mm force 60 N	Shaking the virtual box
[132]	DVR	Handheld	DC Motors	268 g (the weight 146 g, container 122 g)				✓		-	Shake the bottle-liked haptic device
[100]	VR	Wearable (Fingertips)	DC Motors	22 g (exclude electric cables and elastic belt)		✓				3.4 N	Lift the virtual object

TABLE 5. ***(Continued.)*** **Systematic review summary—weight perception with haptics.**

[116]	VR	Handheld	Maxon Motor AG. RE-max21 to wind string Maxon Motor AG. RE16 to rotate the plate	196 g (excluding wires)	✓					Wind string force 1.23 N, torque 5.10 x 10^-1 Nm	Use a chopstick-liked haptic device to grasp and lift the virtual object
[94]	VR	Wearable (Fingertips)	A brake mechanism and two vibration actuators (voice coil actuators)	65 g	✓		✓			-	Grab the virtual box
[104]	VR	Wearable (Arm)	EMS, 8 electrode pairs, actuating (a) wrist, (b) biceps, (c) triceps, and (d) shoulders	-					✓	-	Pushing a virtual wall, and lift, punch and throw the virtual cube
[133]	VR	Handheld	NEMA-14 type stepper motor	Proxy weight 440 g, moving weight 127 g				✓		-	Pick up a virtual object
[134]	VR	Handheld	Water bags + electric pump	1500 g (handheld device: 365 g, wearable device 375 g, the bag can store 760 ml of water)					✓	Pump 330 g in 16.8 seconds	(a) Filling a cup with coffee (b) Watering a plant (c) Holding a container to scoop up dog food (d) Holding an empty cup
[90]	VR	Handheld	Propeller-induced propulsive force	-	✓					4 N force each direction (render 816 g)	Hold a virtual hammer
[87]	VR	Handheld	Propeller-induced propulsive force	1069 g (including tracker, counterbalancing weight, two propellers 400 g)	✓					14 N (7.1 N per propeller x 2)	Hold different virtual cooking utensils, such as frying pans, pots, and rolling bar
[89]	VR	Handheld	MG996R servo motor	598 g	✓			✓		-	Move a virtual wagon from right to left by swinging or rotating the haptic device
[103]	VR	Wearable (Body)	Pneumatics	-	✓					-	Lift a weight by performing barbell curls and pulling down the handle of a cable pull.
[88]	VR	Handheld	Vibration actuator (voice coil actuators)	151 g (actuators) + 65 g (VIVE tracker)			✓			Virtual force: 30 g	Shake a virtual jar to feel coins rattling inside
[96]	VR	Ground-based	Cable-driven parallel robot	-	✓					Horizontal force ±5 N, vertical force 15 N	Grasp/lower/lift the virtual crate
[126], [127]	VR	Handheld	DC motor (Maxon DCX10/Faulhaber 1016 Micro)	-		✓	✓			Shear forces 4.8 N vibrations 170 Hz	Hold the haptic device to move the virtual object
[97]	DVR	Ground-based	Servo motor	-		✓				-	(a) Move a virtual object with an index finger laterally grasp (b) Pull-out and lift-up a virtual object
[102]	VR	Wearable (Head)	Servo motor and Galvanic Vestibular Stimulation (GVS)	-					✓	-	Interact with the virtual objects with an avatar robotic arm
[93]	VR	Wearable (Wrist)	Servo motor (customized Hitech HS-7115TH) + vibration actuator (voice coil actuators)	188 g (PIVOT) + 89 g (VIVE tracker)	✓					3.5 N force (render 350 g weight), 340 ms to move handle 190°	Grab and lift the virtual object

*VR = Full Immersive VR with HMD, DVR = Desktop VR, NV = No Visual, SVR = Semi-Immersive Haptic Workstation
**F = Force, S = Shear Force/Skin Deformation (Fingertips), V = Vibration, W = Weight Shift, O = Others

IX. CONCLUSION

VR- and AR-powered products are envisioned as the next major platform for human communication after mobile phones. Facebook is building out the immersive digital worlds it calls the "metaverse," taking the immersive technology to unprecedented heights, expecting to reach a billion people within the next decade. Advances in 5G technologies and consumer VR hardware in recent years (e.g., Oculus Quest 2 and HTC Vive Cosmos Elite), open up the infinite possibilities of AR and VR application developments. There is thus a pressing need to provide more realistic sensation in humans' virtual interaction process. Despite the advancements in haptic and VR technology, it continues to be a massive challenge to sense the weight of a virtual object with the absence of real gravitational forces. This paper reviews the development of weight perception in VR and discusses the eight most critical challenges and five future directions of weight perception rendering in a virtual environment. We observed that most weight simulation methods were designed and applied to specific application scenarios and setups. The shortcomings of techniques and approaches identified in this study indicate that there is still a gap toward building a robust multi-gesture weight perception simulation that is adaptable to different application needs. The limitations in current approaches need to be overcome with continuous exploration of new techniques and innovations. This study provides a comprehensive view on the topic to aid future researchers in developing more realistic weight perception in VR applications to enhance further the immersive experience of the virtual world, benefiting the research in education, training, and the entertainment industry.

APPENDIX

See Table 5.

REFERENCES

[1] I. E. Sutherland, "A head-mounted three dimensional display," in *Proc. Fall Joint Comput. Conf.*, vol. 1968, Dec. 1968, pp. 757–764, doi: 10.1145/1476589.1476686.

[2] P. Strohmeier and K. Hornbæk, "Generating haptic textures with a vibrotactile actuator," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 4994–5005, doi: 10.1145/3025453.3025812.

[3] S. J. Lederman and R. L. Klatzky, "Extracting object properties through haptic exploration," *Acta Psychol.*, vol. 84, no. 1, pp. 29–40, 1993, doi: 10.1016/0001-6918(93)90070-8.

[4] L. A. Jones, "Perception of force and weight: Theory and research," *Psychol. Bull.*, vol. 100, no. 1, pp. 29–42, 1986.

[5] C. Giachritsis, J. Barrio, M. Ferre, A. Wing, and J. Ortego, "Evaluation of weight perception during unimanual and bimanual manipulation of virtual objects," in *Proc. World Haptics 3rd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Mar. 2009, pp. 629–634, doi: 10.1109/WHC.2009.4810836.

[6] P. Carlson, J. M. Vance, and M. Berg, "An evaluation of asymmetric interfaces for bimanual virtual assembly with haptics," *Virtual Reality*, vol. 20, no. 4, pp. 193–201, Nov. 2016, doi: 10.1007/s10055-016-0290-z.

[7] M. Rietzler, F. Geiselhart, J. Gugenheimer, and E. Rukzio, "Breaking the tracking: Enabling weight perception using perceivable tracking offsets," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–12, doi: 10.1145/3173574.3173702.

[8] T. Al-Hathal and N. Fetais, "Virtual reality glove for falconry," in *Proc. Int. Conf. Comput. Appl. (ICCA)*, Aug. 2018, pp. 95–97, doi: 10.1109/COMAPP.2018.8460398.

