THE SIZE-WEIGHT ILLUSION IN A NATURAL AND AUGMENTED ENVIRONMENT WITH CONGRUENT AND INCONGRUENT SIZE INFORMATION

by

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ABSTRACT

The size-weight illusion (SWI) occurs when the smaller of equally weighted objects is judged to feel heavier than the larger object. Experiment 1 compared the SWI generated in a natural versus augmented-reality environment while grasping and lifting three differently sized cubes of equal weight. Both environments induced the SWI for all twenty participants. Lift kinematics covaried with cube size in both environments. Experiment 2 investigated the influence of incongruent visual size information on the SWI in an augmented environment. Physical cubes were paired with three graphical representations: a smaller, an equal-sized, and a larger cube. The SWI was influenced by both haptic and visual size information. Kinematics covaried with physical size throughout the experiment. Results suggest that vision significantly impacts the bimodal SWI when haptic and visual size information is not redundant. Results have implications for theories of heaviness perception, multimodal interaction, and perception and action in augmented environments.

Keywords: Weight perception; Action; Prehension; Haptic; Vision; Graphic

Subject Terms: Perceptual-motor processes; Sensorimotor integration; Intersensory effects; Touch -- Psychological aspects; Hand – Movements; Human-computer interaction

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1 INTRODUCTION

1.1 Heaviness Perception and the Size-Weight Illusion

Perception is frequently investigated in a unidimensional manner within individual modalities (e.g., brightness in vision, loudness in audition, roughness in touch) (e.g., Woodworth & Schlosberg, 1932). In reality, however, it is rare that our perceptual system acts on information from only one dimension and one modality at any given time. It is important, therefore, to investigate the influence of multimodal contributions to perception and action (e.g., Stein & Meredith, 1990).

One psychophysical quality that has been investigated in this manner for several years is heaviness perception. As early as 1834, Weber noted that objects that were lifted felt heavier than objects that were rested passively on the skin, suggesting that heaviness perception was not entirely determined by an object's physical weight. Since then, researchers have shown that heaviness perception may be dependent on a number of factors besides weight. For instance, heaviness perception seems influenced by resistance to the rotational forces imposed by the limbs when holding and wielding an object, which are affected by the object's geometric properties (Amazeen & Turvey, 1996). Heaviness perception also appears to be affected by the material from which objects are constructed (Ellis & Lederman, 1999; Flanagan & Wing, 1997; Flanagan, Wing, Allison & Spencely, 1995; Wolfe, 1898), by the width of the grip used for grasping, the number of fingers involved, and the contact surface area (Flanagan & Bandomir, 2000).

Most researched, however, is the influence of object size on heaviness perception. In 1891, Charpentier demonstrated that heaviness perception was affected by the size of the objects being compared, independent of their physical weights (see Murray, Ellis, Bandomir & Ross, 1999, for a historical overview). This phenomenon, known as the size-weight illusion (SWI), creates the perception that the smaller of two identically weighted objects feels heavier than the larger object when lifted. While the illusion most typically occurs when people can both see and feel the size of the different objects, it occurs equally strongly when blindfolded or when congenitally blind participants lift objects in their hands (Ellis & Lederman, 1993), suggesting that vision is not necessary to induce the illusion (see also Gordon, Forssberg, Johansson & Westling, 1991b).

However, visual size information in the absence of haptic size information is also sufficient to produce the SWI. For instance, participants who lift objects suspended by string tethers (Ellis & Lederman, 1993) or with a pulley system (Masin & Crestoni, 1988), or those that lift objects using a handle or some type of grasp apparatus (e.g., Flanagan & Beltzner, 2000; Flanagan, King, Wolpert & Johansson, 2001; Gordon et al., 1991a, 1991b; Mon-Williams & Murray, 2000), all experience the SWI despite not haptically feeling the size of the objects. The above findings indicate that strictly unidimensional and unimodal accounts are insufficient to fully explain the SWI, nor heaviness perception in general.

