Influence of Control/Display Ratio on the Perception of Mass of Manipulated Objects in Virtual Environments

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Abstract

This paper describes two psychophysical experiments which were conducted to evaluate the influence of the Control/Display (C/D) ratio on the perception of mass of manipulated objects in Virtual Environments (VE).

In both experiments, a discrimination task was used in which participants were asked to identify the heavier object between two virtual balls. Participants could weigh each ball via a haptic interface and look at its synthetic display on a computer screen. Unknown to the participants, two parameters varied between each trial: the difference of mass between the balls and the C/D ratio used in the visual display when weighing the comparison ball.

The data collected demonstrated that the C/D ratio significantly influenced the result of the mass discrimination task and sometimes even reversed it. The absence of gravity force largely increased this effect.

These results suggest that if the visual motion of a manipulated virtual object is amplified when compared to the actual motion of the user's hand (i.e. if the C/D ratio used is smaller than 1), the user tends to feel that the mass of the object decreases. Thus, decreasing or amplifying the motions of the user in a VE can strongly modify the perception of haptic properties of objects that he/she manipulates.

Designers of virtual environments could use these results for simplification considerations and also to avoid potential perceptual aberrations.

CR Categories: H.5.2 [Information Interfaces and Presentation]: User Interfaces – Evaluation/Methodology, Haptic I/O, User-Centered Design; H.1.2 [Information Systems]: User/Machine Systems – Human Factors, Human Information Processing.

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1. Introduction

Manipulation of objects is one of the most fundamental tasks in Virtual Environments (VE) [2]. This task allows the user to modify some parameters of virtual objects such as their appearance, shape, or position.

In order to reach and manipulate virtual objects, VE generally provide the user with a virtual cursor (for instance a "virtual hand" [2]) which reproduces the movements of his/her real hand [3]. The ratio between the amplitude of movements of the user's real hand and the amplitude of movements of the virtual cursor is called the Control/Display ratio (or C/D ratio) [12].

In many cases the C/D ratio used is different from 1, which means an amplification or a diminution of the user's actual motion in the virtual environment. Inside a CAVE [6], the C/D ratio may be smaller than 1 so to exaggerate the user's motions and enable him/her to cover the large workspace of this VE. Another example is the well-known Go-Go technique introduced by Poupyrev et al. [16] which uses a non-linear C/D ratio to extend the user's virtual arm and grab distant objects more easily.

However, we do not know today the effect of such modifications of the C/D ratio on the perception that the user has of the virtual environment and more especially of the virtual objects he/she manipulates. For instance: does the use of a C/D ratio different from 1 influences the perception of haptic properties of manipulated objects such as their mass?

The present study aims at bringing some answers to these questions. To do so, two experiments were conducted to evaluate the influence of the C/D ratio used on the perception of mass of manipulated virtual objects. A discrimination task was used in which participants were asked to identify the heavier of two virtual balls. We used a haptic interface to catch and manipulate virtual balls of different mass. Participants looked at a visual display of the manipulated balls on a computer screen with varying C/D ratios. In the second experiment, the manipulation was made in a simulated weightlessness condition in order to remove the effect of the gravity force.

The following paper begins with an overview of related work in the field of mass perception and interactions between visual and haptic information in virtual environments. It is followed by a description of the protocol and the results of the two proposed experiments. Then it continues with a general discussion, and the paper ends with a conclusion and a description of potential perspectives.

2. RELATED WORK

The performance of human sensors has been broadly studied and measured since the pioneer work of Weber in the early 1830's. When studying the perception of mass and weight of objects, researchers found values of Weber fractions – i.e. discrimination performance – equal to 10% for the discrimination of mass around 100g [4, 9, 17] . Without the use of the gravity force – i.e. in weightlessness conditions – the human performance decreases, since the Weber fraction for mass discrimination was found to increase to 15% [18].