[9] D. Wang, K. Ohnishi, and W. Xu, "Multimodal haptic display for virtual reality: A survey," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 610–623, Jan. 2020, doi: 10.1109/TIE.2019.2920602.

[10] W. Dangxiao, G. Yuan, L. Shiyi, Z. Yuru, X. Weiliang, and X. Jing, "Haptic display for virtual reality: Progress and challenges," *Virtual Real. Intell. Hardw.*, vol. 1, no. 2, p. 136, 2019, doi: 10.3724/sp.j.2096-5796.2019.0008.

[11] C. Wee, K. M. Yap, and W. N. Lim, "Haptic interfaces for virtual reality: Challenges and research directions," *IEEE Access*, vol. 9, pp. 112145–112162, 2021, doi: 10.1109/ACCESS.2021.3103598.

[12] X. Ye, "A survey on simulation for weight perception in virtual reality," *J. Comput. Commun.*, vol. 9, no. 9, pp. 1–24, 2021, doi: 10.4236/jcc.2021.99001.

[13] E. H. Weber, *E. H. Weber: The Sense of Touch*. London, U.K.: Academic, 1978.

[14] E. L. Amazeen, "Perceptual independence of size and weight by dynamic touch," *J. Exp. Psychol., Hum. Perception Perform.*, vol. 25, no. 1, pp. 102–119, 1999, doi: 10.1037/0096-1523.25.1.102.

[15] C. D. Oberle and E. L. Amazeen, "Independence and separability of volume and mass in the size-weight illusion," *Perception Psychophys.*, vol. 65, no. 6, pp. 831–843, Aug. 2003, doi: 10.3758/BF03194818.

[16] R. R. Ellis and S. J. Lederman, "The role of haptic versus visual volume cues in the size-weight illusion," *Perception Psychophys.*, vol. 53, no. 3, pp. 315–324, May 1993, doi: 10.3758/BF03205186.

[17] F. McGlone and D. Reilly, "The cutaneous sensory system," *Neurosci. Biobehavioral Rev.*, vol. 34, no. 2, pp. 148–159, Feb. 2010, doi: 10.1016/j.neubiorev.2009.08.004.

[18] T. S. Ellenbecker, G. J. Davies, and J. Bleacher, *24—Proprioception and Neuromuscular Control*, J. R. Andrews, G. L. Harrelson, and F. E. Wilk, Eds. Philadelphia, PA, USA: W.B. Saunders, 2012, pp. 524–547.

[19] C. M. Davis and W. Roberts, "Lifting movements in the size-weight illusion," *Perception Psychophys.*, vol. 20, no. 1, pp. 33–36, Jan. 1976, doi: 10.3758/BF03198701.

[20] S. P. Harshfield and D. C. DeHardt, "Weight judgment as a function of apparent density of objects," *Psychonomic Sci.*, vol. 20, no. 6, pp. 365–366, Jun. 1970, doi: 10.3758/BF03335692.

[21] D. J. Murray, R. R. Ellis, C. A. Bandomir, and H. E. Ross, "Charpentier (1891) on the size—Weight illusion," *Perception Psychophys.*, vol. 61, no. 8, pp. 1681–1685, Dec. 1999, doi: 10.3758/BF03213127.

[22] E. E. Brodie and H. E. Ross, "Sensorimotor mechanisms in weight discrimination," *Perception Psychophys.*, vol. 36, no. 5, pp. 477–481, Sep. 1984, doi: 10.3758/BF03207502.

[23] A. B. Valdez and E. L. Amazeen, "Sensory and perceptual interactions in weight perception," *Perception Psychophys.*, vol. 70, no. 4, pp. 647–657, May 2008, doi: 10.3758/PP.70.4.647.

[24] G. Buckingham, "Getting a grip on heaviness perception: A review of weight illusions and their probable causes," *Exp. Brain Res.*, vol. 232, no. 6, pp. 1623–1629, Jun. 2014, doi: 10.1007/s00221-014-3926-9.

[25] M. A. Plaisier, I. A. Kuling, E. Brenner, and J. B. J. Smeets, "When does one decide how heavy an object feels while picking it up?" *Psychol. Sci.*, vol. 30, no. 6, pp. 822–829, Jun. 2019, doi: 10.1177/0956797619837981.

[26] P. Walker, B. J. Francis, and L. Walker, "The brightness-weight illusion: Darker objects look heavier but feel lighter," *Exp. Psychol.*, vol. 57, no. 6, pp. 462–469, Jan. 2010, doi: 10.1027/1618-3169/a000057.

[27] G. Buckingham, E. E. Michelakakis, and J. Cole, "Perceiving and acting upon weight illusions in the absence of somatosensory information," *J. Neurophysiol.*, vol. 115, no. 4, pp. 1946–1953, Apr. 2016, doi: 10.1152/jn.00587.2015.

[28] G. Buckingham, J. S. Cant, and M. A. Goodale, "Living in a material world: How visual cues to material properties affect the way that we lift objects and perceive their weight," *J. Neurophysiol.*, vol. 102, no. 6, pp. 3111–3118, Dec. 2009, doi: 10.1152/jn.00515.2009.

[29] G. Buckingham, N. S. Ranger, and M. A. Goodale, "The material–weight illusion induced by expectations alone," *Attention, Perception, Psychophys.*, vol. 73, no. 1, pp. 36–41, Jan. 2011, doi: 10.3758/s13414-010-0007-4.

[30] M. J. Rowe, "The synaptic linkage for tactile and kinaesthetic inputs to the dorsal column nuclei," *Adv. Exp. Med. Biol.*, vol. 508, pp. 47–55, 2002, doi: 10.1007/978-1-4615-0713-0_7.

[31] G. Buckingham, N. S. Ranger, and M. A. Goodale, "The role of vision in detecting and correcting fingertip force errors during object lifting," *J. Vis.*, vol. 11, no. 1, p. 4, Jan. 2011, doi: 10.1167/11.1.4.

[32] E. J. Saccone, O. Landry, and P. A. Chouinard, "A meta-analysis of the size-weight and material-weight illusions," *Psychonomic Bull. Rev.*, vol. 26, no. 4, pp. 1195–1212, Aug. 2019, doi: 10.3758/s13423-019-01604-x.

[33] L. A. Jones and I. W. Hunter, "Effect of fatigue on force sensation," *Exp. Neurol.*, vol. 81, no. 3, pp. 640–650, 1983, doi: 10.1016/0014-4886(83)90332-1.

[34] L. A. Jones, *The Senses of Effort and Force During Fatiguing Contractions BT—Fatigue: Neural and Muscular Mechanisms*, S. C. Gandevia, R. M. Enoka, A. J. McComas, D. G. Stuart, C. K. Thomas, P. A. Pierce, Eds. Boston, MA, USA: Springer, 1995, pp. 305–313.

[35] P. R. B. L. F. Jones, "Perceptions of effort and heaviness during fatigue and during the size-weight illusion," *Somatosensory Motor Res.*, vol. 14, no. 3, pp. 189–202, Jan. 1997, doi: 10.1080/08990229771051.

