

IS MASS INVARIANT? EFFECTS OF MOVEMENT AMPLITUDE AND DURATION

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Abstract

In everyday life we interact with objects without having the impression that their heaviness changes. Yet, it has been shown that movements improve our ability to perceive the weight of an object (e.g. Brodie & Ross, 1985; Jones, 1986). This study tackles the issue of mass perception in absence of gravitational force. An admittance-controlled haptic device constrained participants' movements along a horizontal line and displayed inertial masses in a zero-gravity virtual environment. Participants produced a simple to-and-fro motion to assess two successively presented inertial masses within a 2I2AFC paradigm. Visual and audio signals were used to impose different movement amplitude and/or duration for the Standard and Comparison stimulus. A Quest method (Watson & Pelli, 1983) was used to find the point of subjective equality (PSE) between the Comparison and Standard stimuli. The results show that the movement amplitude and frequency lead to specific misperceptions of the physical masses.

During everyday interaction with objects, the human hand acts both as a sensing organ to perceive their physical properties and as a motor organ to operate on them through the production of forces. The twofold nature of the hand as a motor and sensing organ makes the distinction between the object and the subject of perception feebler in haptics than in other sensory domains (Lederman & Klatzky, 1987). The information on the stimulus in environment is continuously shaped by the active use of the hand.

A considerable number of studies have been conducted on the perception of weight and heaviness. In his pioneering studies, Weber found that weight discrimination improved considerably if the object was actively lifted instead of being simply placed on the hand (Weber, 1834/1978). Later, it was observed (Waller, 1891; Brodie and Ross, 1984) that weight discrimination is better under voluntary muscle contraction as opposed to galvanic, faradic or reflex activation of the muscles, which points to an involvement of the efferent copies of motor commands in weight perception. Furthermore, weight discrimination is significantly enhanced when actively lifting a weight compared to simply upholding a weight with the hand raised at a constant position, which is itself an improvement upon holding it with the arm resting on a table (Brodie and Ross, 1984). Also, jiggling a lifted weight appears to improve sensitivity (Brodie & Ross, 1985). Finally, it has been shown that mass discrimination in weightlessness improves with more accelerated arm movements (Ross, Schwartz & Emmerson, 1986). Altogether, this research indicates that actively moving a weight improves weight discrimination, presumably because the movement provides additional inertial cues (Brodie & Ross, 1985). Intriguingly, we do not have the subjective impression that the weight of an object changes notwithstanding the large variation of interaction force occurring during its manipulation. In fact, previous research suggests that weight discrimination improves in conditions where the force the object exerts on the hand varies as a result of the movement imparted to the object, compared to when the force is

constant and the object immobile. This paradoxical finding has not yet to receive the attention it deserves.

In this study, we investigated whether the heaviness of an object is modified by the manner in which the object is moved. To avoid possible confounds, the object is moved horizontally in a zero-gravity environment, as if it were sliding on a frictionless table. While previous studies on heaviness perception have focused on differential thresholds, which indicate the minimum variation of intensity that is necessary to perceive two physical stimuli as different from each other, we measured the point of subject equality for two stimuli that were moved in different ways. In particular, we compared the perceived heaviness of an object over three movements of different amplitudes and/or durations. Two of these movements were selected so as to have the same maximum acceleration. If our CNS is able to extract the invariant mass of objects during manipulation, mass perception should not be affected by the characteristics of the movement. However, if maximum force is an important cue of heaviness, then the masses of two objects perceived as equally heavy will depend on the acceleration peaks of the associated movements (see Tan et al., 1995, who showed that maximum force is an important cue in the context of stiffness discrimination). This study makes use of state-of-the-art robotic technologies to simulate weightlessness and to modify the mass of a virtual object according to an adaptive psychophysical method to find out the point of subjective equality between two objects moved in two different ways.

Method

Participants

Twelve right-handed observers (9 female), aged 20-32 years (average 26), took part in the experiment on a voluntary basis, either in exchange for course credits or not. By self-report, all participants had normal tactile sensitivity, normal or corrected-to-normal visual acuity and no neuromuscular abnormalities. One of the participants was one of the authors; all the others were naïve to the purposes of the study. The experiment was conducted in accordance with the Declaration of Helsinki and all participants gave their informed written consent.