The perception of weight and mass seems to be based on multiple factors. Recently, Amazeen and Turvey [1] stated that perceived weight was influenced by the rotational forces applied by the body limbs on an object. Consequently, perceived weight could be function of the inertia matrix of an object [1]. Wolfe [26] documented in 1898 an illusion known as the "material-weight illusion". He showed that, given objects of equal mass but with different materials, objects with denser materials were judged lighter than the others.

Charpentier [5] discovered in 1891 another classical illusion called the "size-weight illusion". He showed that, given two objects of equal weight but different sizes, the smaller object usually feels heavier than the larger one. Surprisingly, the size-weight illusion was found to operate when the information of size of the objects was only provided by vision [8] and not by touch. This suggests that vision have also a role to play in the perception of objects' mass.

The influence of visual information on the perception of objects' dynamic properties is the cornerstone of a theory of event perception called the "Kinetics Specify the Dynamics" (KSD) [20]. Twardy and Bingham [24] reported that seeing the trajectory of an object bouncing on the ground provides relevant information about the dynamics and notably the weight of this object.

More generally, interactions between visual and haptic senses have been widely studied [7]. It seems that vision dominates touch for the perception of spatial properties (size, length, location, etc). For material properties (textures) – which is the domain favoured by touch – the visual dominance seems to be more limited [8]. Ernst and Banks [7] proposed a model to predict the weights of modalities in the sensory integration of haptic and visual cues based on their reliability.

Srinivasan et al. [23] showed that a visual information of displacement have a compelling impact on the perceived stiffness of virtual springs. In some cases, they found that the visual information could even inverse the judgment of participants during a discrimination task. Lécuyer et al. showed [11, 13] that a passive haptic interface combined with appropriate visual feedback could be used to simulate haptic properties such as friction or stiffness. They called this phenomenon "pseudo-haptic feedback". Paljic et al. [15] replicated the results in similar experiments applied to torque perception. They showed that participants were able to compare real torsion springs and virtual torsion springs with two kinds of passive devices – isometric and elastic [27]. They noticed that using the elastic device resulted in higher performance (lower Weber fraction) during the discrimination task.

Lécuyer et al. [12] proposed an interaction technique based on a modification of the Control/Display ratio (C/D ratio) to simulate the perception of surface textures in desktop applications. They used a simple 2D mouse. The principle was to adjust the C/D ratio of the mouse according to the topography of the terrain over which the cursor was travelling. Acceleration (or deceleration) of the cursor indicated negative (or positive) slope of the texture. Results showed that participants could successfully identify bumps and holes by only using the variations of the motion of the cursor and the changes of the C/D ratio.

3. EXPERIMENT 1: INFLUENCE OF C/D RATIO ON THE PERCEPTION OF MASS OF MANIPULATED OBJECTS WITH GRAVITY

In this first experiment, we studied the effect of a visual amplification of the motion of the user in the VE (i.e. use of a C/D ratio smaller than 1 in the visual display) on his/her perception of mass of manipulated objects.

The psychophysical method used was a discrimination task with the constant stimuli method and a forced choice paradigm [7, 13]. Participants were asked to successively weigh two virtual balls and decide which one was the heavier. Balls were displayed on a computer screen, and participants could manipulate them via a haptic interface.

3.1 Participants

Ten participants aged from 23 to 46 (mean=29.7, sd=7.1) with no known perception disorders took part in this experiment. Half of them were women, and all were right handed.

3.2 Experimental Apparatus

We used a force-feedback interface to simulate the mass of virtual balls: a PHANToM Premium 1.0 from SensAble Technologies [21].