[36] S. C. Gandevia, D. I. McCloskey, and E. K. Potter, "Alterations in perceived heaviness during digital anaesthesia," *J. Physiol.*, vol. 306, no. 1, pp. 365–375, Sep. 1980, doi: 10.1113/jphysiol.1980.sp013402.

[37] J. R. Flanagan and C. A. Bandomir, "Coming to grips with weight perception: Effects of grasp configuration on perceived heaviness," *Perception Psychophys.*, vol. 62, no. 6, pp. 1204–1219, Sep. 2000, doi: 10.3758/BF03212123.

[38] B. M. Quaney, D. L. Rotella, C. Peterson, and K. J. Cole, "Sensorimotor memory for fingertip forces: Evidence for a task-independent motor memory," *J. Neurosci.*, vol. 23, no. 5, pp. 1981–1986, Mar. 2003.

[39] V. van Polanen and M. Davare, "Sensorimotor memory biases weight perception during object lifting," *Frontiers Hum. Neurosci.*, vol. 9, pp. 1–11, Dec. 2015, doi: 10.3389/fnhum.2015.00700.

[40] A. Charpentier, "Experimental analysis of some elements of the feeling of weight (analyse experimentale de quelgues elements de lasensation de poids)," *Arch. Physiol. Norm. Pathol.*, no. 3, pp. 122–135, 1891. [Online]. Available: https://www.mendeley.com/catalogue/d5af44d9-46ed-32eb-99fb-19a8923485be/?utm_source=desktop&utm_medium=1.19.8&utm_campaign=open_catalog&userDocumentId=%7B3f6a915a-c33d-425a-bb2d-8eae2b8b82b3%7D

[41] J. C. Stevens and L. L. Rubin, "Psychophysical scales of apparent heaviness and the size-weight illusion," *Perception Psychophys.*, vol. 8, no. 4, pp. 225–230, Jul. 1970, doi: 10.3758/BF03210210.

[42] T. Flournoy, "De l'influence de la perception visuelle des corps sur leur poids apparent [The influence of visual perception on the apparent weight of objects]," *L' Annee Psychol.*, vol. 3, no. 1, pp. 198–200, 1984.

[43] H. K. Wolfe, "Some effects of size on judgments of weight," *Psychol. Rev.*, vol. 5, no. 1, pp. 25–54, 1898, doi: 10.1037/h0073342.

[44] J. R. Flanagan, A. M. Wing, S. Allison, and A. Spenceley, "Effects of surface texture on weight perception when lifting objects with a precision grip," *Perception Psychophys.*, vol. 57, no. 3, pp. 282–290, Apr. 1995, doi: 10.3758/BF03213054.

[45] J. R. Flanagan and A. M. Wing, "Effects of surface texture and grip force on the discrimination of hand-held loads," *Perception Psychophys.*, vol. 59, no. 1, pp. 111–118, Jan. 1997, doi: 10.3758/BF03206853.

[46] G. Rinkenauer, S. Mattes, and R. Ulrich, "The surface—Weight illusion: On the contribution of grip force to perceived heaviness," *Perception Psychophys.*, vol. 61, no. 1, pp. 23–30, Jan. 1999, doi: 10.3758/bf03211946.

[47] C. E. Seashore, *Some Psychological Statistics II. The Material Weight Illusion*, 2nd ed. Iowa City, IA, USA: Univ. of Iowa Studies in Psychology, 1899.

[48] E. L. Amazeen and M. T. Turvey, "Weight perception and the haptic size-weight illusion are functions of the inertia tensor," *J. Express Psychol. Hum. Percept. Perform.*, vol. 22, no. 1, pp. 213–232, Feb. 1996, doi: 10.1037//0096-1523.22.1.213.

[49] M. Streit, K. Shockley, and M. A. Riley, "Rotational inertia and multimodal heaviness perception," *Psychonomic Bull. Rev.*, vol. 14, no. 5, pp. 1001–1006, Oct. 2007, doi: 10.3758/BF03194135.

[50] J. Platkiewicz and V. Hayward, "Perception-action dissociation generalizes to the size-inertia illusion," *J. Neurophysiol.*, vol. 111, no. 7, pp. 1409–1416, Apr. 2014, doi: 10.1152/jn.00557.2013.

[51] F. B. Dresslar, "Studies in the psychology of touch," *Amer. J. Psychol.*, vol. 6, no. 3, pp. 313–368, 1894, doi: 10.2307/1411644.

[52] M. Kahrimanovic, W. B. Tiest, and A. Kappers, "Characterization of the haptic shape-weight illusion with 3D objects," *IEEE Trans. Haptics*, vol. 4, no. 4, pp. 316–320, Jun. 2011, doi: 10.1109/TOH.2011.22.

[53] J. P. Kuhtz-Buschbeck and J. Hagenkamp, "Cold and heavy: Grasping the temperature–weight illusion," *Exp. Brain Res.*, vol. 238, no. 5, pp. 1107–1117, May 2020, doi: 10.1007/s00221-020-05794-y.

[54] J. C. Stevens and J. E. Hooper, "How skin and object temperature influence touch sensation," *Perception Psychophys.*, vol. 32, no. 3, pp. 282–285, May 1982, doi: 10.3758/BF03206232.

[55] J. E. De Camp, "The influence of color on apparent weight. A preliminary study," *J. Exp. Psychol.*, vol. 2, no. 5, pp. 347–370, 1917, doi: 10.1037/h0075903.

[56] M. Vicovaro, K. Ruta, and G. Vidotto, "Influence of visually perceived shape and brightness on perceived size, expected weight, and perceived weight of 3D objects," *PLoS One*, vol. 14, no. 8, pp. 1–25, 2019, doi: 10.1371/journal.pone.0220149.

[57] R. R. Ellis and S. J. Lederman, "The golf-ball illusion: Evidence for top-down processing in weight perception," *Perception*, vol. 27, no. 2, pp. 193–201, Feb. 1998, doi: 10.1068/p270193.

[58] J. R. Flanagan, J. P. Bittner, and R. S. Johansson, "Experience can change distinct size-weight priors engaged in lifting objects and judging their weights," *Current Biol.*, vol. 18, no. 22, pp. 1742–1747, Nov. 2008, doi: 10.1016/j.cub.2008.09.042.

[59] A. J. M. Dijker, "Why barbie feels heavier than ken: The influence of size-based expectancies and social cues on the illusory perception of weight," *Cognition*, vol. 106, no. 3, pp. 1109–1125, Mar. 2008, doi: 10.1016/j.cognition.2007.05.009.

[60] G. Buckingham and M. A. Goodale, "Lifting without seeing: The role of vision in perceiving and acting upon the size weight illusion," *PLoS ONE*, vol. 5, no. 3, p. e9709, Mar. 2010, doi: 10.1371/journal.pone.0009709.

[61] P. Koseleff, "Studies in the perception of heaviness. I.1.2: Some relevant facts concerning the size-weight-effect (SWE)," *Acta Psychol.*, vol. 13, pp. 242–252, 1957. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/0001691857900239?via%3Dihub, doi: 10.1016/0001-6918(57)90023-9.