Experimental Procedure

Participants performed a 2I2AFC task where they had to assess which one of two consecutively presented masses felt heavier. Participants stood up in front of a 3DOF admittance-controlled haptic device (Haptic Master, Moog FCS robotics), which was employed to display the masses in a zero-gravity virtual environment. Participants used a key grasp with the thumb placed above the index finger of the right hand to grasp the spherical end-effector (4 cm diameter) of the robot. The arm was flexed at the elbow joint by 90° and the initial hand position was aligned with each participant's shoulder. The device constrained the movements horizontally along the lateral direction. A XGA Hitachi CP-X327 video projector (1024x768 pixels, 60 Hz refresh rate) displayed the visual feedback on a fronto-parallel screen placed behind the robot at a distance of 154 cm in front of the subject. The visual feedback included a blue horizontal line (32.6x1.1 dva -- or 90x3 cm) on a dark background with two white disks (diameter 0.67 dva – or 1.8 cm) that indicated the extremities of the movement that the subject had to perform and an orange disk (diameter 0.67 dva – or 1.8 cm) that indicated the current position of the device end-effector. The graphic scene was rendered in a buffer that was swapped synchronously with the vertical blank and the delay between the measure of the hand position and its visual rendering did not

exceed one refresh period. The subjects wore headphones that delivered audio signals (beeps) together with a feeble white noise and were instructed to follow visual and audio cues to produce movements of the desired amplitude and velocity.

At the beginning of each trial, the participant placed the robot handle at the starting point, which corresponded to the right white disk. Then, the participant waited for a series of four regularly paced beeps that indicated the desired movement velocity. The movement had to start at the second beep, reach the left mark in synchrony with the third beep, and return to the starting mark at the fourth beep. The movement length was controlled visually. A second series of four beeps controlled the movement velocity during the second stimulus period. At the end of the trial, the participants used a button box in their left hand to indicate which one of the two stimuli felt heavier. A third button was used to start the next trial. The beeps occurred during two stimulus periods that lasted 5 seconds separated by a 1 second inter-stimulus interval (ISI).

The standard and comparison stimuli were associated with movements of different amplitudes and/or frequencies. The effect of movement on mass perception was measured by finding out the mass of the comparison stimulus that felt as heavy as the standard. The haptic device displayed a fixed standard mass of 2.5 kg during one stimulus period and another mass, controlled by an adaptive psychophysical method, during the comparison period. The order of the two stimuli was randomized. The inertia was set to the standard mass during the ISI as well as between trials.

Two movement amplitudes and two frequencies were combined to yield three different movement types: A) a 10 cm movement at a pace of 1Hz, B) a 10 cm movement at a pace of 1.4142 Hz and C) a 20 cm movement at a pace of 1Hz. The amplitude and pace of the movements were chosen after pilot experiments so that the acceleration peak of the shorter and faster movement B would correspond to the longer but slower movement C. The maximum acceleration of the short and slow movement A was expected to be smaller than the maximum acceleration of faster movement B or longer movement C.

We measured the PSE in three conditions that corresponded to the following movement pairs: CB, AB, and AC, the first movement being set as the standard stimulus. For each movement pair, we used an adaptive psychophysical method - the QUEST - to identify the PSE (Watson & Pelli, 1983). The prior distribution was a gaussian probability distribution centred on the standard with standard deviation of 3.0 kg. The likelihood function was a cumulative gaussian probability function covering the whole range of probabilities (guess rate and slip rate set to zero) with a standard deviation of 0.5 kg and the mean of the posterior distribution was used to compute the value of the next stimulus. The QUEST terminated after 20 trials. The three QUESTs corresponding to the three conditions were randomly interleaved to address possible learning or fatigue effects. The whole procedure lasted about twenty minutes and was repeated twice for each participant, yielding a total of 40 judgements in each condition. Before the experiment, all participants underwent a short familiarization session (typically 2-5 minutes) during which they were asked to repeatedly produce the movements A, B, and C, until they were able to produce them accurately.

Data analysis

For each condition, a logistic psychometric function was fitted to the responses of the participants as a function of the comparison stimulus intensity. By definition, the PSE corresponds to the 50th percentile of the psychometric function. The difference between the PSEs of each participant in each condition and the mass of the standard was tested with a one-sample Student tests and the difference between the PSE across conditions was tested with a

