Weight Perception Analysis using Pseudo-Haptic Feedback based on Physical Work Evaluation

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10 **Abstract**

11 Since kinesthetic cues are not present in virtual environments, users have difficulty feeling the
12 heaviness of virtual objects. To address this issue, pseudo-haptic approaches have been proposed to
13 illusorily induce the weight of virtual objects through the user's visual sensory system. In this paper,
14 we used two methods to induce the impression of virtual objects' heaviness. One relies on the direct
15 modification of the control-display (C/D) ratio when lifting objects, and the other depends on
16 controlling this ratio based on a velocity restriction. We innovatively measured each approach's
17 efficiency by analyzing physical work as an objective metric. In addition, we used Borg CR10 to
18 measure users' hand fatigue during the experimental phases. Our findings are discussed in terms of
19 individual lifting behavior in different pseudo-haptic methods. Furthermore, different virtual weight-
20 lifting behaviors were compared to the same real-world weight-lifting behaviors. According to our
21 results, the direct control of the C/D ratio method provides VR users with a more accurate weight
22 perception than the velocity restriction one. Furthermore, with this first method, users' lifting behavior
23 was closer to the behavior when lifting real objects.

24 Keywords: Virtual reality, Pseudo-haptic feedback, Multi-sensory integration, Weight perception,
25 Illusion, Individual-lifting behavior

1   Introduction

One of the significant challenges and research topics in virtual reality (VR) is to enhance the user experience so that users can feel as if they were in a real environment. While many studies have been conducted on this topic (Nguyen & Bednarz, 2020), open problems still remain regarding creating a rich and believable virtual environment (VE). One crucial modality is haptics, which is typically delivered to VR users through haptic feedback (Burdea, 1996). It allows users to select and manipulate objects in a more realistic manner (Ramsamy, et al., 2006). Consequently, it gives users a greater sense of presence (Gibbs, et al., 2022).

By grasping and manipulating an object, humans obtain certain information about it, such as its size, shape, and texture. This information is mainly provided by the vision and haptic senses (Ernst & Banks, 2002). Since visual perception occurs exclusively through the retina, visual information is unimodal. Alternatively, haptic perception involves several sources of information, including force feedback, proprioceptive feedback, and tactile feedback (Aman, et al., 2010). A single, unified haptic perception is thus obtained by combining such information (Sciutti, et al., 2010) (Burdea, 1996) (Burdea, 1999). Humans can recognize weight, inertia, and object hardness based on force feedback, while proprioceptive feedback provides information about body position, and tactile feedback is used to distinguish object surface (Burdea, 1999) (De Tinguy, et al., 2018).

Regarding users' interactions in VEs, visual feedback is usually fully supplied through the devices used (VR head-mounted display (HMD), mixed reality glasses, etc.). However, regarding other senses, the virtual environment does not provide this feedback, or elements from the real world can interfere (e.g., ambient noise vs. displayed sound in the HMD). Therefore, a conflict happens between visual information and other sources of sensory information, especially haptic sensors. In addition, the mismatch between the real and virtual environment leads to difficulty in enabling true haptic feedback (Rietzler, et al., 2018), particularly concerning the kinesthetic feedback, which relies on the physical direction of the force and therefore is difficult to compensate for (Rietzler, et al., 2018). However, about other aspects of the haptic sense, some methods, such as vibration stimuli techniques, have been introduced in the literature and they succeeded in providing tactile feedback sensation. Regarding force feedback, when users perceive an object through their visual sensory system and want to interact with it and move it, they are usually unable to truly grasp or lift it since the object is not real. Thus, they do not correctly perceive its weight. Because of this, in the real world, users cannot perceive their own relative tiredness of lifting such objects in their muscles.

However, perceiving the heaviness of objects cannot be limited only to our haptic sensory system; it also relies on our visual sensory system (Runeson & Frykholm, 1981). Therefore, in VEs, approaches such as the "pseudo-haptic feedback" technique have been developed to benefit from the visual sensory system when evaluating virtual objects heaviness. Such approaches propose to induce heaviness by hacking human perception through visual stimuli, playing on the borders of human perception and sensory illusions. With this illusory method, users can enjoy a haptic experience induced only by visual stimuli only (Lécuyer, 2009). Previous studies have shown that a VR user's experience is improved by using this technique, making it feel closer to a real-world interaction (Yu & Bowman, 2020) (Ujitoko & Ban, 2021).
Even though this method is one of the most effective options for replacing costly and expensive haptic devices, it still requires significant improvement. One of the main challenges of this method is measuring the sense of presence, particularly when subjects are dealing with heavy objects. One particular issue is the need to evaluate and measure the sense of presence when using it, especially when subjects deal with heavy objects. Many studies (Rietzler, et al., 2018), (Maehigashi, et al., 2021),

71 (Lécuyer, et al., 2004), (Zenner & Krüger, 2017) focused on virtually induced weights of objects to
72 VR participants focused on the use of subjective measurements to evaluate their pseudo-haptic
73 methods. One issue regarding such measures is that they depend on the subject's point of view and rely
74 only on intuition. However, few other studiesfocused on objective measurements: in particular, Samad
75 et al. (Samad, et al., 2019) used the concept of work to evaluate their model, in the context of lifting
76 light small cubes (185g). One limitation of this work is that in real environments, humans also
77 manipulate heavier objects, about at least 1 kg and up to 5 kg, in everyday life.

78   We propose and evaluate different pseudo-haptic feedback techniques, used in the context of a lifting
79 task in VR. We build our techniques relying on anisomorphic mapping, i.e., based on a difference
80 between the motions performed by users in the real environment and those they observe in the VE.
81 With these techniques, we allow users to lift "heavy" virtual objects. We propose two different pseudo-
82 haptic feedback models. One is based on applying a determined control-distance (C/D) ratio to the
83 object's displacement, and the other modifies the motion by limiting the maximum displacement speed
84 of the object, both models being linked to the same (C/D) ratio concept. Finally, we simulate different
85 virtual weights with both techniques in our experiments. Furthermore, we consider a control condition
86 (lifting real objects) in which participants raise real objects with actual weights. Finally, we also
87 provide the participants with a lifting technique without haptic or pseudo-haptic feedback as a control
88 condition (isomorphic movements).

89 We propose a mechanism that can diminish visuo-kinesthetic conflicts in VR during lifting tasks and
90 convey the concept of weight to VR users. Additionally, we offer to evaluate such an approach by
91 measuring both the subjective effects of this mechanism (measuring fatigue) and the objective effects
92 (physical activity, in terms of work) of VR users. As a result, this study makes the following
93 contributions:

94 • Designing different manipulation conditions in VR, based on the physical work of
95   expected/targeted objects' weight, to be induced in VR on virtual objects.

96 • Studying the effect of pseudo-haptic feedback on VR users' lifting behaviors and comparing
97   them to lifting real objects.
98 • Extending previous work results from lighter objects (less than 0.5 kg) to heavier objects (1, 2,
99   and 5 kg).
100 • Formalizing the notion of physical work to study different individual behaviors in virtual and
101   real environments by using it as an objective measure of the sense of presence.
102 • Evaluating relationships regarding the sense of presence between objective (physical work) and
103   subjective measurements (sensation of fatigue).

104 **2   Related Work**

105 **2.1   Manipulation interaction techniques**

106 Bowman et al. (Bowman & Hodges, 1999) classified interactions into three categories: navigation,
107 selection, and manipulation. A taxonomy was developed for each type of VE interaction. Regarding
108 on Bowman's taxonomy about manipulation interaction techniques, the techniques are differentiated
109 based on several criteria, such as the way to attach an object to the user or the way to move the object
110 (translation and rotation). In a similar manner, Poupyrev et al. (Poupyrev, et al., 1998) (Poupyrev &
111 Ichikawa, 1999) evaluated manipulation techniques based on a variety of criteria: exocentricity (users
112 act as if they are outside the environment) or egocentricity (users act as if they are inside the

environment). Bowman et al. and Poupyrev et al. determined that the selection and manipulation of interaction techniques could be built in a similar manner and shared many criteria. The selection techniques studied by Argelaguet and Andujar (Argelaguet & Andujar, 2013) are very relevant to understanding manipulation interaction techniques, such as selection tools (e.g., hand, ray, cone) and the C/D ratio. Generally, the C/D is defined as the ratio between the input devices' translational motion and the selection tools' translational motions. The selection technique is called isomorphic when the C/D ratio is equal to 1; otherwise, it is anisomorphic - either scaled up (<1) or down (>1).