[62] D. V. Cross and L. Rotkin, "The relation between size and apparent heaviness," *Perception Psychophys.*, vol. 18, no. 2, pp. 79–87, Mar. 1975, doi: 10.3758/BF03204091.

[63] H. L. Pick and A. D. Pick, "A developmental and analytic study of the size-weight illusion," *J. Exp. Child Psychol.*, vol. 5, no. 3, pp. 362–371, 1967, doi: 10.1016/0022-0965(67)90064-1.

[64] A. M. Gordon, H. Forssberg, R. S. Johansson, A. C. Eliasson, and G. Westling, "Development of human precision grip: III. Integration of visual size cues during the programming of isometric forces," *Exp. Brain Res.*, vol. 90, no. 2, pp. 399–403, Aug. 1992, doi: 10.1007/BF00227254.

[65] M. A. Plaisier and J. B. J. Smeets, "Mass is all that matters in the size-weight illusion," *PLoS One*, vol. 7, no. 8, pp. 1–6, 2012, doi: 10.1371/journal.pone.0042518.

[66] S. C. Masin and L. Crestoni, "Experimental demonstration of the sensory basis of the size-weight illusion," *Perception Psychophys.*, vol. 44, no. 4, pp. 309–312, Jul. 1988, doi: 10.3758/BF03210411.

[67] E. L. Amazeen, "The effects of volume on perceived heaviness by dynamic touch: With and without vision," *Ecol. Psychol.*, vol. 9, no. 4, pp. 245–263, Dec. 1997, doi: 10.1207/s15326969eco0904_1.

[68] E. J. Saccone and P. A. Chouinard, "The influence of size in weight illusions is unique relative to other object features," *Psychonomic Bull. Rev.*, vol. 26, no. 1, pp. 77–89, Feb. 2019, doi: 10.3758/s13423-018-1519-5.

[69] A. J. M. Dijker, "The role of expectancies in the size-weight illusion: A review of theoretical and empirical arguments and a new explanation," *Psychonomic Bull. Rev.*, vol. 21, no. 6, pp. 1404–1414, Dec. 2014, doi: 10.3758/s13423-014-0634-1.

[70] H. E. Ross, "When is a weight not illusory?" *Quart. J. Exp. Psychol.*, vol. 21, no. 4, pp. 346–355, Nov. 1969, doi: 10.1080/14640746908400230.

[71] A. M. Gordon, H. Forssberg, R. S. Johansson, and G. Westling, "Visual size cues in the programming of manipulative forces during precision grip," *Exp. Brain Res.*, vol. 83, no. 3, pp. 477–482, Feb. 1991, doi: 10.1007/BF00229824.

[72] J. R. Flanagan and M. A. Beltzner, "Independence of perceptual and sensorimotor predictions in the size–weight illusion," *Nature Neurosci.*, vol. 3, no. 7, pp. 737–741, Jul. 2000, doi: 10.1038/76701.

[73] M. S. Grandy and D. A. Westwood, "Opposite perceptual and sensorimotor responses to a size-weight illusion," *J. Neurophysiol.*, vol. 95, no. 6, pp. 3887–3892, Jun. 2006, doi: 10.1152/jn.00851.2005.

[74] J. Ross and V. Di Lollo, "Differences in heaviness in relation to density and weight," *Perception Psychophys.*, vol. 7, no. 3, pp. 161–162, May 1970, doi: 10.3758/BF03208648.

[75] C. Wolf, W. M. B. Tiest, and K. Drewing, ''A mass-density model can account for the size-weight illusion,'' *PLoS ONE* vol. 13, no. 2, Feb. 2018, Art. no. e0190624.

[76] R. Booth and P. Goldsmith, ''Detecting finger gestures with a wrist Worn piezoelectric sensor array,'' in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2017, pp. 3665–3670, doi: 10.1109/SMC.2017.8123202.

[77] R. R. Ellis and S. J. Lederman, ''The material-weight illusion revisited,'' *Perception Psychophys.*, vol. 61, no. 8, pp. 1564–1576, Dec. 1999, doi: 10.3758/BF03213118.

[78] E. Weber, ''Der tastsinn und das gemeingefühl,'' in *Handwörterbuch der Physiologie*, R. Wagner, Ed. Braunschweig, Germany: Vieweg, 1850, pp. 481–588.

[79] J. C. Stevens and B. G. Green, ''Temperature-touch interaction: Weber's phenomenon revisited,'' *Sens. Processes*, vol. 2, no. 3, pp. 206–209, Sep. 1978.

[80] J. C. Stevens, ''Thermal intensification of touch sensation: Further extensions of the weber phenomenon,'' *Sens. Processes*, vol. 3, no. 3, pp. 240–248, Sep. 1979.

[81] J. Galie and L. A. Jones, ''Thermal cues and the perception of force,'' *Exp. Brain Res.*, vol. 200, no. 1, pp. 81–90, Jan. 2010, doi: 10.1007/s00221-009-1960-9.

[82] C. Summerfield and F. P. de Lange, ''Expectation in perceptual decision making: Neural and computational mechanisms,'' *Nature Rev. Neurosci.*, vol. 15, no. 11, pp. 745–756, Oct. 2014, doi: 10.1038/nrn3838.

[83] I. Herbst and J. Stark, ''Comparing force magnitudes by means of vibro-tactile, auditory, and visual feedback,'' in *Proc. IEEE Int. Workshop Haptic Audio Visual Environ. Appl.*, Oct. 2005, pp. 67–71, doi: 10.1109/HAVE.2005.1545654.

[84] J. M. Suchoski, A. Barron, C. Wu, Z. F. Quek, S. Keller, and A. M. Okamura, ''Comparison of kinesthetic and skin deformation feedback for mass rendering,'' in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2016, pp. 4030–4035, doi: 10.1109/ICRA.2016.7487593.

[85] P. Figueroa, J. Borda, D. Restrepo, P. Boulanger, E. Londoño, and F. Prieto, ''A multimodal interface for artifact's exploration,'' in *Proc. IEEE Virtual Reality Conf.*, Mar. 2009, pp. 279–280, doi: 10.1109/VR.2009.4811054.

[86] K. B. Chen, K. Ponto, R. D. Tredinnick, and R. G. Radwin, ''Virtual exertions: Evoking the sense of exerting forces in virtual reality using gestures and muscle activity,'' *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 57, no. 4, pp. 658–673, Jun. 2015, doi: 10.1177/0018720814562231.

[87] S. Je, M. J. Kim, W. Lee, B. Lee, X.-D. Yang, P. Lopes, and A. Bianchi, ''Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2D plane,'' *Proc. 32nd Annu. ACM Symp. User Interface Softw. Technol. (UIST)*, 2019, pp. 763–775, doi: 10.1145/3332165.3347926.

[88] Y. Tanaka, A. Horie, and X. A. Chen, ''DualVib: Simulating haptic sensation of dynamic mass by combining pseudo-force and texture feedback,'' in *Proc. ACM Symp. Virtual Real. Softw. Technol. (VRST)*, 2020, pp. 1–10, doi: 10.1145/3385956.3418964.

[89] A. Zenner and A. Krüger, ''Drag: On: A virtual reality controller providing haptic feedback based on drag and weight shift,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–12, doi: 10.1145/3290605.3300441.