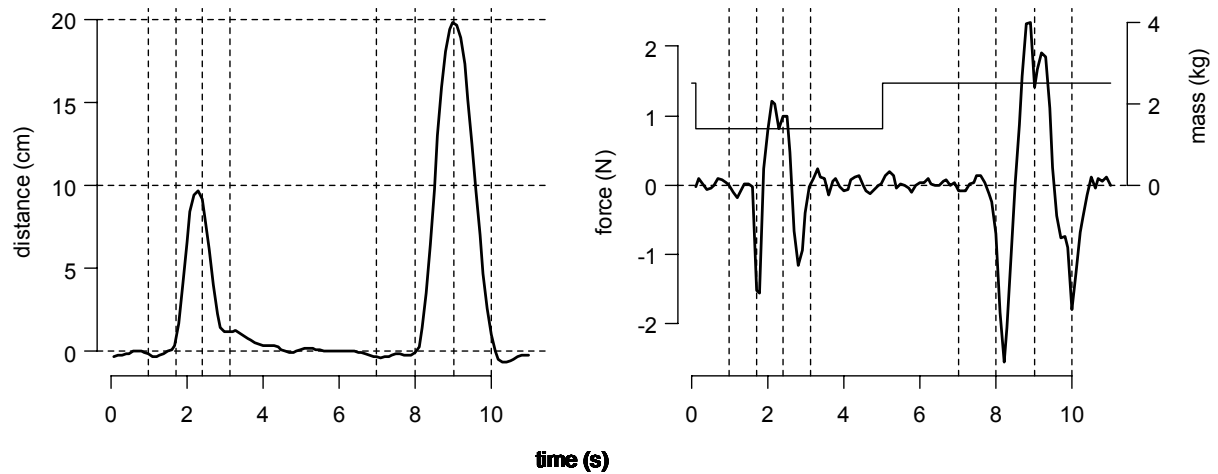


Figure 1. Position of the hand (*left panel*) and force (*right panel*) during a trial in condition CB. In this trial, the first stimulus corresponded to the comparison stimulus (1.38 kg, 10 cm, 1.414 Hz) while the second stimulus corresponded to standard (2.5 kg, 20 cm, 1 Hz). The vertical dashed lines indicate the beeps and the thin line in the right panel indicates the mass.

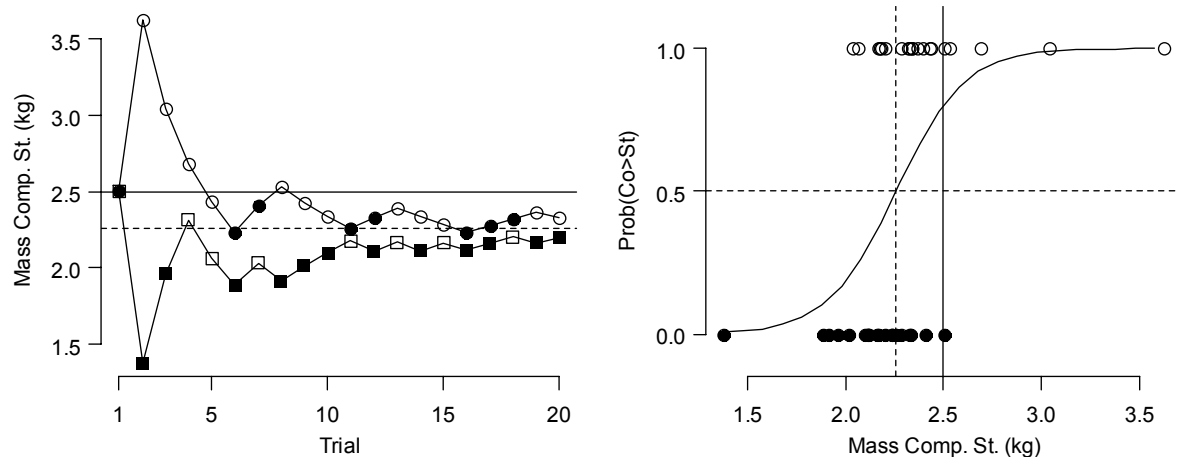


Figure 2. *Left panel:* Evolution of the comparison stimulus computed by the QUEST in condition AB for one participant in the two experimental sessions (squares=session 1, circles=session 2). Empty and solid markers indicate positive and negative responses respectively. The solid line represents the standard stimulus while the dotted line represents the PSE. *Right panel:* Psychometric function computed from the participants' responses in condition AB (both sessions). The psychometric function represents the probability of judging the comparison stimulus (CO) heavier than the standard and the dotted lines indicate the PSE (2.25 Kg).

one-way repeated measures ANOVA. The degrees of freedom were adjusted for possible deviations from the sphericity condition with Greenhouse and Geisser's epsilon (ϵ).

Results and discussion

The amplitude and/or pace of the movement during the presentation of the Standard and Comparison stimuli differed markedly in the three conditions (see Table 1). The mass of the Comparison stimulus was adjusted until it was perceived as equally heavy to the mass of the Standard. Overall, participants produced movements with the desired amplitude and frequency. As planned, maximum acceleration did not differ significantly in condition CB ($F[1, 11]= 0.068, p=.8$), while it differed in conditions AB ($F[1, 11]= 71, p<.001$) and AC ($F[1, 11]= 120.6, p<.001$). A close look at the results shows some deviance from visual and audio cues. For example, short movements were slightly larger than instructed and large movements were slightly shorter but the difference rarely exceeded 5%. Moreover, precise conformance did not really matter as long as participants produced markedly different movements during the presentation of the two stimuli.