These different taxonomies for selection and manipulation techniques (Bowman & Hodges, 1999) (Bowman, et al., 2001) (Poupyrev, et al., 1998) (Poupyrev & Ichikawa, 1999) (Argelaguet & Andujar, 2013) suggest that two main criteria should be considered when designing an interaction technique. First, the manipulation support (3D hand, raycast, etc.), and second, the nature of the mapping between the real and virtual movements. It has been demonstrated that C/D ratios different than 1 can be implemented for various selection and manipulation techniques. These techniques could be either using virtual hands, as with the Go-Go technique (Poupyrev, et al., 1996), or using raycast, as with the PRISM technique (Frees, et al., 2007) and the virtual pads technique (Andujar & Argelaguet, 2007). These studies utilized different C/D ratios in order to optimize interaction (for instance in downscaling the C/D ratio to provide more precision). However, few studies have attempted to provide pseudo-haptic feedback to users using anisomorphic manipulation techniques.

2.2   Haptic and pseudo-haptic feedback

Simulating a virtual objects' weight is challenging, as no kinesthetic cues are present in such environments. Researchers have traditionally concentrated on grounded haptic devices such as the Phantom device to overcome this problem (Pacchierotti, et al., 2017), (Burdea, 1999), (Massie, et al., 1994). In spite of the advantages of these devices, such as their dynamic range and degrees of freedom (Nisar, et al., 2018), their main disadvantages are their complexity, limited workspace, and cost (Pacchierotti, et al., 2017) (Samad, et al., 2019). Regarding movable haptic devices, numerous portable and wearable haptic devices provide significant range of motion; nonetheless, these mostly concentrate on tactile feedback. Such devices have mainly been designed to deliver tactile feedback (Nisar, et al., 2018). Nonetheless, it is worth mentioning that Choi et al (Choi, et al., 2017) developed a haptic glove called Grabity, which provides touch, texture, and weight sensations (but reduces the user's natural range of motion).

Following another approach, VR researchers have developed a pseudo-haptic technique to evoke haptic perception through visual cues (Ujitoko & Ban, 2021). As a result, they can provide haptic perception without using expensive or restrictive haptic devices. It is also consistent with findings by Ernst and Banks (Ernst & Banks, 2002) who found that visual-haptic perception dominates in judging objects' shape, size, and position. For example , in the literature, Rock and Victor (Rock & Victor, 1964) asked participants to wear distorted glasses and grasp a square, while they perceived rectangles through the lenses, and their results showed the importance of vision through the users' difficulties to grasp. Due to this, the object's shape is mostly perceived by vision, known as "visual capture" (Ernst & Banks, 2002). These statements and results have prompted numerous VR research studies to employ the pseudo-haptic technique, namely to simulate different haptic sensations of virtual objects, including friction, stiffness, and texture (De Tinguy, et al., 2018) (Lécuyer, 2009), or to simulate the heaviness of objects (Jauregui, et al., 2014), (Palmerius, et al., 2014), (Yu & Bowman, 2020), (Samad, et al., 2019), (Lee, et al., 2019).

157 Pseudo-haptic feedback can be provided by manipulating the C/D ratio (Poupyrev, et al., 1996)
158 (Argelaguet & Andujar, 2013). To induce friction, Lécuyer et al. designed a coupling between slowing
159 down the velocity of the object's movement and incrementing the reaction force coming from the
160 device, creating some illusory force feedback (Lécuyer, et al., 2000). Other studies (Dominjon, et al.,
161 2005), (Nakakoji, et al., 2011), (Nakakoji, et al., 2010) designed experiments to induce the weight of
162 the object using the C/D ratio approach. While these experiments were conducted in a simple 2D
163 environment, the comparison with VE interactions with virtual objects is hard to perform. Nonetheless,
164 these studies were able to demonstrate that the C/D ratio method is effective.

165 Recent studies on weight perception in VR environments using pseudo-haptic feedback have
166 demonstrated that the pseudo-haptic method had an impact on increasing the sense of presence (Samad,
167 et al., 2019), (Rietzler, et al., 2018). A close connection between this illusionary approach and a sense
168 of presence resulted in a narrow line between increasing or eliminating the feeling of presence during
169 the VR experience. Rosa et al. (Rosa, et al., 2015) designed experiments to produce illusory weight
170 and temperature by influencing vibrational perception with visual signals like size and speed. In light
171 of their findings, Based on their findings, it can be stated that if the visual stimulus shows the gaining
172 of the weight of the virtual object, and at the same time, the tactile feedback has low intensity, the
173 illusory weight is not only intangible but also destructive to the sense of presence. It should be noted
174 that they did not quantify the relationship between visual and vibrotactile stimuli and perception of
175 weight in their experiment.

176 To conclude, according to the literature, it would be helpful to design and evaluate an isomorphic
177 manipulation technique to improve the user experience in VR without compromising the sense of
178 presence. In addition, in our study, we propose to link anisomorphic interaction techniques to the
179 importance of physics when lifting objects. Indeed, variations in the C/D ratio applied to lifted objects
180 can be linked to variations in the lifted weight.

181 **3   Materials and methods**

182 **3.1   Overview**

183 First, we propose an approach based on physics to compute pseudo-haptic feedback in a virtual reality
184 environment while performing a lifting task. Second, we evaluate the responses of VR users to this
185 feedback through an experiment. Finally, we use both objective and subjective measures to determine
186 the effect of this feedback on the effort performed by the users and their perception of this effort.

187 Relying on our physical model, we developed and implemented two anisomorphic pseudo-haptic
188 manipulation techniques. We also implemented an isomorphic manipulation technique without any
189 feedback regarding the lifting task and object weights. Lastly, we also asked our VR users to lift real
190 objects (with their real expected weight) within the virtual environment, thus providing real haptic
191 feedback, as a baseline in terms of effort. Accordingly, we developed a repeated-measure experiment
192 in which participants were required to vertically move a water water carrier –that we called it in the
193 experiment water bottle- with different masses under the four conditions described above.

194 **3.2   Our methods for pseudo-haptic feedback: from a physics model to anisomorphic**
195 **manipulations**

196 We propose an approach based on physics to produce pseudo-haptic feedback, in which the sole
197 opposition force to a vertically lifted object is its weight, when friction is ignored. Thus, the user must

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198 produce at least a force equivalent to the weight of the lifted object, but in the opposite direction.
199 Traditional VR setups, however, do not provide real props that users can use to interact with virtual
200 objects. As a result, users only need to compensate for the weight of a VR controller during such a
201 lifting operation, in contrast to the actual weight of the virtual object being viewed. Therefore, the
202 relationship between the force exerted by the user to lift the VR controller and the force expected based
203 on the weight of the virtual object viewed can be expressed as a ratio function called *k(m)*:

204
$$(EQ\ 1):\ k(m) = \frac{\overrightarrow{||Weight_{controller}||}}{\overrightarrow{||Weight_{object}||}} = \frac{mass_{controller}}{m}$$

205 Where m is the mass of the object. Then, we propose to use this ratio function to provide pseudo-haptic
206 feedback; it is converted into either a ratio of work (EQ 2) or a ratio of power (EQ 3) as follows:

207
$$(EQ\ 2):\ W = \overrightarrow{||F||} * d * \cos(\theta) = \overrightarrow{||F||} * d, \quad when\ \theta = 0$$

208
$$(EQ\ 3):\ P_{instantaneous} = \overrightarrow{||F||} * v * \cos(\theta) = \overrightarrow{||F||} * v, \quad when\ \theta = 0$$

209 In this equation, *d* is the displacement distance, *v* is the motion velocity, and *F* is the force applied. In
210 addition, we propose to use (EQ 2) to provide pseudo-haptic feedback in a distance-based approach
211 and (EQ 3) in a velocity-based approach. In our case, $\theta = 0$ as the movement is on the vertical axis.