[90] S. Heo, C. Chung, G. Lee, and D. Wigdor, ''Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force,'' in *Proc. Extended Abstr. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–4, doi: 10.1145/3170427.3186544.

[91] D. Trinitatova and D. Tsetserukou, ''DeltaTouch: A 3D haptic display for delivering multimodal tactile stimuli at the palm,'' in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 73–78, doi: 10.1109/WHC.2019.8816136.

[92] J. M. Suchoski, S. Martinez, and A. M. Okamura, ''Scaling inertial forces to alter weight perception in virtual reality,'' in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2018, pp. 484–489, doi: 10.1109/ICRA.2018.8462874.

[93] R. Kovacs, E. Ofek, M. G. Franco, A. F. Siu, S. Marwecki, C. Holz, and M. Sinclair, ''Haptic PIVOT: On-demand handhelds in VR,'' in *Proc. 33rd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2020, pp. 1046–1059, doi: 10.1145/3379337.3415854.

[94] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer, ''Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality,'' in *Proc. 30th Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2017, pp. 119–130, doi: 10.1145/3126594.3126599.

[95] 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, doi: 10.1109/TOH.2020.3009599.

[96] C. Faure, A. Fortin-Cote, N. Robitaille, P. Cardou, C. Gosselin, D. Laurendeau, C. Mercier, L. Bouyer, and B. J. McFadyen, ''Adding haptic feedback to virtual environments with a cable-driven robot improves upper limb spatio-temporal parameters during a manual handling task,'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 10, pp. 2246–2254, Oct. 2020, doi: 10.1109/TNSRE.2020.3021200.

[97] J. Park, B. Son, I. Han, and W. Lee, ''Effect of cutaneous feedback on the perception of virtual object weight during manipulation,'' *Sci. Rep.*, vol. 10, no. 1, pp. 1–10, Dec. 2020, doi: 10.1038/s41598-020-58247-5.

[98] S. B. Schorr and A. M. Okamura, ''Fingertip tactile devices for virtual object manipulation and exploration,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 3115–3119, doi: 10.1145/3025453.3025744.

[99] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo, ''Evaluation of wearable haptic systems for the fingers in augmented reality applications,'' *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 511–522, Oct. 2017, doi: 10.1109/TOH.2017.2691328.

[100] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer, ''HapTip: Displaying haptic shear forces at the fingertips for multi-finger interaction in virtual environments,'' *Frontiers ICT*, vol. 3, Apr. 2016, doi: 10.3389/fict.2016.00006.

[101] E. Pezent, M. K. O'Malley, A. Israr, M. Samad, S. Robinson, P. Agarwal, H. Benko, and N. Colonnese, ''Explorations of wrist haptic feedback for AR/VR interactions with tasbi,'' in *Proc. Extended Abstr. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, doi: 10.1145/3334480.3383151.

[102] T. Teo, F. Nakamura, M. Sugimoto, A. Verhulst, G. A. Lee, M. Billinghurst, and M. Adcock, ''Feel it: Using proprioceptive and haptic feedback for interaction with virtual embodiment,'' in *Proc. ACM SIGGRAPH Emerg. Technol.*, 2020, pp. 2019–2020, doi: 10.1145/3388534.3407288.

[103] S. Günther, M. Makhija, F. Müller, D. Schön, M. Mühlhäuser, and M. Funk, ''PneumAct: Pneumatic kinesthetic actuation of body joints in virtual reality environments,'' in *Proc. Designing Interact. Syst. Conf.*, Jun. 2019, pp. 227–240, doi: 10.1145/3322276.3322302.

[104] P. Lopes, S. You, L.-P. Cheng, S. Marwecki, and P. Baudisch, ''Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 1471–1482, doi: 10.1145/3025453.3025600.

[105] M. Hoppe, P. Knierim, T. Kosch, M. Funk, L. Futami, S. Schneegass, N. Henze, A. Schmidt, and T. Machulla, ''VRHapticDrones: Providing haptics in virtual reality through quadcopters,'' in *Proc. 17th Int. Conf. Mobile Ubiquitous Multimedia*, Nov. 2018, pp. 7–18, doi: 10.1145/3282894.3282898.

[106] P. Abtahi, B. Landry, J. J. Yang, M. Pavone, S. Follmer, and J. A. Landay, ''Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality,'' in *Proc. Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–13, doi: 10.1145/3290605.3300589.

[107] I. Rakkolainen, A. Sand, and R. Raisamo, ''A survey of mid-air ultrasonic tactile feedback,'' in *Proc. IEEE Int. Symp. Multimedia (ISM)*, Dec. 2019, pp. 94–98, doi: 10.1109/ISM46123.2019.00022.

[108] D. Ablart, W. Frier, H. Limerick, O. Georgiou, and M. Obrist, ''Using ultrasonic mid-air haptic patterns in multi-modal user experiences,'' in *Proc. IEEE Int. Symp. Haptic, Audio Vis. Environments Games (HAVE)*, Oct. 2019, pp. 4–9, doi: 10.1109/HAVE.2019.8920969.

[109] G. S. Giri, Y. Maddahi, and K. Zareinia, ''An application-based review of haptics technology,'' *Robot.*, vol. 10, no. 1, pp. 1–18, 2021, doi: 10.3390/robotics10010029.

[110] Y. Yoon, D. Moon, and S. Chin, ''Fine tactile representation of materials for virtual reality,'' *J. Sensors*, vol. 2020, pp. 1–8, Jan. 2020, doi: 10.1155/2020/7296204.

[111] 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,'' in *Proc. 19th Int. Symp. Robot Hum. Interact. Commun.*, Sep. 2010, pp. 513–519, doi: 10.1109/ROMAN.2010.5598622.

[112] N. Gurari and G. Baud-Bovy, ''Customization, control, and characterization of a commercial haptic device for high-fidelity rendering of weak forces,'' *J. Neurosci. Methods*, vol. 235, pp. 169–180, Sep. 2014.

[113] D. Trinitatova and D. Tsetserukou, "TouchVR: A wearable haptic interface for VR aimed at delivering multi-modal stimuli at the user's palm," in *Proc. SIGGRAPH Asia XR*, vol. 1, 2019, pp. 42–43, doi: 10.1145/3355355.3361896.

[114] E. Pezent, A. Israr, M. Samad, S. Robinson, P. Agarwal, H. Benko, and N. Colonnese, "Tasbi: Multisensory squeeze and vibrotactile wrist haptics for augmented and virtual reality," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 1–6, doi: 10.1109/whc.2019.8816098.

[115] G. Hannig and B. Deml, *Efficient Bimodal Haptic Weight Actuation* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 6191. Berlin, Germany: Springer, 2010, pp. 3–10, doi: 10.1007/978-3-642-14064-8_1.

[116] G. Kato, Y. Kuroda, I. Nisky, K. Kiyokawa, and H. Takemura, "Design and psychophysical evaluation of the HapSticks: A novel non-grounded mechanism for presenting tool-mediated vertical forces," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 338–349, Jul. 2017, doi: 10.1109/TOH.2016.2636824.