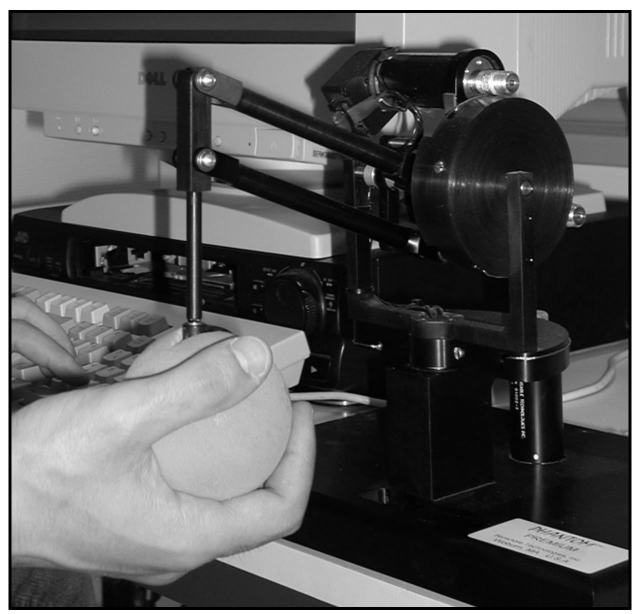

Figure 1. Grasping of the device through a foam ball

Participants caught the extremity of the device with the hand as shown on Figure 1. A physical foam ball was placed at the extremity of the device. This ball was used as a "prop" [10], in order to provide the participant with a passive haptic feedback of the ball manipulated in the simulation.

Simulation of the mass of the ball was performed using a virtual coupling [22] between the extremity of the device and a virtual ball. The coupling was made of a spring (K) and a damping (energy dissipation coefficient b) in parallel (K=700N.m-1, b=0.999). A 4th order Runge-Kutta integrator was used to numerically solve the dynamics 2nd order differential equation. Both inertia and weight of the ball could then be simulated. The frequency of the haptic feedback was of approximately 1 kHz.

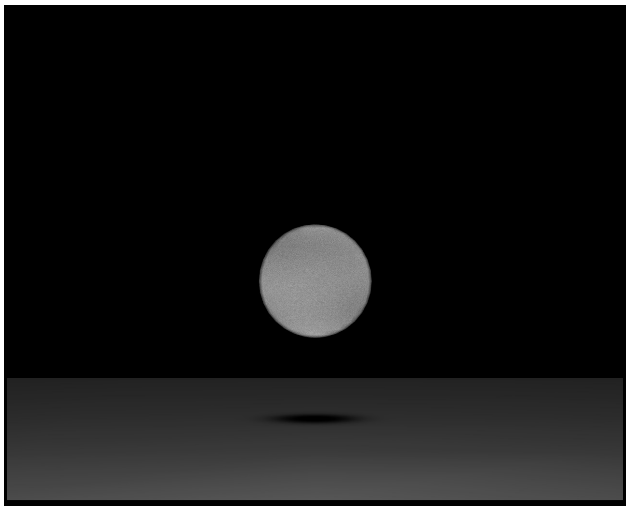

Figure 2. Screenshot of the visual display

Graphic simulation was rendered using the Virtools Dev. 2.5 software [25] (see Figure 2). The visual display consisted in a ground (represented by a horizontal plane at the bottom of the screen) and the manipulated ball which looked as similar as possible to the one attached to the PHANToM – i.e. same radius (4cm), colour (green) and same texture (foam). A shadow of the ball was added to provide the participant with depth information. Visual feedback was displayed on a 21" screen in monoscopic condition, with a frame rate of 85Hz.

3.3 Procedure

The participants were seated with their heads located at a distance of 40cm from the screen. The participants' line of sight was aligned with the centre of the screen. The tip of the PHANToM was positioned to match their arm length. It was caught and manipulated with the dominant hand while the other hand was used to enter answers on the keyboard. The dominant hand, forearm and arm were hidden to the participants using a paper mask (see Figure 3). By masking the hand of the participants, we ensured that the only possible visual feedback during the experiment was provided by the computer screen, which was necessary to guaranty an identical experimental protocol for every participant.