212 **3.2.1 Distance-based approach: our "direct-weight" technique**
213 From (EQ1), (EQ2) transforms to the following:

214
$$\frac{Wcontroller}{WObject} = \frac{\overrightarrow{||Weight_{controller}||} * d_{controller}}{\overrightarrow{||Weight_{object}||} * d_{object}} = k(m) * \frac{d_{controller}}{d_{object}}$$

215 Furthermore, the condition of feedback that fully compensates for the difference in mass between the
216 object and the controller implies a ratio of work equal to 1:

217
$$\frac{Wcontroller}{WObject} = 1 \quad \Leftrightarrow \quad k(m) * \frac{d_{controller}}{d_{object}} = 1$$

218
$$\Leftrightarrow d_{object} = k(m) * d_{controller} \quad \Leftrightarrow \quad d_{object} = \frac{massController}{m} * d_{controller}$$

219 To allow ranges of masses for our virtual objects that can be easily more than ten times the mass of
220 the VR controller, a constant *c* can be added in the previous equation as follows:

221
$$(EQ\ 4):\ d_{object} = (\frac{massController}{m} + c) * d_{controller}$$

222 This constant also limits the ratio between the two distances since the mass ratio tends to zero as m
223 increases. Through such a limit, pseudo-haptic feedback is prevented from being applied when it would
224 introduce such an excessive difference between real and viewed displacements. This limitation would

225 cause the VR user to lose the feeling of presence. Additionally, it determines the minimum mass for
226 obtaining some pseudo-haptic feedback, that is, the mass for which the ratio applied is 1, as shown
227 below:

228 $$(EQ\ 5): \frac{d_{object}}{d_{controller}} = 1 \quad \Leftrightarrow \quad \frac{massController}{m_{min}} + c = 1 \quad \Leftrightarrow \quad m_{min} = \frac{massController}{1-c}$$

229 Lastly, we used the relationship defined in (EQ 4) between distances to generate pseudo-haptic
230 feedback in VR based on the masses of the virtual object and the controller. In VR, the object is scaled
231 down compared to the distance traveled by the controller when using a C/D ratio greater than 1. In this
232 paper, this pseudo-haptic technique is referred to as **the direct-weight method** (direct modification of
233 C/D ratio, related to weight ratio), which is based on distances.

3.2.2 Velocity-based approach: our "speed-control" technique

235 From (EQ1), (EQ3) transforms to the following:

236 $$\frac{P_{instantaneous_{controller}}}{P_{instantaneous_{object}}} = \frac{||\overrightarrow{Weightcontroller}|| * v_{controller}}{||\overrightarrow{WeightObject}|| * v_{object}} = k(m) * \frac{v_{controller}}{v_{object}}$$

237 Further, conditions of feedback that fully compensates for the difference of masses between the object
238 and controller mean a ratio of *power* equal to 1:

239 $$\frac{P_{instantaneous_{controller}}}{P_{instantaneous_{object}}} = 1 \quad \Leftrightarrow \quad k(m) * \frac{v_{controller}}{v_{object}} = 1$$

240 $$v_{object} = k(m) * v_{controller} \quad \Leftrightarrow \quad v_{object} = \frac{massController}{m} * v_{controller}$$

241 For the same reason as in Section 3.2.1, a constant c is used here to allow a greater range of mass
242 values for the mass m:

243 $$(EQ\ 6): v_{object} = \left(\frac{massController}{m} + c\right) * v_{controller}$$

244 As a result, the following algorithm is applied for each determined mass m:

245 $$(EQ\ 7A): if\ V_{controller} < V_{max_{object}},\ then\ v_{object} = v_{controller}$$
246 $$(EQ\ 7B): else\ v_{object} = V_{max_{object}}/v_{controller}$$

247 Finally, we used the relation defined in (EQ 6), (EQ 7A), and (EQ 7B) between velocities to describe
248 some pseudo-haptic feedback in VR depending on the mass of the virtual object and the controller; it
249 consists of applying a C/D ratio higher than 1, defined by the opposite of $(\frac{massController}{m} + c)$ as in
250 Section 3.2.1, but this time only when the velocity of the real motion is above a determined maximum
251 speed. In this paper, we called this pseudo-haptic technique, based on velocity restriction, **the speed-**
252 **control technique** (modification of C/D ratio related to weights ratio, limiting to a maximum speed
253 related to object mass).

254 **3.3   Stimuli creation**

255 **3.3.1 Virtual objects, real objects, and VR controller**

256 In our experiment, we asked users to lift virtual water bottles under three conditions and real water
257 bottles in one control condition (a real-world condition with the real weight, but still in VR, to prevent
258 external differences between experimental conditions). This choice of water bottle was made because
259 of its practicality to have multiple and identical real objects in terms of shape, but with possible
260 different masses. In addition, it was easy to track such an object, with a HTC Vive tracker fixed on it.
261 Moreover, water bottle grips can be easily grabbed by users, even when immersed in VR. Figures 1-A
262 and B show a real and virtual bottle respectively, with their tracker attached. Regarding the VR
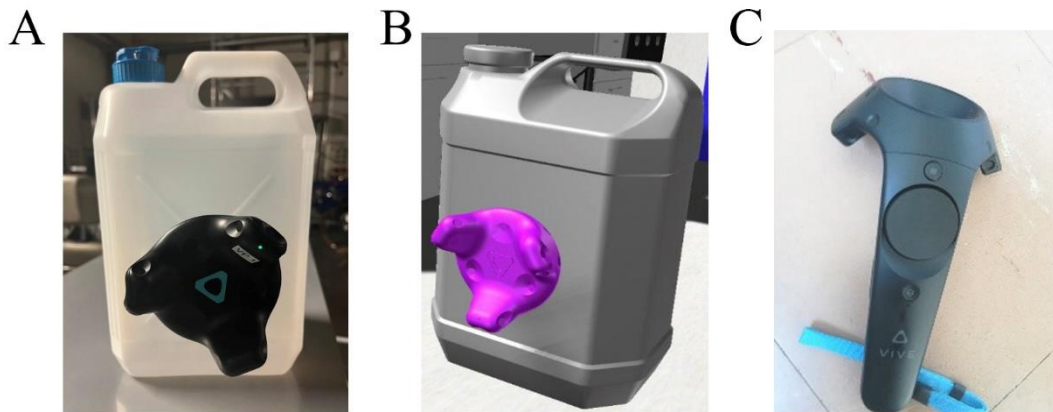263 controller, an HTC Vive controller with a mass of 308 g was used, as shown in Figure 1-C.

264

265   **Figure 1.** Real bottle (A) and virtual bottle (B) representations in our experiment, and (C) their
266   tracker, the HTC Vive VR controller. Mass of 308 g, lifted by users during their task in VR.

267

268 **3.3.2 Incongruous lifting conditions: techniques with pseudo-haptic feedback**

269 Our two techniques with pseudo-haptic feedback (direct-weight and speed-control), both anisomorphic
270 manipulations, could also be called incongruous conditions. Indeed, they were both designed to induce
271 a conflict between the visual feedback of the motion, represented in VR by the bottle displacement,
272 and the actual arm motion, shown in VR by the controller displacement. Figure 2 shows such a
273 difference regarding the positions between the two elements during the lifting task. In these conditions,
274 VR users could observe the bottle moving precisely in the same direction and orientation that they
275 moved their hand, but with a difference in speed or distance concerning their natural velocity/position.
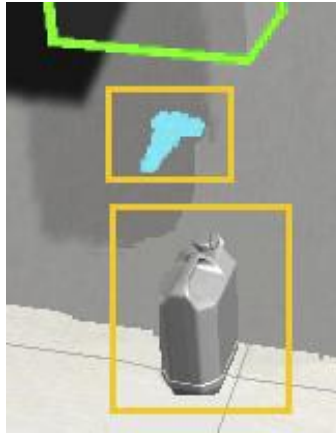
276

277   Figure 2. Incongruous conditions: visual discrepancy caused by differences in position/velocity
278   between the controller and the object, highlighted in yellow here.

279   *C/D ratio, visual discrepancy, and objects masses*

280   First, as explained by (EQ 5) and as used in our two techniques through (EQ 4) and (EQ 6), a constant
281   *c* had to be defined concerning the chosen experimental conditions and not with the physics model
282   itself. In our experiment, we set *c* to a value of 0.5 for the following reasons and implications:

283   i) The constant of 0.5 makes the functions d(m) and v(m) in (EQ 4) and (EQ 6) tend towards 0.5.
284   This avoids distortions in the presence sensation caused by a visual discrepancy between real and
285   virtual movements.

286   ii) Regarding objects' masses, a value of 0.5 gives a minimum mass (m_{min}) of 0.616 g according to (EQ
287   5) for a 0.308 g VR controller. Thus, it would mean that pseudo-haptic feedback would start for masses
288   above 0.616 g, with ratios decreasing then from 1 to 0.5. This would allow for interesting intermediate
289   points at 1 and 2 kg and a 5 kg point that would be already close to the 0.5 limits. As a result, the
290   masses used in our experiment were fixed to 0.616, 1, 2, and 5 kg. In addition, these values would
291   allow a significant evaluation of our pseudo-haptic techniques with masses that are already well beyond
292   the 0.308 gr of the VR controller and close to the masses of many everyday objects.

293

294   *Direct-weight condition*

295   Regarding this first incongruous condition, apart from the constant *c* and considered objects' masses,
296   no additional parameter was required to be set for our experiment.