The main outcome of this study is that the mass of the Comparison stimulus differed from the Standard mass in conditions AB ($t[11]=-4.37, p<.01$) and AC ($t[11]=-3.89, p<.01$) but not in condition CB ($t[11]=0.69, p= 0.5$). A one-way repeated-measure ANOVA confirms that the PSEs differed across conditions ($F[1.36, 15]= 13.3, \epsilon =0.68, p<.01$) and that the PSEs were higher in condition CB than in condition AC and AB, which did not differ from each other (Scheffé's a posteriori test, $p<.01$). These results show that movement amplitude and pace can influence the perception of the mass of the moved object. When only one of the two movement attributes changed, participants perceived a lighter mass that was moved faster or over a longer distance as equally heavy as a heavier mass that was moved more slowly or over a shorter distance. For example, in condition AB, a mass of 2.18 kg moved over 10.6 cm in 0.76 sec was perceived to be as heavy as a mass of 2.5 kg moved over the same distance in 0.97 sec and, in condition AC, a mass of 2.23 kg moved over 19.7 cm in 1 sec was perceived to be as heavy as the standard 2.5 kg mass moved over 10 cm in the same time. In contrast, the mass (2.52 kg) associated with the Comparison stimulus did not differ from the Standard (2.5 kg) in condition CB where the larger movement (19.8 cm) was covered at a slower pace (1.1 sec) than the shorter movement (10.7 cm in 0.8 sec), so that the acceleration peaks would match.

In the Introduction, we hypothesized that participants might use maximum force, the product of mass and maximum acceleration, as a cue for mass. As a matter of fact, Tan et al. (1995) found that, when possible, participants used the maximum (final) force to discriminate the stiffness of springs. As predicted, the results confirm that the PSE is equal to the Standard when the acceleration peaks and, thus, peak forces are matched, even if the movement amplitude and pace differ. More generally, if the two masses are perceived as equally heavy when the acceleration peaks are not equal, this hypothesis predicts the two masses should

Table I. Movement characteristics and PSEs.

	<i>CB condition</i>		<i>AB condition</i>		<i>AC condition</i>	
	<i>St</i> 20 cm, 1 Hz	<i>Co</i> 10 cm, 1.414 Hz	<i>St</i> 10 cm, 1 Hz	<i>Co</i> 10 cm, 1.414 Hz	<i>St</i> 10 cm, 1 Hz	<i>Co</i> 20 cm, 1 Hz
<i>PSE (kg)</i>	2.5	2.52±0.24	2.5	2.18±0.26	2.5	2.23±0.26
<i>Duration</i> * (s)	2.14±0.21	1.59±0.16	1.93±0.21	1.52±0.16	1.89±0.19	2.11±0.24
<i>Amplitude (cm)</i>	19.84±0.89	10.72±0.89	10.61±0.75	10.57±0.93	10.75±0.85	19.72±0.88
<i>A_{max} (m/s²)</i>	1.21±0.26	1.20±0.29	0.81±0.19	1.28±0.30	0.84±0.19	1.27±0.32
<i>F_{max} (kg)</i>	3.03±0.65	3.08±0.69	2.01±0.47	2.74±0.68	2.11±0.47	2.81±0.72

* Duration of the whole to-and-fro movement

differ exactly by the amount necessary to make the product between the acceleration peaks and the corresponding masses equal. While we observed a decrease of the PSE when the Comparison stimulus was more accelerated than the standard, the compensation was only partial. As a matter of fact, while maximum acceleration increased by about 50% in condition AB and AC, the mass associated with the Comparison stimulus decreased by less 12-15%. As a result, maximum force was about 30% larger during the Comparison period than during the Standard period in those conditions (see Table I). In other words, the mass varied less than one would predict if participants based their estimate only on maximum force. Current research aims at identifying the processes that allow one to perceive mass with more stability than predicted by the peak force hypothesis.

In conclusion, our results show that mass perception is not perfectly invariant with respect to the movement characteristics. This finding however is not necessarily in contradiction with the observation, reported in the Introduction, that sensitivity improves in weight discrimination tasks when the object is moved. However, it shows that one needs to properly match the movements used to compare two weights to avoid the biases reported in this study.

Acknowledgments

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