1.2 Perception, Action, and the Size-Weight Illusion

Daily, objects of various sizes, shapes and weights are lifted with smooth, fluid movements. The forces needed to lift an object depend on, amongst other things, the coefficient of friction between the fingers and the contact surface of the object and, crucially, the object's weight. Since weight cannot be determined prior to lifting, fluid lifting movements are dependent on an appropriate estimation of object weight, based on its appearance (e.g., size, material, density, shape) and/or past experiences with the object or others like it. Given that an object's weight is typically proportional to its size, people usually, appropriately, grip and lift larger objects with more force. Grip (i.e., normal) and load (i.e., vertical) forces, as well as their rates of change, have been shown to be precisely scaled to the expected weight of an object (Johansson & Westling, 1984, 1988) and these lift forces ultimately result in an object being lifted with a particular acceleration and velocity that depends primarily on the relationship between the applied forces and the weight of the object.

It has been suggested that when common objects of different size actually weigh the same amount (e.g., during SWI experiments), a discrepancy will exist between the actual and expected weight of the objects. As such, forces will be applied erroneously, and these forces will translate into greater or lesser vertical acceleration immediately after object lift-off, depending on the magnitude of difference between the expected and actual weight. It has been theorized, then, that the SWI is due to a sensory mismatch created by this erroneous force production and subsequent movement errors (Davis & Roberts, 1976; Murray et al., 1999; Ross, 1969).

With the above theory in mind, several researchers have investigated the relationship between the perceptual SWI and the actions that accompany it. Studies have compared subjective reports of object heaviness with participants' pre-lift expectations of it, as evidenced by the grip and load forces employed to lift the objects (e.g., Flanagan & Beltzner, 2000; Flanagan et al., 2001; Gordon et al., 1991a, b; Mon-Williams & Murray, 2000) and/or by the movement kinematics produced from such lifting forces (Davis & Roberts, 1976; Gordon et al., 1991a - c). In support of the hypothesis, Davis and Roberts (1976) observed that in instances in which the SWI occurred (i.e., the larger of two objects was judged to feel lighter), the larger object was usually lifted with a greater peak acceleration, peak velocity, and peak deceleration than the smaller object. In addition, Gordon et al. (1991a - c) found that when lifting boxes of different sizes but equal weight, grip and lift forces and their rates, as well as vertical acceleration of the object, increased with object size, despite heaviness perception decreasing with object size. Based on these studies, it would appear that movements associated with the unexpectedly faster-lifted larger object give rise to a judgment of relative lightness and provide the basis for the SWI.

Interestingly, however, some of these studies have highlighted action-perception dissociations that sometimes exist during the SWI. As stated, many people will use more force to grip and lift a large object than a small one, indicating the rational expectation that the object with the greater size will also have a greater weight. However, participants often continue to report the smaller object as feeling heavier long after their motor system has adapted to the actual weight of the objects, and scaled the grip and load forces appropriately (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). Additionally, Davis and Roberts (1976) observed that lift actions and subjective reports of heaviness do not always covary uniformly; the illusion sometimes occurred in the absence of any kinematic differences, and sometimes did not occur despite the presence of kinematic differences. Similarly, Mon-Williams and Murray (2000) observed that erroneous motor programming was neither necessary nor sufficient to cause the SWI.

Discrepancies between what people do and what they report have been taken as evidence of the independence of perception and action mechanisms in the SWI. They have also been taken as evidence against a sensory mismatch explanation of the SWI, since it would appear that reliable perceptual effects are not dependent on a consistent pattern of actions resulting in sensory mismatches. The illusion is made even more intriguing by the fact that it often persists despite the participant being told that the objects actually have the same weight (e.g., Flanagan & Beltzner, 2000; Flournoy, 1894). The SWI, therefore, is far from being entirely understood.

1.3 Rationale and Overview of the Present Study

The SWI remains an interesting phenomenon, in part, because either of visual or haptic size cues is sufficient to induce the illusion if presented in the absence of the other, but when size cues from both modalities are available, the illusion seems to be influenced by haptic cues only (Ellis & Lederman, 1993). Also interesting and unclear is the relationship between actions and perceptions during the illusion. Given that the SWI is traditionally a bimodal phenomenon, occurring in the presence of both haptic and visual size cues, it seems important to develop a methodology in which to conduct bimodal SWI investigations that would allow size cues to each modality to be controlled independently of one another while allowing both action and perception to be analysed. SWI experiments to date, due to logistical limitations, have removed either haptic or visual size cues while analysing forces and movement kinematics (e.g., Flanagan & Beltzner, 2000; Flanagan et al., 2001; Gordon et al., 1991a - c; Mon-Williams & Murray, 2000; Grandy & Westwood, 2006). The present study proposes a new methodology, via an augmented reality environment, that might be used to overcome some of these challenges.