297   *Speed-control Condition*

298   For this second condition, in addition to the constant *c* and masses of the objects, the $V_{max_{object}}$
299   parameter had to be set for our experiment according to (EQ 7A-7B), determined for a lifting task in
300   VR without any extra mass. If this value could be measured empirically with some users in a pre-
301   experiment, it could also be estimated theoretically, based on Fitts' Law studies and notably K. T.
302   Hagadorn's (Hagadorn, 2004). The originality of these values explains the Fitts' law applicability for
303   human movement in three dimensions, in the manipulation technique of moving objects, instead of
304   being related to 2D Fitts' law with selection or pointing tasks (Gillan, et al., 1990) (MacKenzie, 1993).

305   Additionally, this study also found that different Fitts' laws could exist depending on the mass of the
306   manipulated object. Therefore, we used the coefficients given in this study for objects of less than
307   450g, i.e., a = 0.2138 and b = 0.473, in their formula, as follows:

308                      $(\text{EQ 8}): MT = a + Log2(2 * d/w) * b$

309   where *MT* is the task completion time, *d* the manipulation distance, and *w* the size of the target to reach.

310   The distance in our experiment was 1 m, and the target size was 0.4 m, yielding an MT of 1.32 s, which
311   implies an average speed of 0.75 m/s. From this average speed, we then needed to compute the
312   maximum speed during a vertical lifting task. For that, we captured a lifting task motion and computed
313   the instantaneous speed, as shown in Figure 3. Due to strength and other individual variability, the
314   maximum speed value cannot be directly considered as our experiment's value. However, the shape of
315   the velocity profile for this type of task can be maintained and analyzed (the same across multiple
316   users). Such motion can be decomposed in terms of velocity phases into acceleration and deceleration,
317   both representing half of the movement. From that, the maximum speed can be computed from the
318   average, by representing this velocity profile with two affine functions, f1 (ascending) and f2
319   (decreasing), as follows:

320
$$(\text{EQ 9}): V_{average} = \frac{1}{2} * \int_{0}^{0.66} f1(t) + \frac{1}{2} * \int_{0.66}^{1.33} f2(t)$$

321
$$\Leftrightarrow V_{average} = \frac{1}{2} * \left(\frac{0 + v_{max}}{2}\right) + \frac{1}{2} * \left(\frac{v_{max} + 0}{2}\right) \Leftrightarrow V_{average} = \frac{1}{2} * v_{max} \Leftrightarrow V_{max} = 2 * v_{average}$$

322   Thus, for our experiment, we found and set the **maximum speed** to **1.5 m/s** (0.75×2) for masses below
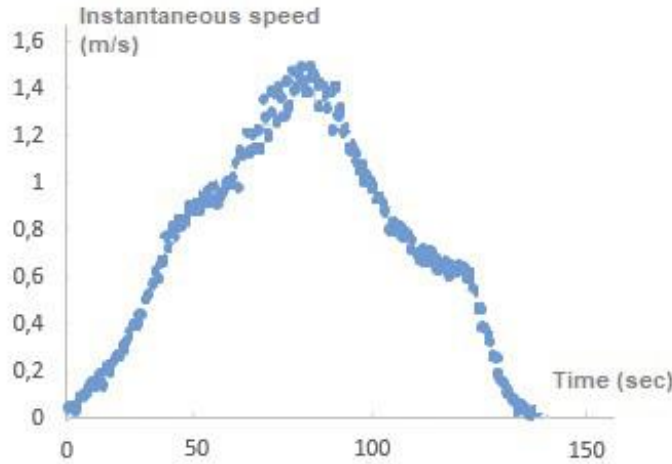323   or equal to 0.616 g, and for higher masses, we computed it from (EQ 6), based on this value.

325   Figure 3. Hand motion instantaneous speed across time for a lifting task (1 m distance, no extra mass).

326   3.3.3 Congruous conditions: absence of pseudo-haptic feedback – no weight at all or real weight

327   Besides the two conditions described in the previous section, our experiment also included the
328   following two congruent conditions without visual discrepanc. When visual feedback aligned with the
329   actual hand motion, the condition named "isomorphic condition". This condition refers to "traditional"
330   virtual manipulation technique with no haptic feedback and thus the same visual input and natural

331   motions for any masses lifted and the other condition is "haptic condition," which is refer to the
332   "traditional" real manipulation technique, with full haptic feedback by lifting a real object with its
333   actual expected mass.

3.4   Apparatus

335   This study required users to stand throughout the whole experiment when lifting the objects from
336   bottom to top . However, they were permitted to rest at any time, especially between blocks of four
337   conditions. Physically, they were placed in a room facing a 46 cm high box at a distance, allowing
338   them to comfortably grasp and lift the objects placed on the box without bending. The virtual
339   environment displayed within the VR headset shared the same characteristics (room size, user's
340   position, orientation, and relative distance to the objects to lift) – see Figure 4-A.

341   A HTC Vive Pro VR headset was used for our experiment, equipped with two cameras, hand
342   controllers to manipulate virtual objects, and hand trackers to record arm movements. The HTC vive
343   pro has a1440 x 1600 pixel resolution with a 110 degree field of view.This HMD featured, an electronic
344   gyroscope, and an eye comfort setting system (IPD).

345   The hand controller provides an indication of the position of the subject's dominant hand (left or right)
346   in the real environment, allowing the rendering engine to generate a visual representation of the hand
347   in VR in all conditions that involved virtual objects to lift. Hand trackers for lifting real objects,
348   attached to the wrist of the subjects, provide locational information to the rendering engine. This
349   information is used in order to generate a model of the subject's hand and the visual feedback about the
350   position of the user's dominant hand in haptic condition. Additionally, one tracker was placed on the
351   real object to track its displacement and to display it in the virtual environment accordingly, as shown
352   in Figures 4-B and C.

353

354   Figure 4. A) Virtual environment displayed in the VR HMD. B) User's view before starting to lift the
355   bottle, grabbing the bottle (visual feedback in blue). C) View of the end of the task (bottle in green).

3.5   Participants

357   Twenty right-handed users (6 women and 14 men, ranging from 18 to 44 years with a mean age of
358   26.24±7.98 SD) participated in our experiment. All were healthy and had no neurological, muscular,
359   or cognitive disorders, with normal or corrected-to-normal vision. Users' heights ranged from 156 to
360   185 cm, with a mean height of 173.74±6.57 cm. Users from different backgrounds, either from inside
361   or outside the university, agreed to participate voluntarily without compensation.

3.6   Experimental procedure

363   We conducted two phases of our experiment: the training and the main phases. In both phases, user
364   task was to lift an object upward with a single joint arm movement, with natural self-selected speed

365 (with rotation around the shoulder and maintaining the arm entirely extended). This object was visible
366 in the environment as a water bottle and had to be placed at a defined height, represented by a green
367 window (see Figure 4).

368 The training phase was meant to introduce users to our unusual manipulation techniques, compared to
369 real-world lifting, notably for the incongruous conditions that cause conflicts between the actual hand
370 movement and the given visual feedback. It would then help users to avoid "failing" to accomplish
371 their lifting motion in terms of performance and "naturalness". In this phase, eight lifting movements
372 are performed before each manipulation interaction condition, in order to teach users how to perform
373 upward lifting in our VR setup.

374 The main phase was divided into four blocks of lifting trials, one for each manipulation condition. With
375 all our techniques, grabbing was always done through direct contact with objects, using a virtual hand
376 metaphor. Each block included 20 trials, each consisting of five repetitions of lifting objects of four
377 different masses (0.616, 1, 2, and 5 kg); see section 3.3.2 for more details. In all trials, users performed
378 vertical arm motions almost exclusively at a distance of 1 m, starting from a similar point (46 cm from
379 the ground).The mass of the objects was never disclosed to the users. Furthermore, the virtual objects
380 displayed all had the same design, without any variation in size or color. The users were asked to
381 perform natural and self-selected-speed movements under all conditions, with congruent conditions
382 more favourable because of the absence of visual discrepancy, and incongruous conditions more
383 challenging due to pseudo-haptic feedback.

384 We used a repeated-measure design to increase the number of measures and control differences
385 between users, as they are usually not equal in terms of strength A Latin-square order was used between
386 participants, with the order of blocks within each block, i.e., between masses of objects, randomized
387 for each participant. Thus, we used 20 of the 24 possible orders across our four manipulation
388 conditions.

389 **3.7 Data gathering and measures**

390 **3.7.1 Kinematic features and physical work**

391 In order to collect kinematic data on hand position and velocity, we tracked the VR hand controller in
392 non-haptic conditions and the VR hand tracker in haptic conditions. Next, we applied a low-pass filter
393 (Butterworth) with a cut-off frequency of 6 Hz to the velocity data.