The participants were instructed that the ball displayed on the screen was a representation of the physical ball at the tip of the PHANToM. They were asked to look at the computer screen during the whole experiment and to keep the visual ball within the screen limits. They were given the task of choosing which of two successive balls was the heavier.

The participants started each trial with their hands lying on a resting-support, just below the PHANToM. The ball displayed on the screen (=visual ball) was coloured in red and resting on the visual ground. The extremity of the PHANToM (=physical ball) was forced to stay at an initial position -on the virtual ground- using the force feedback of the device. When the colour of the visual ball turned green, the physical ball was released and the participants were asked to grasp the physical ball, lift it and weigh it for 6 seconds. Once the 6 seconds were elapsed, the visual ball turned to red again. The participants had to release the physical ball, and the PHANToM automatically moved the physical ball back to its initial position. This operation was then repeated with the second ball. After having weighed the two balls, participants were asked to choose the heavier ball of the two. They entered their answers using the "1" or "2" key of the keyboard. The next trial was then automatically launched.

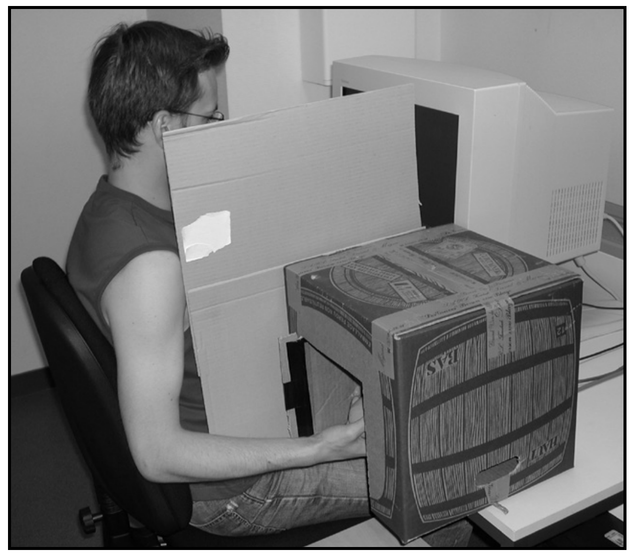

Figure 3. Experimental set-up

Trials were automatically sequenced in series. Participants could take breaks at the end of each series. At the end of the experiment, they had to fill in a questionnaire. Before starting the experiment, participants had to complete a learning series of 9 trials.

The whole experiment lasted around 90 min including the learning phase and breaks. No response feedback was given to the participant after each comparison.

3.4 Conditions

One reference ball was used in each trial with a constant mass of 100g (Mref=100g). The C/D ratio used when weighing the reference ball was always equal to 1 (CDRref=1).

The reference ball was compared with a set of comparison balls defined by one mass (Mcomp) and one C/D ratio (CDRcomp). The mass of the comparison ball was systematically heavier than Mref since Mcomp was possibly equal to: 110, 120 or 140g. These three values of Mcomp correspond to three Differences of mass (Dm1=10%, Dm2=20% and Dm3=40%).

Five possible C/D ratios were used when weighing the comparison ball: CDRcomp=1, 1/2 (0.5), 1/5 (0.2), 1/10 (0.1), or 1/15 (0.0667). Four values of CDRcomp are strictly smaller than 1 – which means an amplification of the motion of the user in the visual display of the VE.

The 3 Dm x 5 CDRcomp resulted in 15 experimental conditions. The 15 trials were presented randomly within one series of trials. Each experimental condition was tested 16 times for a total amount of trials of 240 trials. Each experimental condition was presented in a counterbalanced order, i.e. the reference ball was randomly tested 8 times first and 8 times second within a pair.

3.5 Collected data

The participants' answers to the discrimination task – i.e. to the question: "which ball was heavier?" were collected for each trial of the experiment.