The main goals of the present study are to: (a) discover whether an augmented-reality environment can be used to induce a bimodal (both haptic and visual size cues available) SWI in a manner similar to lifting in a natural environment; (b) determine whether visual size cues mediate bimodal SWIs in which both visual and haptic size cues are present; and (c) better understand the relationship between lift kinematics and heaviness perception and the effect of repeated lifts on this relationship. To these ends, Experiment 1 uses a SWI paradigm to compare lifting actions and heaviness perceptions between a natural and an augmented environment. Provided with this baseline, Experiment 2 investigates the relative influence of haptic and visual size cues on action and perception in the SWI by providing participants with both congruent and incongruent size cues between modalities.

2 EXPERIMENT 1: COMPARING THE SIZE-WEIGHT ILLUSION IN AN AUGMENTED VERSUS NATURAL ENVIRONMENT

Several methodologies have been used to investigate the size-weight illusion (SWI), but one potentially useful tool that has rarely been used in SWI research is augmented reality (Kawai, Henigman, MacKenzie, Kuang, & Faust, 2006; Kawai, Summers, MacKenzie, Ivens & Yamamoto, 2002). Augmented reality environments allow computer-generated graphics to be superimposed over physical, graspable objects. As such, this paradigm allows the parameters of the graphic image to be precisely controlled and provides the possibility of independently manipulating information that is presented to the visual and haptic modalities. It would seem a useful tool, therefore, in multimodal perception studies such as the SWI.

Comparing the magnitude of a SWI created in an augmented environment with that created in a natural environment could help provide insight into how augmented (and potentially virtual) reality environments affect heaviness and other types of multimodal perception. Additionally, comparing perceptions derived from interactions with objects in augmented environments may help indicate how well these environments simulate natural environments, that is, how closely interactions in augmented environments mirror interactions in real environments. As such, the present experiment attempted to create a visuo-haptic SWI in an augmented environment and compare it to a more traditional

SWI created in a natural environment. A lack of significant differences in lifting movements and heaviness perception between the two environments would indicate that the augmented environment used here adequately represents the natural environment for this type of grasping and lifting task. Any differences arising between the two environments might lead to a better understanding of heaviness perception and the SWI, and might have implications for the design of augmented environment interfaces. Finding the SWI to occur similarly in both environments would provide confidence in using the augmented environment in further SWI studies.

In both environments, the SWI was assessed by analysing psychophysical reports of object heaviness using the method of absolute magnitude estimation (Stevens, 1975). In addition, kinematic measurements derived from lifting movements (i.e., peak displacement, peak velocity, peak acceleration, and peak deceleration) were analysed, thus allowing for a comparison of perceptual and motor mechanisms in both environments. The use of these indicators allowed for observation of perception-action covariance or dichotomies in the two experimental environments, wherein participants' psychophysical judgments matched or did not match with expectations inferred from their lift kinematics.

2.1 Hypotheses

It was hypothesized that:

(a) participants would experience the SWI (i.e., judge smaller cubes to feel heavier than larger cubes) in both the Natural and Augmented environments, given the observed robustness of the illusion;

(b) participants would initially lift with greater peak velocity, peak acceleration and peak deceleration for larger cubes than for smaller ones, suggesting that participants had a conscious or unconscious expectation that larger cubes were likely to weigh more than smaller ones, consistent with previous studies (e.g., Davis & Roberts, 1976; Flanagan & Beltzner, 2000, Gordon et al., 1991a, 1991b; Kawai et al., 2002; Mon-Williams & Murray, 2000). Further, this would occur in both environments;

(c) the effect discussed in (b) might dissipate over the course of repeated lifts (see Flanagan & Beltzner, 2000; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000), suggesting that the motor system eventually adapts to the actual (in this case, equal) weight of the cubes, regardless of heaviness perception;

(d) the SWI created in the Augmented environment would be slightly larger in magnitude than in the Natural environment (based on personal communication with C. L. MacKenzie, April 2006).