394 From this data, we extracted the following parameters: 1) movement duration (MD): the time between
395 lifting onset and termination; and 2) displacement (disp): the whole vertical displacement of the user's
396 real hand when lifting the bottle. In addition, we computed the physical work done by the users to
397 perform the lifting task using the following formula:

398

399 $$(EQ\ 10): W = m_{controller} G h + m_{controller} * \int_{s}^{e} \alpha\, dx$$

400 This formula comes from the general principle of physics about forces, as expressed by the following:

401 $$(EQ\ 11): \sum_{1=1}^{n} F = m_{controller} * a$$

402   Where m is the controller's mass, and a is the acceleration caused by users' movement. Then, still in
403   physics, work can be defined by the following equation at each instant: (EQ 12): $dw = F.dx$, where
404   dw is the element of work at each time, F is the force obtained from (EQ 11), and dx is the
405   displacement. In this study, two main forces were applied to the object, as shown in Figure 5. The first
406   one is the users' hand force (F) applied to lift the object upward, and the second is gravity (P).
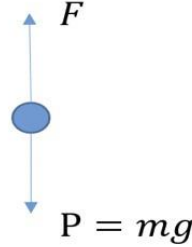
407

408   Figure 5. Forces applied to an object during the lifting task.

409   F is the force applied by the participants' hand on the object. Therefore, according to the physic base
410   rules, we obtain

411   (EQ 13): $\vec{F} + \vec{P} = m\vec{a}$ $\Leftrightarrow$ $\vec{F} - \vec{P} = m\,\vec{a}$ Since *F and P are not in the same direction*

412   Then, using the formula $P = mg$, we can obtain the following equation along the vertical axis:

413   (EQ 14): $F = mg + ma$

414   Using (EQ 12), we can express the work of the force applied by the hand of the users between the
415   starting point, called (s) here, and the end point, called (e) here, as follows:

416   (EQ 15): $W = \int_{S}^{e} dw = \int_{S}^{e} F.dx$ $\Leftrightarrow$ $W = \int_{S}^{e} mg + m\,a$ $\Leftrightarrow$ $W = \int_{S}^{e} mg\,dx + \int_{S}^{e} ma\,dx$

417   Finally, from (EQ 15), (EQ 10) is obtained and used to compute the user's hand work when lifting.

418   **3.7.2 Perceived fatigue**

419   We used the Borg CR10 (Borg, 1990) questionnaire to evaluate the effect of pseudo-haptic feedback.
420   A modified version of it was used to compare how users perceived tiredness after different object lifting
421   conditions. This provides a self-report measure of the perceived effort, relying on a 10-point self-report
422   inventory with defined levels. Users were asked to give each manipulation condition a score according
423   to its difficulty, allowing for the measure of their hand fatigue.

424   **3.8   Hypotheses**

425   As part of this study, we examined how pseudo-haptic feedback can enhance perception of an object's
426   weight in VR. We are also interested in understanding how we can create artificial tiredness in users'
427   arms in a manner similar to the tiredness produced by lifting real objects. Additionally, we sought to
428   determine which pseudo-haptic techniques would enhance users' perception of weight in VR in
429   comparison with real lifting behaviors. A further objective was to understand the inter-subject
430   variability caused by different simulations of weight perception models based on individual lifting
431   behaviors. Therefore, the following hypotheses were investigated in this experiment:

- How does modifying the C/D ratio affect the physical work obtained from distance control and speed control? In order to replicate the haptic experience (real bottle lifting) in VR, we sought to determine which pseudo-haptic models could accomplish this.
- What are the effects of different proposed models on the fatigue level experienced by VR users?
- How do individuals perceive different weight lifting conditions in terms of perception (non-haptic) and execution (haptic)?

4   Results

4.1   Statistical Analysis

Statistical analyses were performed with SPSS software (version 26, IBM SPSS) on all variables. A two-way analysis of variance (ANOVA) was performed on different variables ($\alpha = 0.05$). The independent variables were "condition" (4 levels; haptic, isomorphic, speed-control, direct-weight) and "weight" (4 levels; 0.616, 1, 2, 5 in kg). In addition, for each condition, a one-way ANOVA test was separately applied to see the effect of real and virtual weight (independent variable) on physical work (dependent variable). To control false discovery rate, we used the Benjamini–Hochberg (B-H) model at a level of 0.05 (Benjamini & Hochberg, 1995). In all our tables, the symbol * indicates a p-value < 0.05, ** a p-value < 0.01, and *** a p-value < 0.001.

4.2   Quantitative Analysis

After the training session, all users could perform lifting movement correctly. Table 1 shows the mean and standard deviation of kinematic (movement duration MD, arm displacement Disp) and kinetic (physical work) features. It should be highlighted that Disp for congruous conditions was approximately 1 meter, but that, for incongruous conditions, it increased in relation with the object mass (reaching more than 2 meters for 5 kg in the direct-weight condition; Table 1-displacement).

A significant change in MD was observed when subjects were asked to lift bottles of different weights (F (3, 1598) =10.578, $p < 0.0001$, $\eta_p^2 = 0.019$). Different conditions also influenced MD (F(3, 1598) = 71.208, $p < 0.0001$, $\eta_p^2 = 0.118$). Furthermore, the interaction between conditions and weight significantly affected MD (F(9,1589) = 7.317, $p < 0.0001$, $\eta_p^2 = 0.04$). According to the Tukey post hoc analysis, MD significantly changed in relation to all multiple comparison conditions ($p < 0.0001$). A pair-wise comparison of B-H results did not reveal any false p-values. As a result of posthoc analysis, MD values for 0.616 and 1 kg were not statistically different ($p > 0.05$), as well as for 2 and 5 kg ($p > 0.05$), while MD values for all other comparisons were notably different ($p < 0.05$). In addition, the results of the B-H test confirm those obtained from the posthoc analysis.

Conditions significantly affected Disp (F(3,1598) = 94.224, $p < 0.0001$, $\boldsymbol{\eta_p^2 = 0.15}$) as well as weight (F(3,1598) = 44.998, $p < 0.0001$, $\boldsymbol{\eta_p^2 = 0.078}$). The interaction effect of condition and weight on disp was also significant (F(9,1598) = 36.369, $p < 0.0001$, $\boldsymbol{\eta_p^2 = 0.170}$). Multiple-comparison Tukey post hoc analysis showed that there is a significant effect of different weights on Disp ($p < 0.0001$), except for 0.616 and 1 kg ($p > 0.05$). However, Tukey post hoc for all multiple comparisons of different

471 conditions showed significant discrepancy between different conditions (p < 0.0001), except for speed-
472 control and haptic (p > 0.05). B-H method confirmed all post-hoc results (no false discovery).

473 Physical work significantly changed by different weights (F (3, 1598) = 22.593, p < 0.0001, $\boldsymbol{\eta_p^2} =$
474 $\boldsymbol{0.041}$) as well as conditions (F (3, 1598) =118.036, p < 0.0001, $\boldsymbol{\eta_p^2 = 0.181}$). The interaction
475 between condition and weight for work was also significant (F (9, 1598) =10.578, p < 0.0001, $\boldsymbol{\eta_p^2 =}$
476 $\boldsymbol{0.09}$). Tukey's HSD test for multiple comparison found that the mean value of work was significantly
477 different between haptic and isomorphic (p < 0.0001, 95% C.I. = 41.65,58.00) as well as between
478 haptic and direct-weight (p < 0.0001, 95% C.I. = 39.2055.26) and between haptic and speed-control (p
479 < 0.0001, 95% C.I. = 40.08,56.28). Meanwhile, the mean value of work significantly changed between
480 different weights. Post hoc HSD analysis demonstrated that there is a significant difference between
481 0.616 and 2 kg (p < 0.0001, 95% C.I. = -18.84,-2.66), as well as between 0.616 and 5 kg (p < 0.0001,
482 95% C.I. = -30.65,-14.49), 1 and 2 kg (p = 0.026, 95% C.I. = -16.93,-0.75), 1 and 5 kg (p < 0.0001,
483 95% C.I. = -28.74,-12.57), and 2 and 5 kg (p = 0.01, 95% C.I. = -19.91,-3.72). The B-H method also
484 confirmed the Tukey post hoc results and did not detect any false p-values for multiple comparison of
485 conditions or weights.