We considered that "correct answers" referred to those that are "haptically consistent" ("HC" answers), i.e. consistent with the difference of mass between the two balls (Dm). Since Dms were all greater than the Weber fraction found for mass discrimination [4, 9, 17], participants should get at least 75% correct answers if they only discriminated masses on the basis of haptic force and kinaesthetic displacement information (blind test), independently of the C/D ratio used for the comparison ball.

3.6 Results

Data plotted on Figure 4 suggest that the average percentage of haptically consistent correct answers decreases when the C/D ratio used with the comparison ball (CDRcomp) decreases. This means that if the motion of the user was amplified when weighing the comparison ball (which was the heavier one), the difference of mass was less perceptible. This suggests that the perceived mass of the comparison ball get closer to the one of the reference ball. Thus, in other words, the comparison ball was perceived as lighter when the motions of the user were amplified (when the C/D ratio was decreased).

We may notice that the percentage of HC correct answers is superior to 75% for all Dm used, when the C/D ratio is equal to 1. This result is consistent with [4, 9, 17] who estimated that the Weber fraction for mass discrimination was equal to 10%.

An Analysis of Variance (ANOVA) with repeated measures was run on the percentage of correct answers in each trial. The three within subject factors were the Difference of mass (Dm1=10%, Dm2=20%, Dm3=40%), the C/D ratio of the comparison ball (CDRcomp1=1, CDRcomp2=0.5, CDRcomp3=0.2, CDRcomp4=0.1, CDRcomp5=0.0667) and the rank of Trials (T1 to T16).

The C/D ratio of the comparison ball significantly affected the percentage of haptically consistent answers. When CDRcomp decreased under the value of 1, the percentage of HC responses also decreased from a high correctness value and approached the zone of subjective equivalence, i.e. the 50% of HC correct answers value (mean for percentage of HC answers with CDRcomp1 =mCDRcomp1=85.4%; sd=35%; mCDRcomp2=76.5%; sd=43%; mCDRcomp3=62.9%; sd=48%; mCDRcomp4=58.8%; sd=49%; mCDRcomp5=58.8%; sd=49%; $F(4,36)=14.089$, $p<0.0001$). This zone also corresponds to the zone of maximal ambiguity from a decisional point of view.

The difference of mass Dm also significantly affected the percentage of haptically consistent answers. The percentage of HC correct answers increased when Dm increased (mean for percentage of HC answers with Dm1=mDm1=52.1%; sd=50%; mDm2=65.4%; sd=47%; mDm3=87.9%; sd=33%; $F(2,18)=113.707$, $p<0.0001$).

Finally, we observed a small (although significant: $F(15,135)=1.950$, $p<0.03$) effect of the rank of Trials which did not seem to correspond to any noticeable regularity or learning effect.

No two-ways or higher level interaction was significant.

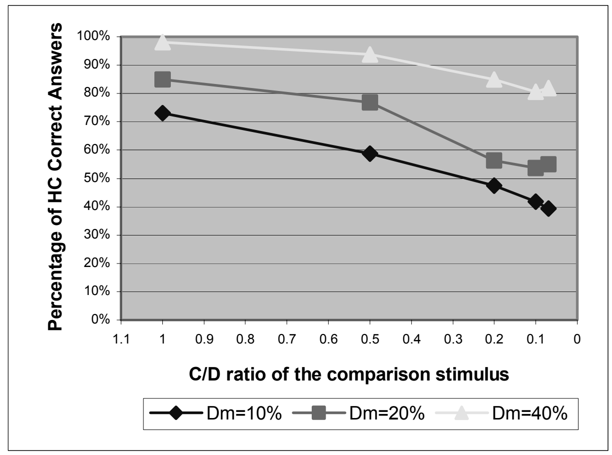

Figure 4. Experiment 1: percentage of HC correct answers vs. C/D ratio

When observing the results of each participant separately, we noticed that the modification of the C/D ratio did not seem to influence all the participants with the same intensity. It occurred that for half of the participants (n=5), the percentage of HC correct answers could sometimes reach values strictly smaller than 25%, when the value of the C/D ratio used was decreased. This means that the judgment of these five participants could be totally inverted: the reference ball was then perceived as heavier than the comparison one.