2.2 Method

2.2.1 Participants

Twenty volunteers (aged 18-38 years) from Simon Fraser University were recruited through use of posters and word of mouth. Participants all had reported normal or corrected-to-normal vision, normal hand function, no known muscular or cutaneous problems, and were self-professed right-handed individuals. All were naïve as to the purpose of the experiment. Participants were paid an honorarium of $10 and were informed that participation would require one hour of their time. Ethics approval was obtained from the Simon Fraser University Research Ethics Committee.

2.2.2 Task and Materials

All experimental tasks took place in the Virtual Hand Lab (VHL) at Simon Fraser University. Participants grasped and lifted cubes in each of two different environments: a natural environment (Natural) in which they could feel and see the size of the physical cube, and a computer graphics augmented environment (Augmented) in which participants could feel the size of the physical cube but saw a graphic representation of the cube instead of the actual physical cube. In the Augmented environment, graphic cube size always matched physical cube size (i.e., the sizes were always congruent), so as to resemble information that was presented in the Natural environment.

The three-dimensional position of the cube was recorded throughout each lift. Participants provided a verbal judgement of cube heaviness at the height of each lift, using the method of Absolute Magnitude Estimation (Stevens, 1975; Zwislocki & Goodman, 1980).

Three different sizes of cubes were lifted in each environment: Small (3 cm sides), Medium (4.5 cm sides) and Large (6 cm sides). Participants lifted each cube 10 times in each environment, resulting in a total of 30 lifts in each environment and 60 lifts total. Cubes were presented pseudorandomly, such that no cube was presented more than twice consecutively. Trials were blocked by environment and counterbalanced across participants. The experiment took approximately 35 minutes to complete, including instruction and calibration time.

At the outset of the experiment, participants were shown more than three physical cubes in order to make them believe that many different cubes would be lifted throughout the experiment.

Physical cubes: Electrical tape and a firm, laminated foam presentation-board material (X-Acto Sturdy Board, Hunt Co., Statesville, NC) were used to construct three cubes of varying size: 3 cm (27cc), 4.5 cm (91.125 cc), and 6 cm (216 cc), each with sides differing by 1.5 cm between them (Figure 2.1a). Equal weighting of all of the cubes (57 g) was achieved by carefully applying lead shot, foam and/or pieces of the cardboard material to the interior walls of the cubes in such a way that the mass was concentrated centrally in each cube. Cubes were weighted to have densities (from 2.111 kg/L to 0.264 kg/L) that were distributed around approximately 1 kg/L, the density of commonly manipulated objects (Gordon, Westling, Cole & Johansson, 1993). A detailed rationale for the selection of cube sizes and cube weight is presented in the Appendix.

Graphical cubes: For the Augmented environment, three graphic cubes were generated to be congruent in size with the three physical cubes (Figure 2.1b).