486 Table 1. Kinematics features and physical work of weight lifting movement with different masses in
487 VR.

	Masses (kg)	Haptic	Isomorphic	Speed-control	Direct-weight
Disp (m)	0.616	1.27±0.05	1.01±0.30	1.17±0.29	1.00±0.76
	1	1.39±0.94	0.94±0.06	1.27±0.40	1.23±0.12
	2	1.22±0.91	0.96±0.19	1.54±0.77	1.79±0.32
	5	1.16±0.54	0.96±0.12	1.56±0.61	2.47±0.68
MD (s)	0.616	4.6±0.6	1.3±0.56	1.7±0.5	1.5±0.68
	1	3.6±0.46	1.3±0.51	1.8±0.39	2.3±0.12
	2	4.5±0.59	1.2±0.51	2.3±0.99	3.7±0.18
	5	4.2±0.55	1.2±0.51	2.4±0.79	5.2±0.37
Work (J)	0.616	21.88±39.93	4.94±2.10	5.30±1.65	4.62±0.62
	1	28.91±51.86	4.51±0.63	5.75±2.26	5.43±0.80
	2	61.72±101.57	4.64±1.07	7.01±3.96	7.99±1.78
	5	106.51±135.02	4.63±0.93	7.02±3.16	11.16±3.00

488

4.2.1 Haptic Condition

490 Figure 6 illustrates the mean value and standard deviation of the physical work performed by 20
491 subjects as they lifted real bottles in an upward movement with a real mass. Mean ± SD of physical
492 work for this condition related to different weights released the tight connection between mass and
493 physical work values (see Table 1-physical work, column Haptic). Because users were lifting real
494 bottles here, the value of the physical work was significantly greater than that for the other conditions
495 (see Table 1-physical work column Haptic). Results of one-way ANOVA for different weights
496 (independent variable, four levels) in this condition on work values (dependent variable) showed that
497 (F (3, 390) =18.041, p < 0.0001). Tukey post hoc revealed significant differences for all paired
498 comparisons (p < 0.05), except between weights of 0.616 and 1 kg (p > 0.05) and 1 and 2 kg (p > 0.05).
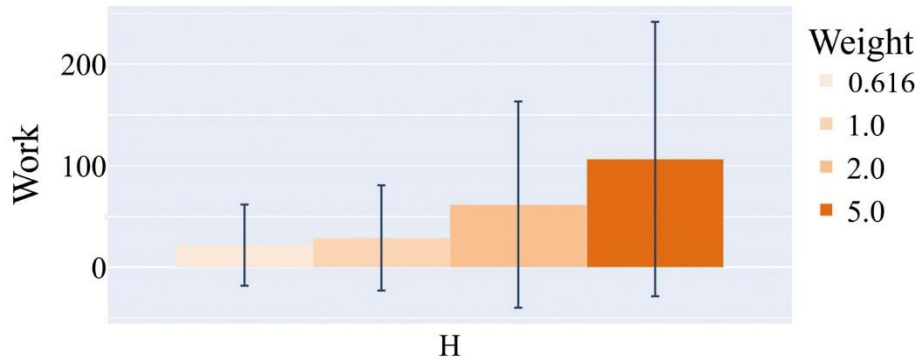499 B-H results confirm post hoc results.

Figure 6. Mean ±SD of work for 20 users for the reference (Haptic) condition.

4.2.2 Isomorphic condition

Figure 7-I shows the result of mean ± SD of work for 20 users in the isomorphic condition. The mean values of the physical work related to this condition for different masses are the same (see Table 1- physical work, column Isomorphic). As a result of the group analysis (one-way ANOVA) showed that, that the related physical activity did not vary significantly with different weights 0.616, 1, 2, and 5 kg as the virtual object's mass increased $F(3, 391) = 1.923$, $p = 0.126$).

4.2.3 Speed-Control condition

In this condition, the subjects saw a visual conflict when their maximum velocity reached the threshold. For example, when subjects' performance corresponded to lifting lighter virtual objects (0.616 or 1 kg) using the controller, they could easily adjust their velocity to achieve the authorized threshold. However, during the lifting of heavier objects (2 or 5 kg), the velocity of the virtual bottles usually was not aligned to the actual hand movement. Figure (7-S) illustrates the mean and standard deviation for physical work performed by twenty users under a speed control condition. As part of the speed control condition, a one-way ANOVA was conducted in order to compare the effects of virtual weight on work. ANOVA analysis confirms that virtual weights significantly affect physical activity ($F (3, 396) = 9.204$, $p < 0.0001$). The Tukey post hoc analysis revealed a significant difference in work values between 0.616 and 2 kg (p 0.0001, 95% confidence interval = -2.76, -0.65), 0.616 and 5 kg (p 0.0001, 95% confidence interval = -2.75,-0.66)), 1 and 2 kg ($p = 0.012$, 95% confidence interval = -2.31, -0.19), and 1 and 5 kg ($p = 0.011$, 95% confidence interval = -2.32, 0.21). Based on the B-H results, no significant differences were observed between the work values associated with weights of 0.616 and 1 kg and 2 and 5 kg (p-value > 0.05).

4.2.4 Direct-weight condition

As Table 1- physical work (column direct-weight) shows, by increasing the weight of the virtual object, subjects' physical work also increased (see Figure 7-D). In addition, the results of one-way ANOVA revealed that virtual weight has a significant effect on physical work ($F (3, 421) = 282.456$, $p < 0.0001$). Tukey post hoc analysis showed that different virtual weights significantly affect physical work (p < 0.05). B-H test results confirmed the Tukey post hoc results.

529   Table 2. ANOVA results for kinematic feature physical work between different masses for each
530   condition.

	Conditions	Masses (Kg)	Physical Work one way -ANOVA(p-value)	Significance
Congruous Conditions	Haptic	0.616	5.537e-11cf0.05***	<0.001
		1		
		2		
		5		
	Isomorphic	0.616	0.1252 > 0.05	0.125
		1		
		2		
		5		
Incongruous Condition	Speed-control	0.616	6.724e-06 < 0.05***	<0.001
		1		
		2		
		5		
	Direct-Weight	0.616	2.023e-100 < 0.05***	<0.001
		1		
		2		
		5		

531
532   Table 3 demonstrates the results of a one-tailed paired sample t-test between pair conditions with the
533   similar masses. Despite the small masses, these results suggest that the amount of physical effort users
534   expend when lifting a virtual object is significantly different from real weightlifting. This analysis
535   confirms that there is no significant difference between direct weights and isomorphics for the small
536   mass (0.616 kg) (p-value > 0.05). In a similar manner, there are no differences between speed control
537   and isomorphic conditions (p-value > 0.05). Statistical differences were evident for all masses (p-
538   value< 0.05) except for 1 kg (p-value > 0.05).
539

540   Table 3. Results of t-test analysis for physical work between different conditions and same masses
541   (D=direct-weight, H=haptic, S=speed-control, I=isomorphic).

Conditions /mass	H-I (p-value)	H-D (p-value)	H-S (p-value)	D-S (p-value)	D-I (p-value)	S-I (p-value)
0.616 kg	5.06 e-05 ***	3.67e-05 ***	7.02e-05 ***	0.0001 ***	0.1583	0.191
1 kg	9.21 e-06 ***	1.84e-05 ***	2.37e-05 ***	0.177	1.45e-16 ***	6.64e-07 ***
2 kg	2.70 e-07 ***	1.08e-06 ***	7.31e-07 ***	0.025**	5.61e-37 ***	6.94e-08 ***
5 kg	3.52 e-11 ***	3.50e-10 ***	8.24e-11 ***	3.43e-18 ***	2.61e-43 ***	5.00e-11 ***

542

543
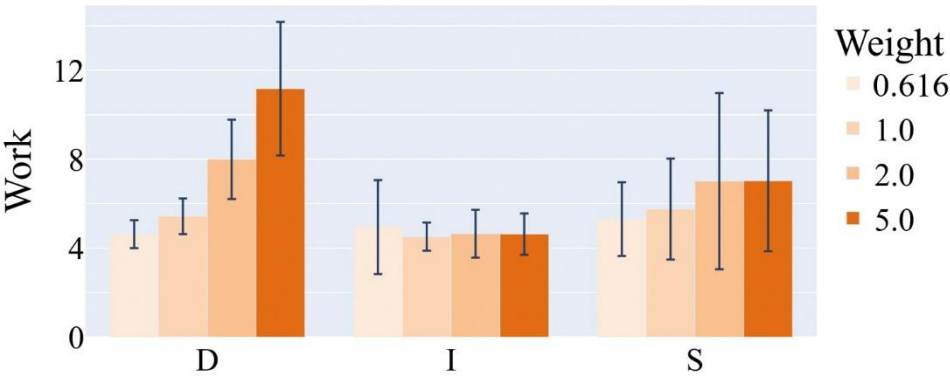
Figure 7. Mean ±SD of work for 20 users for the VR (non-haptic) conditions. From left to right: D=direct weight condition, I=Isomorphic condition, S=speed control condition.

546

Figure 8 indicates the 20 individual behaviors in the haptic and non-haptic conditions. By increasing the mass of the object, in the control condition, users follow a constant trend (also see Table 2, Isomorphic). However, in other conditions, users' physical work follows an increasing trend.