3.7 Conclusion

At the end of this first experiment, it occurred that the C/D ratio did influence significantly all the participants during the discrimination task. Indeed, the manipulated virtual ball was perceived as lighter than its actual weight when using small C/D ratios (i.e. when amplifying the display of the participant's motion in the VE).

We observed that half of the participants were strongly influenced – having their perception totally inverted by the change of the C/D ratio. The other half was also significantly disturbed, but not completely mislead.

4. Experiment 2: Influence of C/D Ratio on the Perception of Mass of Manipulated Objects without Gravity

A second experiment was carried out to evaluate the influence of the gravity force on the above results.

The protocol of this experiment was thus the same as in experiment 1, except that we removed the gravity force from the haptic simulation.

4.1 Participants

Ten new participants aged from 22 to 60 (mean=31.7, sd=11.3) took part in the experiment. There were 8 men and 2 women, all of them were right handed and with no known perception disorders.

4.2 Apparatus

Apparatus used was the same as in experiment 1. Gravity was removed from the dynamics simulation. The computation of the force-feedback of the PHANToM consisted mainly in simulating the inertia forces due to the manipulation of the ball.

4.3 Procedure

The same procedure as in experiment 1 was used.

4.4 Conditions

The experimental plan and conditions were identical to the ones of experiment 1, apart from the three possible masses used for the comparison balls which were fixed after preliminary testing to: 170, 240 and 310g. These values implied new differences of mass: Dm1=70%, Dm2=140% and Dm3=210%. These mass differences are much greater than the Weber fraction measured for mass discrimination in weightlessness conditions of 15% [18].

4.5 Results

Data plotted on Figure 5 show that the average number of HC correct answers decreased strongly when the C/D ratio decreases.

The effect of the C/D ratio is much stronger here than in the first experiment since the average percentage of HC correct answers falls under 25%, for differences of mass which are larger than before (Dm=70% or 140%) and for identical CDRcomp (1/10 or 1/15). In these cases, the judgment of participants has thus been totally inverted: they globally perceived that the heavier ball was the reference one, although it was the comparison one.

An ANOVA was run on the percentage of haptically consistent answers in each trial. The three within subject factors were still the Difference of mass (Dm1=70%, Dm2=140%, Dm3=210%), the C/D ratio of the comparison ball (CDRcomp1=1, CDRcomp2=0.5, CDRcomp3=0.2, CDRcomp4=0.1, CDRcomp5=0.0667) and the rank of Trials (T1 to T16).

ANOVA showed a strong effect of the C/D ratio on the haptically consistent answers ($F(4,36)=45.844$, $p<0.0001$). For the highest modality of the factor (CDRcomp1=1) we found 85.4% of HC answers (sd=35%). We observed only 29% (sd=45%) on the opposite extreme (CDRcomp5=0.0667). Between these two poles, the percentage of HC answers decreased as the C/D ratio decreased (mCDRcomp2=70%, sd=46%; mCDRcomp3=49%, sd=50%; mCDRcomp4=35.2%, sd=48%).

The difference of mass Dm still affected the percentage of HC correct answers. The percentage of HC answers increased when Dm increased (mDm1=40.3%; sd=49%; mDm2=54.4%; sd=50%; mDm3=66.6%; sd=47%; $F(2,18)=31.743$, $p<0.0001$).

No significant main effect was found for Trials ($F(15,135)=1.024$, n.s.).