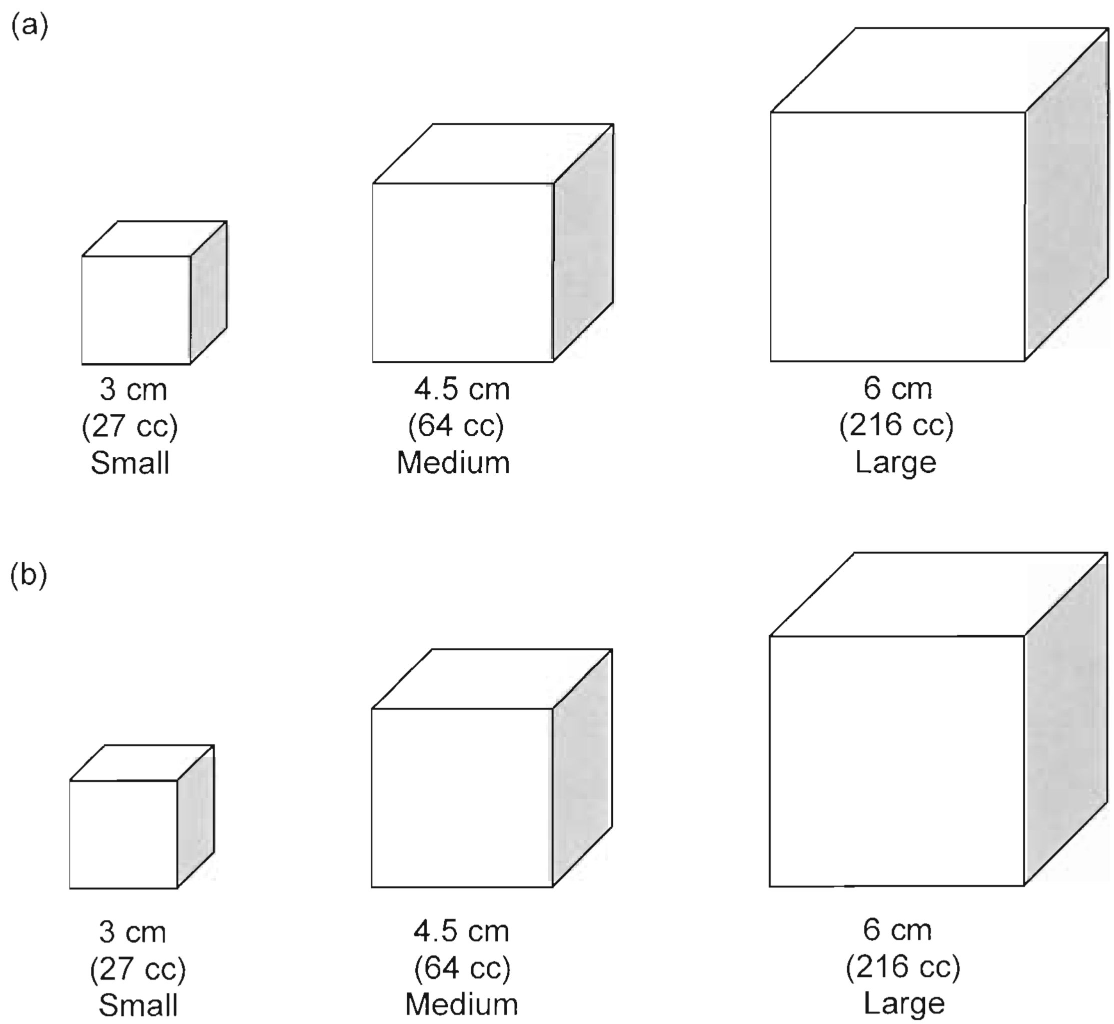

Figure 2.1 (a) Physical cubes and (b) Graphical cubes used in Experiment 1.

2.2.3 Experimental Apparatus

Participants performed all experimental tasks while sitting in a height adjustable chair in front of a table in the Virtual Hand Lab (VHL). In the

Augmented condition, a flat-screen computer monitor was positioned face-down over the workspace so as to display computer-generated graphics onto a half-silvered mirror placed parallel to and midway between the computer screen and the tabletop (Figure 2.2a). The image on the screen was reflected in the mirror so that the computer-generated graphic image of the cube appeared to be located on the table surface. A piece of black cardboard was placed under the mirror so that the participants could see neither their hand nor the physical cube through the mirror. Participants wore CrystalEyes™ goggles (StereoGraphics, San Rafael, California) to obtain a stereoscopic, head-coupled view of the graphics. Three infrared emitting diodes (IREDs) were attached to the left side of the goggles and one IRED marker was attached to each physical cube. A two-sensor OPTOTRAK 3020 3D motion analysis system (Northern Digital Inc., Waterloo, Canada) tracked the 3D position of the IREDs at a sampling rate of 100 Hz. The tabletop surface was covered with a firm, laminated foam presentation-board material (X-Acto Sturdy Board, Hunt Co., Statesville, NC). Participants wore headphones to reduce the possible influence on heaviness perception of any sounds made by replacing the cubes onto the table after each trial. Such sounds were minimal for all participants across all conditions.

In the Natural condition, participants performed the same tasks but no computer graphics were displayed and participants simply looked, without goggles, through the half-silvered mirror to view the actual physical cube (Figure 2.2b). As such, participants were able to see both their hand and the physical cube during lifts in the Natural condition.