Figure 8-A shows different individual behaviors for the non-haptic conditions. In the direct-weight condition (D), by increasing the heaviness of the virtual bottle, users follow the same trend as the haptic condition (see Figure 8-B). It is therefore evident that in the direct weight condition, by increasing the mass of the object, the physical work of the users is augmented (work performed by approximately 95% of users), in a similar manner to the haptic condition (75% of users). The increase in mass also affected the work value of each user in the speed-control condition (see Figure 8-A, S); however, this fluctuation between 2 and 5 kg was not substantial (T-test, p-value = 0.05), and only 30% of the users' physical work value increased. The isomorphic condition (see Figure 8-A, I) shows that work values did not change statistically across masses (see Table 2), and only 5% of users could determine the object's weight.
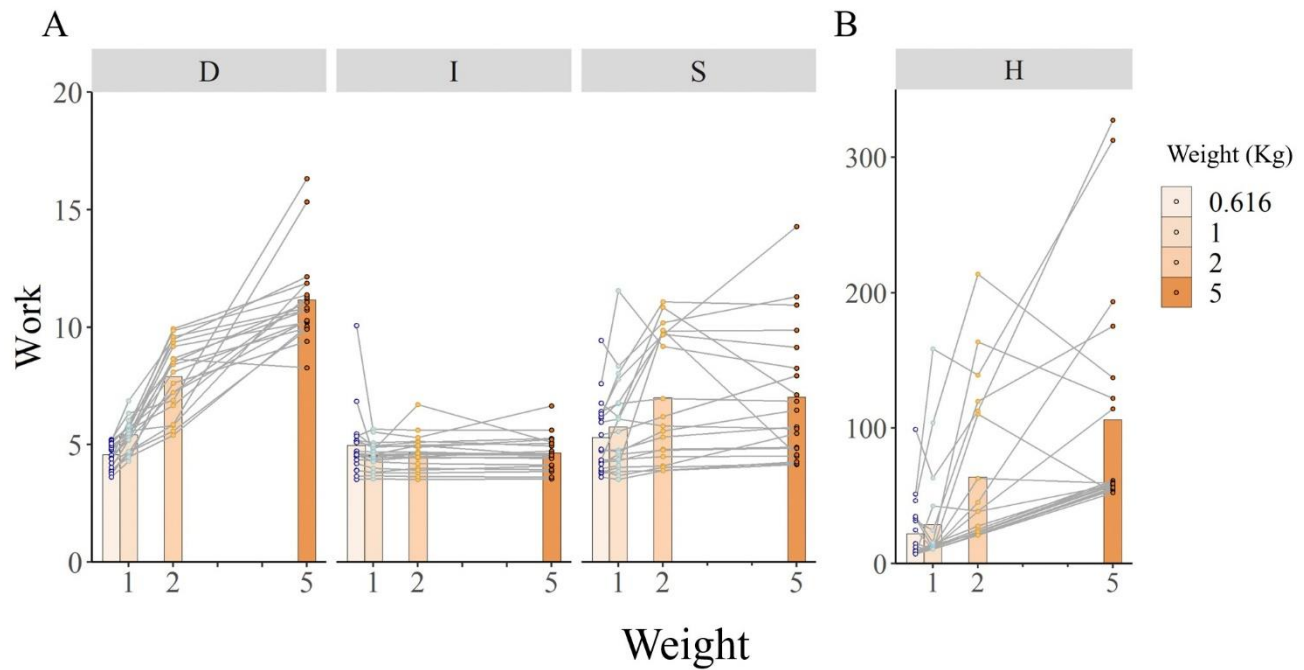
Figure 8. Differences between different users' behaviors in haptic and non-haptic conditions. A) Individual values (dots) and mean values (bar plot) of work in different conditions in VR for different masses. B) Individual and mean values of "physical work" (bar plot) in reference conditions (haptic). Data are shown as mean ±SD. Gary lines present users' behavior trends for different masses.

4.3   Qualitative Analysis

4.3.1 Borg CR10

After each condition, users were asked to complete a Borg CR10 questionnaire to measure their level of fatigue. To assess the level of fatigue among 20 subjects, we calculated the mean and standard deviation of the fatigue levels (Figure 9). In contrast to the other conditions, users did not experience tiredness in their hands when they were in the isomorphic condition. The mean values of the fatigue questionnaire for the direct-weight and haptic conditions are 3.65±2.4 and 3.65±2.66, respectively. It is noteworthy that although the users reported the same level of fatigue in their hands during the haptic and direct-weight conditions, the level of tiredness in these conditions increased in comparison with the isomorphic condition. According to the one-way ANOVA test, subjects' sense of tiredness was significantly affected by the conditions under which they were tested ($F_{(3, 77)} = 6.600$, $p < 0.0005$). Based on the post-hoc analysis, there are no significant differences between the haptic and direct-weight conditions, nor between the haptic and speed-control conditions ($ps > 0.05$). In addition, the B-H results support the conclusions reached in the post-hoc analysis.
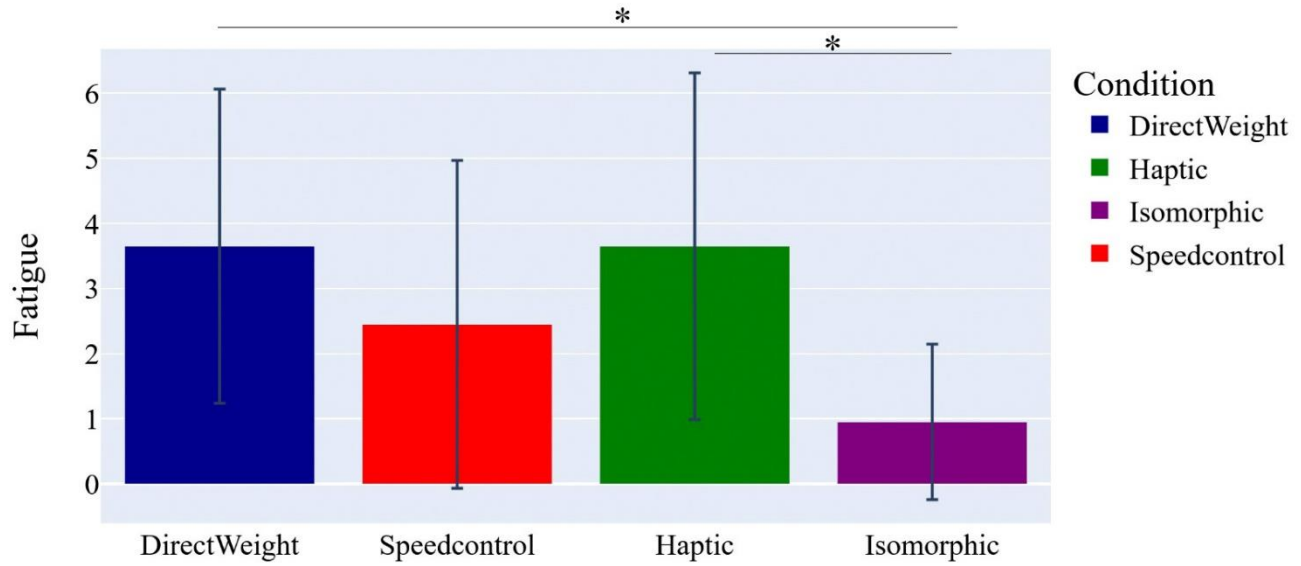
579

Figure 9. Results of the modified Borg CR10 questionnaire: mean and standard deviation of fatigue for 20 users after performing each condition.

4.3.2 Presence Questionnaire

Another questionnaire we used to subjectively measure the sense of presence in our VE was a presence questionnaire (Witmer & Singer, 1998). After performing each condition, users were asked to fill out this questionnaire and explain how they felt.

Table 4. Results of ANOVA test for presence questionnaire features between different conditions (H: Haptic, I: isomorphic, S: speed-control, D: direct-weight).