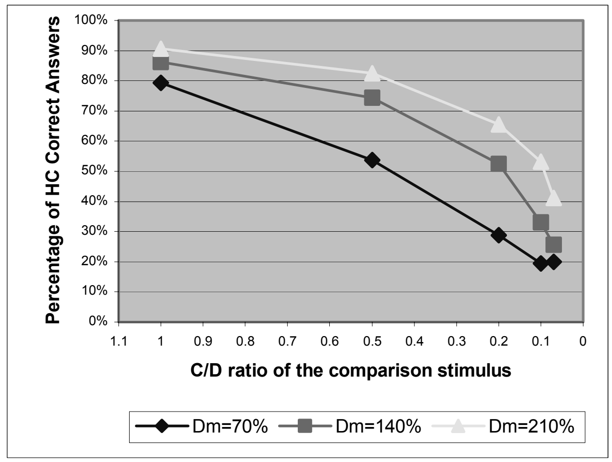

Figure 5. Experiment 2: percentage of HC correct answers vs. C/D ratio

When observing the results of each participant separately, we noticed that only 2 participants managed to keep their percentage of HC correct answers above 40% in every conditions. Furthermore, 4 participants scored less than 10% haptically consistent answers with small values of C/D ratio, even with the maximum Dm of 210%. One of them even scored a 0% HC correct answers in the maximum Dm condition and with the smaller CDRcomp.

4.6 Conclusion

As in the previous experiment, the manipulated ball tended to be perceived as significantly lighter than its actual weight when using a C/D ratio smaller than 1. In addition, the absence of gravity greatly increased the influence of the C/D ratio. The participants had their judgment generally inverted with small C/D ratios.

5. General discussion

Taken together, the results of the two conducted experiments show that using a C/D ratio smaller than 1 (meaning amplifying the visual motion of the user in the VE) tends to modify the haptic perception of the mass of the manipulated object. Indeed, in both experiments, when a small C/D ratio was used (i.e. when the motions of the participant were amplified), he/she tended to perceive the manipulated object as lighter than its actual weight. In some cases, for high amplifications (i.e. for low C/D ratios), the judgment of the participants when comparing the two balls of different weights could even be inverted. This implies that a high amplification of the visual motion of the haptically heavier ball could surprisingly make it perceived as the lighter one.

The reasons for this perceptual bias remain unknown and require further investigation. However, it is consistent with related work which demonstrated that a visual information of displacement could modify the haptic perception of stiffness [13, 23], torque [15] or texture [12].

$$E = \frac{1}{2} m v^2 \quad (1)$$

$$m = \frac{2E}{v^2} \quad (2)$$

The cross-modal association made by the participants could stem from the physical relation that exists between mass, velocity and energy (e.g. Equation 1) and which finds confirmation in our every day's experience. Let us try to illustrate hereafter this assumption. Let us consider the comparison of two virtual balls simulated haptically with an equal mass for simplicity of exposition (m1=m2 and dM=0), but with different C/D ratios (CDR1 > CDR2). Müller and Schumann stated that, when comparing the weight of two objects, the second object is generally lifted with approximately the same force as the force required to lift the first object [14]. In response to an identical motor impulse, the same quantity of energy is thus perceived by the participant when manipulating the two balls. Two conflicting sensorial feedbacks – visual and haptic – are provided to the participants concerning the velocity of the manipulated ball. According to Hatwell et al. [8], in the case of a conflict in the spatial field, the visual cue is expected to capture the haptic one. In other words, in our experiment, the perceived velocity of the ball would be the visual one. The two C/D ratios used would thus lead to the perception of two different velocities: v1 and v2. Since CDR1 is greater than CDR2, v1 would be perceived as smaller than v2. It is well known that kinetic energy (E) is linked to mass (m) and velocity (v), according to Equation 1. Therefore, considering a constant energy (E) and two different velocities v1 and v2, if the participants referred unconsciously to Equation 2 – which stems from Equation 1 – they would perceive two different masses m1 and m2. Thus, since the resulting m1 is greater than m2, the first object would be perceived as heavier than the second one. This argumentation would partially explain the phenomena observed in our study but, of course, future work is necessary to verify and extend the assumptions made here.