[117] S. Je, H. Lee, M. J. Kim, and A. Bianchi, "Wind-blaster: A wearable propeller-based prototype that provides ungrounded force-feedback," in *Proc. ACM SIGGRAPH Emerg. Technol. (SIGGRAPH)*, New York, NY, USA, 2018, pp. 1–2, Art. no. 23, doi: 10.1145/3214907.3214915.

[118] T. Sasaki, R. S. Hartanto, K.-H. Liu, K. Tsuchiya, A. Hiyama, and M. Inami, "Leviopole: Mid-air haptic interactions using multirotor," in *Proc. ACM SIGGRAPH Emerg. Technol. (SIGGRAPH)*, New York, NY, USA, 2018, pp. 1–2, Art. no. 12, doi: 10.1145/3214907.3214913.

[119] Y. Kurita, S. Yonezawa, A. Ikeda, and T. Ogasawara, "Weight and friction display device by controlling the slip condition of a fingertip," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2011, pp. 2127–2132, doi: 10.1109/iros.2011.6094613.

[120] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity grabber: Wearable haptic display to present virtual mass sensation," in *Proc. ACM SIGGRAPH Emerg. Technol. (SIGGRAPH)*, 2007, pp. 3–6.

[121] K. Minamizawa, H. Kajimoto, N. Kawakami, and S. Tachi, "A wearable haptic display to present the gravity sensation–preliminary observations and device design," in *Proc. 2nd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. (WHC)*, Mar. 2007, pp. 133–138, doi: 10.1109/WHC.2007.15.

[122] K. Minamizawa, S. Fukamachi, N. Kawakami, and S. Tachi, "Interactive representation of virtual object in hand-held box by finger-Worn haptic display," in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Mar. 2008, pp. 367–368.

[123] S. Scheggi, G. Salvietti, and D. Prattichizzo, "Shape and weight rendering for haptic augmented reality," in *Proc. IEEE Int. Workshop Robot Hum. Interact. Commun.*, Sep. 2010, pp. 44–49, doi: 10.1109/ROMAN.2010.5598632.

[124] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "Design and development of a 3RRS wearable fingertip cutaneous device," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2015, pp. 293–298, doi: 10.1109/AIM.2015.7222547.

[125] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: A wearable haptic device to avoid occlusions in hand tracking," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 134–139, doi: 10.1109/HAPTICS.2016.7463167.

[126] P. Preechayasomboon and A. Israr, "Crossing the chasm: Linking with the virtual world through a compact haptic actuator," in *Proc. Extended Abstr. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–4, doi: 10.1145/3334480.3383137.

[127] P. Preechayasomboon, A. Israr, and M. Samad, "Chasm: A screw based expressive compact haptic actuator," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–13, doi: 10.1145/3313831.3376512.

[128] N. Rosa, W. Hürst, W. Vos, and P. Werkhoven, "The influence of visual cues on passive tactile sensations in a multimodal immersive virtual environment," in *Proc. ACM Int. Conf. Multimodal Interact.*, Nov. 2015, pp. 327–334, doi: 10.1145/2818346.2820744.

[129] T. Mizuno, J. Maeda, and Y. Kume, "Weight sensation affected by vibrotactile stimulation with a handheld vision-tactile-force display device," in *Proc. 10th Int. Conf. Electr. Eng./Electron., Comput., Telecommun. Inf. Technol.*, May 2013, pp. 4–9, doi: 10.1109/ECTICon.2013.6559590.

[130] T. Amemiya and T. Maeda, "Asymmetric oscillation distorts the perceived heaviness of handheld objects," *IEEE Trans. Haptics*, vol. 1, no. 1, pp. 9–18, Jan. 2008, doi: 10.1109/TOH.2008.5.

[131] T. Yamamoto and K. Hirota, "Recognition of weight through shaking interaction," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2015, pp. 451–456, doi: 10.1109/WHC.2015.7177753.

[132] R. Koshiyama, T. Kikuchi, J. Morita, and M. Sugimoto, "VolRec: Haptic display of virtual inner volume in consideration of angular moment," in *Proc. 12th Int. Conf. Adv. Comput. Entertainment Technol.*, Nov. 2015, pp. 10–13, doi: 10.1145/2832932.2832970.

[133] A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 23, no. 4, pp. 1285–1294, Apr. 2017, doi: 10.1109/TVCG.2017.2656978.

[134] C.-H. Cheng, C.-C. Chang, Y.-H. Chen, Y.-L. Lin, J.-Y. Huang, P.-H. Han, J.-C. Ko, and L.-C. Lee, "GravityCup: A liquid-based haptics for simulating dynamic weight in virtual reality," in *Proc. 24th ACM Symp. Virtual Reality Softw. Technol.*, Nov. 2018, pp. 1–2, doi: 10.1145/3281505.3281569.

[135] S. J. Lederman and L. A. Jones, "Tactile and haptic illusions," *IEEE Trans. Haptics*, vol. 4, no. 4, pp. 273–294, Oct. 2011, doi: 10.1109/TOH.2011.2.

[136] T. Kanamori, D. Iwai, and K. Sato, "Pseudo-shape sensation by stereoscopic projection mapping," *IEEE Access*, vol. 6, pp. 40649–40655, 2018, doi: 10.1109/ACCESS.2018.2858268.

[137] A. Lécuyer, "Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback," *Presence, Teleoperators Virtual Environ.*, vol. 18, no. 1, pp. 39–53, Feb. 2009, doi: 10.1162/pres.18.1.39.

[138] P. Issartel, F. Gueniat, S. Coquillart, and M. Ammi, "Perceiving mass in mixed reality through pseudo-haptic rendering of Newton's third law," in *Proc. IEEE Virtual Reality (VR)*, Mar. 2015, pp. 41–46, doi: 10.1109/VR.2015.7223322.

[139] R. Yu and D. A. Bowman, "Pseudo-haptic display of mass and mass distribution during object rotation in virtual reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 26, no. 5, pp. 2094–2103, May 2020, doi: 10.1109/TVCG.2020.2973056.

[140] Y. Hirao, T. M. Takala, and A. Lecuyer, "Comparing motion-based versus controller-based pseudo-haptic weight sensations in VR," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces Abstr. Workshops (VRW)*, Mar. 2020, pp. 305–310, doi: 10.1109/VRW50115.2020.00069.

[141] Y. Taima, Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, "Controlling fatigue while lifting objects using pseudo-haptics in a mixed reality space," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 175–180, doi: 10.1109/HAPTICS.2014.6775451.

[142] L. Dominjon, A. Lécuyer, J. M. Burkhardt, P. Richard, and S. Richir, "Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments," in *Proc. IEEE Virtual Reality*, Feb. 2005, pp. 19–26, doi: 10.1109/VR.2005.49.

[143] M. Samad, E. Gatti, A. Hermes, H. Benko, and C. Parise, "Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–13, doi: 10.1145/3290605.3300550.