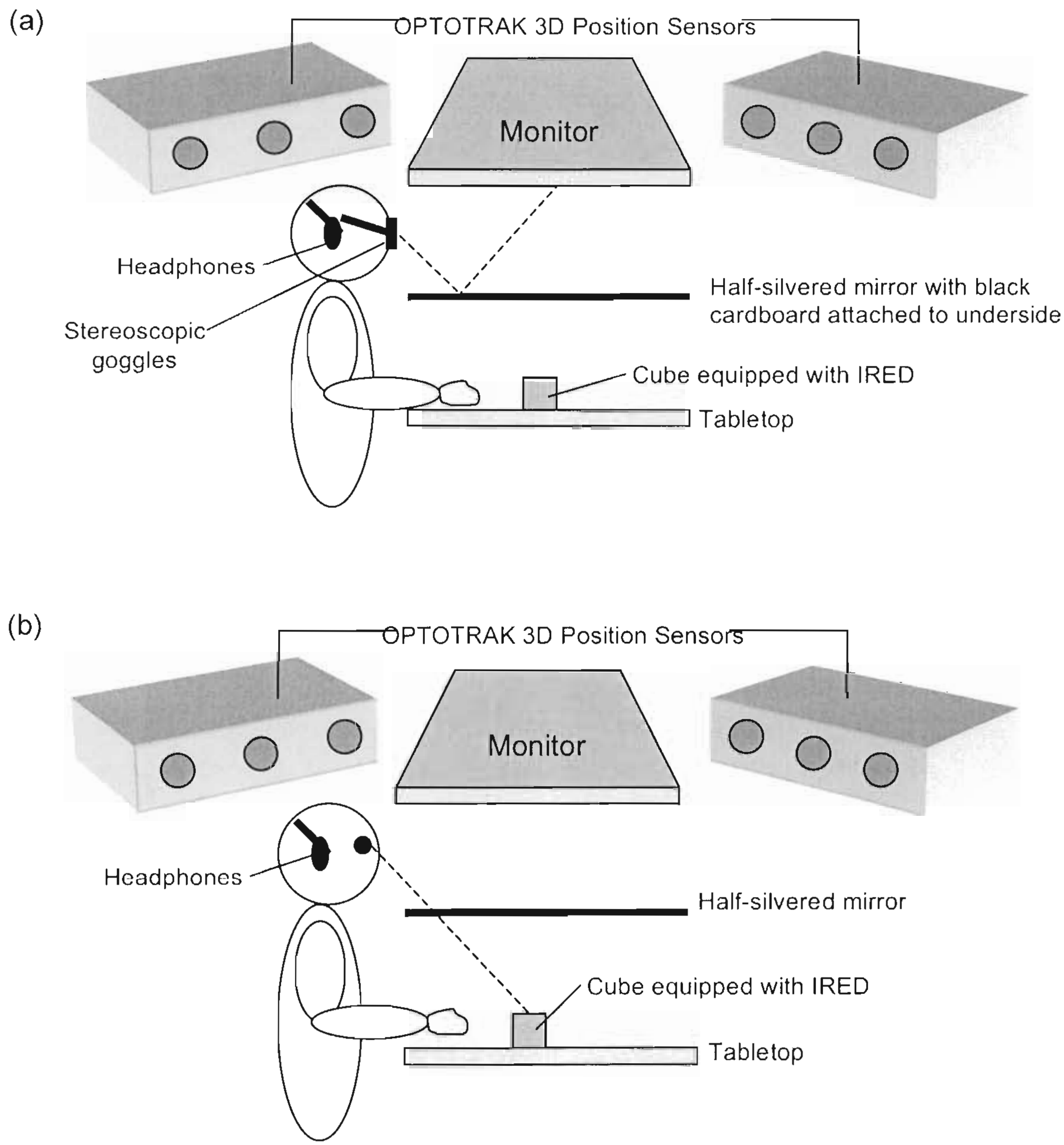

Figure 2.2 Experimental setup for (a) the Augmented environment and (b) the Natural environment. In the Augmented environment, participants wear goggles to see a 3D graphical cube reflected in the opaque mirror; in the Natural environment, no goggles are worn and participants see through the transparent mirror to the actual cube and workspace. Infrared emitting diodes (IREDs) are placed on the cube and goggles.

2.2.4 Trial Procedure

At the outset, each participant experienced a customized VHL eye calibration to measure interocular distance, to ensure that the graphical display in the augmented environment was head-coupled and that the stereoscopic images were fused so that the cube appeared as a single three-dimensional image.