The effect of the C/D ratio was much stronger when the gravity force was removed from the simulation, i.e. when the weighing was simulated in weightlessness conditions. The absence of gravity removed some haptic information, and this probably increased the general influence of vision over the haptic modality. Another simple explanation is that the gravity force – when simulated – was applied constantly and continuously to the manipulated object. Therefore, when weighing and comparing the mass of the two balls with gravity, the participants did not need to make many motions and could simply use the information provided by the gravity force. The influence of the C/D ratio could thus be visible if and only if the user moves the virtual objects. Furthermore, in weightlessness condition, the performance of the haptic sense for mass discrimination decreases [18]. According to the model proposed by Ernst and Banks [7], the weight of the haptic sense in the visuo-haptic integration process is then also expected to decrease. This could explain why a higher influence of vision over touch was observed when no gravity was applied. Moreover, Ross showed in [19] that the performance of mass discrimination in weightlessness improved with arm movements of higher acceleration. In our experiment, when lower C/D ratios were used, participants had to do very little movements on account of motion amplification. This could have led the participant to do lower acceleration motions, making thus the discrimination performance drop. This could have resulted in a greater decrease of the reliability (performance) of the haptic modality, leading to a higher weight of vision in the final process of sensory integration [7].

Our results suggest that comparing two virtual objects of equal mass, the perceived mass of one of the two might be modified only by modifying its C/D ratio. This means that different sensations of mass could be simulated by modifying the C/D ratio of any interface. This suggests that mass can be added to the list of the haptic properties that can be simulated with a pseudo-haptic feedback [11, 13, 15]. Such a pseudo-haptic feedback could thus be used to easily provide the user with additional information of mass of objects when manipulating low cost input devices.

Furthermore, this illusion could also be used to overcome limitations of current haptic interfaces. It could extend their apparent range of displayable forces. The fact that this effect is stronger in weightlessness is particularly interesting for simulating operations in zero-gravity conditions such as in space, or even in simulations of industrial assembly/maintenance operations in virtual reality for which gravity is often removed due to simplification and/or comfort issues.

However, since the perceived mass of virtual objects may be greatly distorted by an amplification of its motion in VE, designers of virtual environments using haptic feedback should also carefully consider the value of the C/D ratio they use. Indeed, the haptic perception of mass may be altered even with a haptic interface that perfectly reflects the actual mass of the object. Changing the C/D ratio generates a modification of the haptic perception of the scene. Consequently, using interaction techniques based on motion amplification might be hazardous, notably in applications where realistic haptic sensations (e.g. of mass) are important.

6. Conclusion

Two experiments were conducted to investigate the influence of the C/D ratio on the perception of mass of virtual objects in VE.

They showed that the use of a C/D ratio different from 1 could strongly modify the perceived mass of manipulated objects. When the C/D ratio was smaller than 1 (meaning an amplification of the user's real motions in the visual display of the VE), the participants perceived the manipulated object as lighter than its actual weight. Our results showed that in some cases it was even possible to reverse weight sensation, i.e. to make a heavy object feel lighter than a light object by only decreasing its C/D ratio.

This illusion phenomenon could be used by designers of virtual environments in order to extend the capacities of the devices used, or also to prevent some perceptual aberrations in applications where realistic haptic sensations must be preserved.

Future work. Future work could first investigate the use of a C/D ratio superior to 1 – which is expected to increase the perceived mass of manipulated virtual objects. Second, we would like to study the influence of the manipulation strategy on the occurrence of the phenomenon. For instance, is this illusion still observable with gravity if the ball is manipulated with very few motions, or if the ball is caught when it is thrown from above? Third, we would like to study the influence of this phenomenon on user's performance during the simulation of an industrial operation in virtual reality such as with a maintenance or assembly operation. Fourth, we could investigate the possibility of providing weight sensations without any force-feedback, i.e. when using a passive input device.

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