[144] D. A. G. Jauregui, F. Argelaguet, A.-H. Olivier, M. Marchal, F. Multon, and A. Lecuyer, "Toward 'pseudo-haptic avatars': Modifying the visual animation of self-avatar can simulate the perception of weight lifting," *IEEE Trans. Vis. Comput. Graphics*, vol. 20, no. 4, pp. 654–661, Apr. 2014, doi: 10.1109/TVCG.2014.45.

[145] K. L. Palmerius, D. Johansson, G. Höst, and K. Schönborn, *An Analysis of the Influence of a Pseudo-Haptic Cue on the Haptic Perception of Weight* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 8618. Berlin, Germany: Springer, 2014, pp. 117–125, doi: 10.1007/978-3-662-44193-0_16.

[146] Y. Hirao and T. Kawai, "Augmented cross-modality: Translating the physiological responses, knowledge and impression to audio-visual information in virtual reality," *Electron. Imag.*, vol. 2019, no. 2, pp. 60402-1–60402-8, Jan. 2019, doi: 10.2352/J.ImagingSci.Technol.2018.62.6.060402.

[147] E. Bäckström, "Do you even lift? An exploratory study of heaviness perception in virtual reality," Degree Proj. Comput. Sci. Eng., KTH Roy. Inst. Technol., Stockholm, Sweden, Tech. Rep. TRITA EECS-EX-2018:576, 2018.

[148] J. Lee, J.-I. Kim, and H. Kim, "Force arrow 2: A novel pseudo-haptic interface for weight perception in lifting virtual objects," in *Proc. IEEE Int. Conf. Big Data Smart Comput. (BigComp)*, Feb. 2019, pp. 1–8, doi: 10.1109/BIGCOMP.2019.8679400.

[149] J. Lee, "Force arrow: An efficient pseudo-weight perception method," *J. Korea Soc. Comput. Inf.*, vol. 23, no. 7, pp. 49–56, 2018.

[150] C. Keller, J. Bluteau, R. Blanch, and S. Coquillart, "PseudoWeight: Making tabletop interaction with virtual objects more tangible," in *Proc. ACM Int. Conf. Interact. tabletops Surface (ITS)*, 2012, pp. 2–5. [Online]. Available: http://hal.archives-ouvertes.fr/hal-00757680/

[151] K. Ponto, R. Kimmel, J. Kohlmann, A. Bartholomew, and R. G. Radwin, "Virtual exertions: A user interface combining visual information, kinesthetics and biofeedback for virtual object manipulation," in *Proc. IEEE Symp. 3D User Interfaces (3DUI)*, Mar. 2012, pp. 85–88, doi: 10.1109/3DUI.2012.6184189.

[152] J. Hummel, J. Dodiya, R. Wolff, A. Gerndt, and T. Kuhlen, "An evaluation of two simple methods for representing heaviness in immersive virtual environments," in *Proc. IEEE Symp. 3D User Interfaces (3DUI)*, Mar. 2013, pp. 87–94, doi: 10.1109/3DUI.2013.6550202.

[153] E. Sikstrom, A. de Gotzen, and S. Serafin, "Self-characterstics and sound in immersive virtual reality—Estimating avatar weight from footstep sounds," in *Proc. IEEE Virtual Reality (VR)*, Mar. 2015, pp. 283–284, doi: 10.1109/VR.2015.7223406.

[154] K. Oshima, S. Hashiguchi, F. Shibata, and A. Kimura, "Analysis of R-V dynamics illusion behavior caused by varying the weight of real object," in *Proc. IEEE Symp. 3D User Interfaces (3DUI)*, Mar. 2017, pp. 213–214, doi: 10.1109/3DUI.2017.7893347.

[155] Y. Kataoka, S. Hashiguchi, F. Shibata, and A. Kimura, "R-V dynamics illusion: Psychophysical phenomenon caused by the difference between dynamics of real object and virtual object," in *Proc. Int. Conf. Artif. Real. Telexistence Eurographics Symp. Virtual Environ. (ICAT-EGVE)*, 2015, pp. 133–140, doi: 10.2312/egve.20151320.

[156] M. Streit, K. Shockley, M. A. Riley, and A. W. Morris, "Rotational kinematics influence multimodal perception of heaviness," *Psychonomic Bull. Rev.*, vol. 14, no. 2, pp. 363–367, Apr. 2007, doi: 10.3758/BF03194078.

[157] Y. Hirao, R. Mitsuya, and T. Kawai, "Weight sense representation using corss-modality in virtual reality," *Virtual Real. Soc. Jpn.*, vol. 23, no. 4, pp. 263–270, 2018. [Online]. Available: https://www.jstage.jst.go.jp/article/tvrsj/23/4/23_263/_article/-char/ja

[158] A. Lécuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet, "Pseudo-haptic feedback: Can isometric input devices simulate force feedback?" in *Proc. Virtual Real. Annu. Int. Symp.*, Mar. 2000, pp. 83–90, doi: 10.1109/VR.2000.840369.

[159] H. E. Ross and M. F. Reschke, "Mass estimation and discrimination during brief periods of zero gravity," *Perception Psychophys.*, vol. 31, no. 5, pp. 429–436, Sep. 1982.

[160] E. Weber, H. Ross, and D. J. Murray, *E.H. Weber On The Tactile Senses*. Hove, U.K.: Psychology Press, 1996.

[161] C. Giachritsis and A. Wing, *Unimanual and Bimanual Weight Discrimination in a Desktop Setup*. Berlin, Germany: Springer, 2008.

[162] H. Kjnoshita, S. Kawai, and K. Ikuta, "Contributions and co-ordination of individual fingers in multiple finger prehension," *Ergonomics*, vol. 38, no. 6, pp. 1212–1230, Jun. 1995, doi: 10.1080/00140139508925183.

[163] H. Kinoshita, T. Murase, and T. Bandou, "Grip posture and forces during holding cylindrical objects with circular grips," *Ergonomics*, vol. 39, no. 9, pp. 1163–1176, Sep. 1996, doi: 10.1080/00140139608964536.

[164] A. M. Gordon, H. Forssberg, and N. Iwasaki, "Formation and lateralization of internal representations underlying motor commands during precision grip," *Neuropsychologia*, vol. 32, no. 5, pp. 555–568, May 1994.

[165] Y. Boger, (2017). *Understanding Predictive Tracking and Why it's Important for AR/VR Headsets*. Accessed Sep. 8, 2021. [Online]. Available: https://www.roadtovr.com/understanding-predictive-tracking-important-arvr-headsets/

[166] J. J. Jerald, "Scene-motion- and latency-perception thresholds for head-mounted displays," Univ. North Carolina, Chapel Hill, NC, USA, Tech. Rep. TR10-013, 2010.

[167] J. Carmack. *Latency Mitigation Strategies*. Accessed: Aug. 30, 2021. [Online]. Available: https://danluu.com/latency-mitigation/

[168] S. Davis, K. Nesbitt, and E. Nalivaiko, "A systematic review of cybersickness," in *Proc. Conf. Interact. Entertainment*, Dec. 2014, pp. 1–9, doi: 10.1145/2677758.2677780.