Presence questionnaire feature	Conditions	ANOVA (p-value)
Quality of interface	H, I, S, D	0.444 > 0.05
Possibility to examine	H, I, S, D	0.889 > 0.05
Self-evaluation	H, I, S, D	0.224 > 0.05
Haptic	H, I, S, D	0.320 > 0.05
Realism	H, I, S, D	0.124 > 0.05
Possibility to act	H, I, S, D	0.246 > 0.05

588

A plot of the mean values of quality of the interface, possibility to examine, self-evaluation of performance, haptics, realism, and possibility to act is shown in Figure 10. It is evident from this figure that users had similar feelings in all conditions. Table 4 presents the results of an ANOVA group analysis for each feature of this questionnaire among all users under different conditions. Under different experimental conditions, there was no significant difference in presence features (see Table 4, p-value > 0.05).
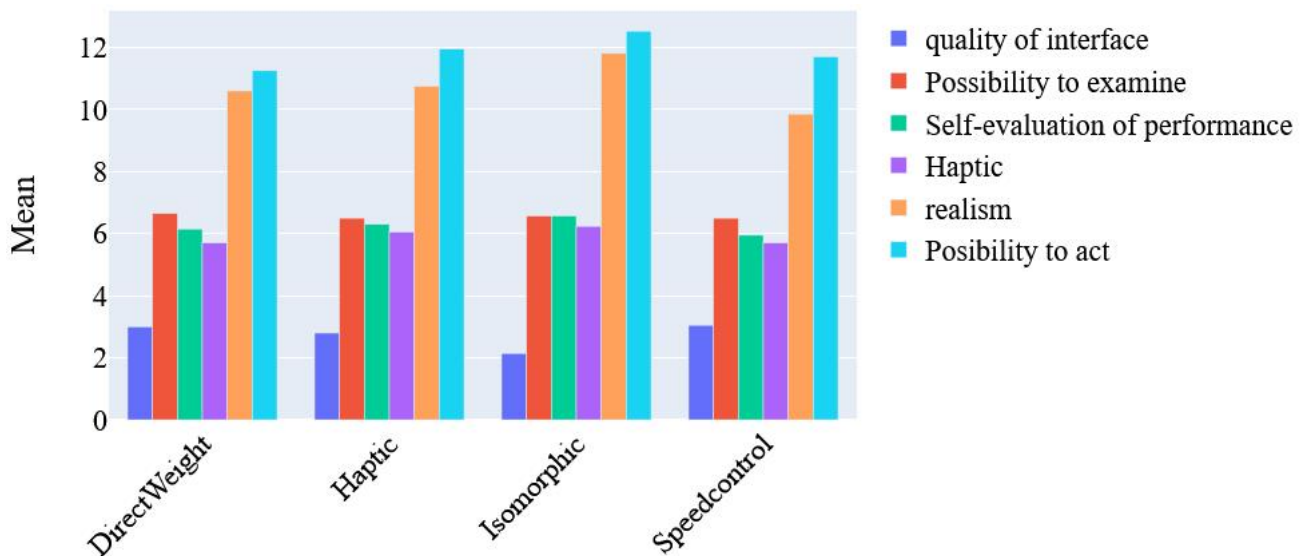
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595

Figure 10. Presence questionnaire: Mean of responses of 20 users to measure the different features of presence questionnaire, completed by users after each condition.

598

5   Discussion

In this study, we conducted an experiment in the context of lifting an object in virtual reality. Four conditions were evaluated, two congruous and two incongruous, in terms of perceived and performed movements. We used a haptic as the reference condition. Finally, we assessed the perception of the effort to lift the object for each condition through objective measurements (physical work) and subjective measurements (Borg CR10 questionnaire and presence questionnaire).

As expected and as a consequence of our pseudo-haptic feedback approaches, the actual hand displacement feature (disp; see Table 1-displacement) showed that the value of the disp is approximately 1 meter in the congruous conditions. While in incongruous conditions (speed-control and direct-weight), by increasing the weight of the virtual object, the value of the disp feature increases.

Two-way ANOVA results also showed that the displacement feature remained consistent during bottle lifting with different weights in different conditions. However, when subjects lifted 0.616 and 1 kg, their hand displacement remained consistent, while heavier bottles led to changes in displacements. Therefore, according to the displacement feature, the weight of one kilogram could be a threshold weight that participants can lift both in VR and real environments without noticing any difference in their hand displacements.

Regarding movement duration, the result of the two-way ANOVA showed that it was not stable for congruous and incongruous conditions and different weights. This inconsistency of the movement duration showed that users tried to compensate for the weight of the object by incrementing their actual hand movement distance. Therefore, logically, this displacement increase leads to an increased movement duration.

The results of the fatigue questionnaire showed that users sensed the same amount of fatigue in their hands when they were lifting real objects in haptic conditions and when they lifted virtual bottles in

622 the direct-weight condition. Similarly, the results of the presence questionnaire showed that users in
623 non-haptic conditions had the same sense of presence that they had in haptic conditions. More
624 generally, Table 4 confirms that there were no significant differences between users' feelings of
625 presence in different conditions. These results demonstrate that users were immersed in the VE and
626 that we succeeded in inducing the same amount of tiredness in haptic and direct-weight conditions.

627 Despite the large differences in physical work between haptic and isomorphic conditions, pseudo-
628 haptic approaches strongly impact individual physical work (see Figures 6 and 7). Our formulation did
629 not take into account the mass of the subjects' arms, which may explain the large discrepancy. The
630 formula for work (EQ 10) implies that work is directly related to the weight of an object. However,
631 Figure 8 indicates that for some individuals, the value of work decreases when the weights of the
632 objects are increased from 2 to 5 kg in the haptic condition. Meanwhile, all users, with the exception
633 of one, appear to be able to increase the value of their work as a result of increasing the weight of the
634 virtual objects. In VR, users modify their lifting behaviors, and our pseudo-haptic methods affect their
635 movement patterns. This cannot be accidental; comparing direct-weight to isomorphic conditions,
636 users did not recognize the weights of the virtual objects in the isomorphic condition since there was
637 no pseudo-haptic feedback. Therefore, they performed the same hand movements for all weights in the
638 isomorphic condition.

639 Likewise, in speed-control conditions, users are able to observe the effects of visuomotor conflict on
640 their hand movements. Comparatively to the isomorphic condition, visual feedback has a significant
641 impact on the work's value. In speed control, however, the virtual bottle's velocity changes as a function
642 of the weight of the bottle. For 0.616 kg, there is no statistically significant difference between the
643 isomorphic condition and the speed-control condition, whereas for heavier weights (1, 2, and 5 kg),
644 there are significant differences. In other words, the integration of multi-sensory conflict affects the
645 acceleration and displacement of the users' hands, resulting in them performing more actions on the
646 controller.

647 By comparing the findings between the speed-control and direct-weight conditions, we discovered that
648 the direct-weight condition caused subjects to increase their weights to 2 and 5 kilograms more
649 effectively (post hoc-Tukey, p-value 0.05). While subjects perceived the difference between 2 and 5
650 kilograms in the speed-control condition (post hoc Tukey, p-value > 0.05).

651 Our methods (direct-weight and speed control) have been shown to simulate fatigue similar to haptic
652 conditions in the hands of users (Borg CR10). Therefore, our methods were successful in terms of
653 enhancing the user's sense of presence.

654 We identify a number of benefits for VR designers who are faced with the challenge of providing
655 virtual object weight to the user of a VR hand controller. This study's primary strength is direct
656 interaction with virtual objects using a VR controller and trackers. Secondly, we induced heavier
657 weights that are close to the weight of objects that people encounter in their daily lives, while previous
658 studies focused on objects that weigh less than 500 grams (Samad, et al., 2019). A pseudo-haptic model
659 can successfully induce these weights in VR participants without any additional haptic devices, when
660 the weight of the virtual object is equal to or less than 1 kg. However, for heavier virtual weights such
661 as (2 and 5 kg), subjects may experience the same fatigue in their hands as in the haptic condition. To
662 avoid discrepancies between visual and kinaesthetic cues, extra haptic devices should be used. Doing
663 so ensures that the subject will not be affected by the VR environment in terms of their sense of
664 presence.

665   Consequently, these approaches could be beneficial in other VR fields and decrease the reliance of VR
666   on hardware devices. Weight perception can be used to interact more naturally with virtual objects
667   rather than limiting the interaction with the VE. The other contribution of our work is the use of the
668   physical work formula as an objective measurement evaluator based on kinematic data. As a result,
669   subjective judgment is not required. There is generally no real-world testing of haptic interfaces in the
670   evaluation process, which results in inaccurate weight perception assessment results (Lim, et al., 2021).
671   We conducted different lifting conditions with both real objects and virtual bottles to clearly evaluate
672   the object's weight perception.

673 **6   Conclusion**

674   Inducing the a feeling of weight of virtual objects to VR users is a difficult task due to lack of force
675   feedback cues. This research focused on simple force feedback simulation approaches, through visual
676   cues, instead of using expensive and large hardware and physical interfaces. By utilizing the concept
677   of pseudo-haptic feedback, we designed two different approaches based on the C/D ratio concept and
678   aimed to evaluate the effect of each approach on human behavior lifting in VR without extra real weight
679   and compared it with the effect of real object lifting. To evaluate our findings, we benefited from the
680   concept of physical work and different questionnaires (fatigue, presence). According to our findings,
681   the modified C/D ratio method based on distance control can induce virtual object heaviness (and in a
682   better way than velocity control), with object lifting behavior close to real object lifting one. This
683   finding could be interesting for VR developers who want to develop more reliable VE with such tasks.

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689 **References**

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