[169] J. Renninger. (2000). *Understanding Damping Techniques for Noise and Vibration Control*. [Online]. Available: https://earglobal.com/media/9891/understandingdampingtechniques.pdf

[170] I. G. Ritchie and Z.-L. Pan, "High-damping metals and alloys," *Metall. Trans. A*, vol. 22, no. 3, pp. 607–616, Mar. 1991, doi: 10.1007/BF02670281.

[171] D. D. L. Chung, "Review: Materials for vibration damping," *J. Mater. Sci.*, vol. 36, no. 24, pp. 5733–5737, 2001, doi: 10.1023/A:1012999616049.

[172] D. Miljkovic, "Methods for attenuation of unmanned aerial vehicle noise," in *Proc. 41st Int. Conv. Inf. Commun. Technol., Electron. Microelectron. (MIPRO)*, May 2018, pp. 914–919, doi: 10.23919/MIPRO.2018.8400169.

[173] K. Zhu and L. Shi. (2016). *Motion Control in VR—Real-time Upper Limb Tracking Via IMU and Flex Sensor*. [Online]. Available: https://stanford.edu/class/ee267/Spring2016/report_zhu_shi.pdf

[174] Y. A. M. Barhoush, V. Nanjappan, F. Thiel, G. V. Georgiev, D. Swapp, and B. Loudon, "A novel experimental design of a real-time VR tracking device," *Proc. Des. Soc.*, vol. 1, pp. 171–180, Aug. 2021, doi: 10.1017/pds.2021.18.

[175] I. Rock and J. Victor, "Vision and touch: An experimentally created conflict between the two senses," *Science*, vol. 143, no. 3606, pp. 594–596, Feb. 1964.

[176] Y. Lee, I. Jang, and D. Lee, "Enlarging just noticeable differences of visual-proprioceptive conflict in VR using haptic feedback," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2015, pp. 19–24, doi: 10.1109/WHC.2015.7177685.

[177] J. Rossignac, M. Allen, W. J. Book, A. Glezer, I. Ebert-Uphoff, C. Shaw, D. Rosen, S. Askins, J. Bai, P. Bosscher, J. Gargus, B. Moon Kim, I. Llamas, A. Nguyen, G. Yuan, and H. Zhu, "Finger sculpting with digital clay: 3D shape input and output through a computer-controlled real surface," in *Proc. Shape Model. Int.*, May 2003, pp. 229–231, doi: 10.1109/SMI.2003.1199620.

[178] A. A. Stanley and A. M. Okamura, "Deformable model-based methods for shape control of a haptic jamming surface," *IEEE Trans. Vis. Comput. Graphics*, vol. 23, no. 2, pp. 1029–1041, Feb. 2017, doi: 10.1109/TVCG.2016.2525788.

[179] T. Hoshi and H. Shinoda, "Airborne ultrasound tactile display," in *Pervasive Haptics: Science, Design, and Application*, H. Kajimoto, S. Saga, M. Konyo, Eds. Tokyo, Japan: Springer, 2016, pp. 121–138.

[180] B. Duvernoy, I. Farkhatdinov, S. Topp, and V. Hayward, *Electromagnetic actuator for tactile communication* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 10894. Cham, Switzerland: Springer, Sep. 2018, pp. 14–24, doi: 10.1007/978-3-319-93399-3_2.

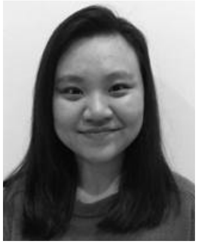
[181] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A review of surface haptics: Enabling tactile effects on touch surfaces," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 450–470, Jul. 2020, doi: 10.1109/TOH.2020.2990712.

[182] G. Korres and M. Eid, "Haptogram: Ultrasonic point-cloud tactile stimulation," *IEEE Access*, vol. 4, pp. 7758–7769, 2016, doi: 10.1109/ACCESS.2016.2608835.

WOAN NING LIM (Senior Member, IEEE) received the Bachelor of Computer Science (Hons.) and Master of Engineering (electrical) degrees from the Universiti Teknologi Malaysia, in 1998 and 2000, respectively. She is currently a Senior Lecturer with the School of Engineering and Technology, Sunway University. She is also a Researcher at the Research Centre for Human-Machine Collaboration (HUMAC), with research interests in human–computer interaction focuses on virtual reality and augmented reality, mobile computing, machine learning, and image processing. She has vast experience in the IT industry, worked in several multinational organizations, such as Shell IT International, DHL Asia Pacific IT Services, and Standard Chartered Scope International. She was involved in a few research grants projects, such as the Sunway Internal Grant and the MOHE Fundamental Research Grant Scheme (FRGS).

KIAN MENG YAP (Senior Member, IEEE) has spent 20 years working in data networks (IT), telecommunications, computer networking, haptics, manufacturing industries, and electronic control systems in machinery. His research interest includes the haptic over the distributed virtual environment (DVE) in HCI environment. His research project on DHVE is meant to have multi-sensory feedback data, such as voice, audio, and force over the fixed and wireless networks. He is the principal investigator of few projects that are supported by the Ministry of Higher Education (MOHE), ERGS, MCMC, Lancaster University, U.K., PPRN, industrial partners, and Sunway University Internal Grant. He is the Founder of the House of Multimodal Evolution (H.O.M.E.) Laboratory, which is to provide novel and innovative multimodal applications and communications toward the technology world. He is also the Founder of the Research Centre for Human-Machine Collaboration (HUMAC), that aims to be nation's main technology hub and to demonstrate its commitment to sustainable development. His current research interests include haptics, drones, odour sensing/tracking, tele-haptics, tele-robotics, materials sensing, assistive technology for visual and hearing impaired, and AR/VR.

YUNLI LEE (Senior Member, IEEE) received the BIT degree (Hons.) in software engineering from Multimedia University, Malaysia, in 2002, the master's degree in software from Dongseo University, South Korea, in 2004, and the Ph.D. degree in engineering (digital media) from Soongsil University, South Korea, in 2009. She is an Associate Professor with the Department of Computing and Information Systems, School of Engineering and Technology, Sunway University. She is also a Researcher with the Research Centre for Human-Machine Collaboration (HUMAC). Her current research interests include ultrasound imaging, the time series of FOREX data, technology modules for seniors, and augmented reality technology. She is currently a Professional Technologist of MBOT and the Malaysia Director of the International Association for Convergence Science & Technology (IACST).



CHYANNA WEE received the degree (Hons.) in computer networking and security from Sunway University, where she is currently pursuing the master's degree in computer science. She is currently affiliated with the Research Centre for Human-Machine Collaboration (HUMAC). Her research interests include human–computer interaction, with a focus on perceptual interfaces (virtual reality and haptics), human-centered artificial interfaces, and usable programming.

CHING CHIUAN YEN is the Dean's Chair with the Division of Industrial Design, the Co-Director of Keio-NUS CUTE Center, and the Deputy Director of the Centre for Additive Manufacturing, National University of Singapore. He is a keen supporter of transdisciplinary design and research collaborations and has received more than SDG 30 million grants as a principal investigator (PI), a Co-PI, or a collaborator from government agencies and industries. He teaches human-centered design to design students. His research interests include interaction design, particularly sensory interactions and simulations.

• • •