Participants made all lifts with the right hand, to eliminate potential differences in heaviness sensitivity due to handedness (as noted by Weber, 1834). The Optotrak cameras were positioned in such a way as to limit occlusion of the IREDs in the workspace. In both environments, participants began each trial with the right thumb and index finger together on a start mark, indicated by a textured circle, on the table in front of them, 21 cm ahead of the near edge of the table and 6.5 cm to the right of the midline. The experimenter then placed a cube on the table centred on the subject's midline at a location 11 cm further ahead of the start mark such that its faces were at a 45-degree angle to the participants' midline (Figure 2.3). Upon cube placement, the participant reached forward and grasped the cube between their thumb and index finger using a precision grip. The participant lifted the cube vertically to a height of approximately 11 cm, held it for approximately 1 s, provided a verbal estimate of heaviness, based on the method of Absolute Magnitude Estimation (Stevens, 1975; Zwislocki & Goodman, 1980), and then replaced the cube on the table and returned to the start position. The experimenter then exchanged the cube for another, initiating the next trial.

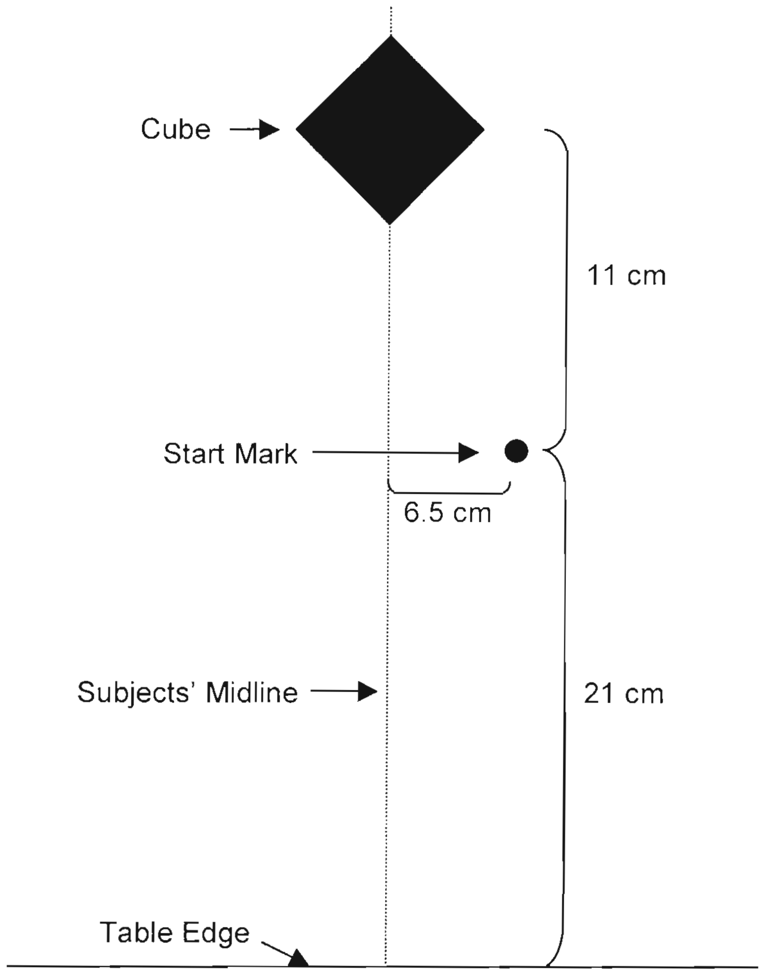

Figure 2.3 Tabletop setup (top view). Participants began each trial with their right thumb and index finger on the Start Mark prior to reaching for the cube. Diagram is not to scale.

2.2.5 Instructions to Participants

"We are investigating heaviness perception in natural and computer-augmented environments. Your job will be to grasp and lift each of these cubes [display the set]. These cubes vary slightly in size and weight. After each lift, you will provide an estimate of how heavy each cube feels. These lifts will take place in either a "natural environment", in which no computer is involved, or in an "augmented environment" in which a computer-generated graphic cube will be superimposed over the physical cube. In all trials, your job will be to lift the cube, then provide a verbal estimate of each cube's heaviness. You will wear headphones at all times to reduce the amount of noise that you hear."

2.2.6 Instructions for Absolute Magnitude Estimation

"To provide a verbal estimate of each cube's heaviness, you will assign a number to each lift in such a way that your impression of how large the number is matches your impression of how heavy the cube was that you just lifted. So, you would assign a larger number to a heavier-feeling cube, a smaller number to a lighter-feeling cube. You may use any numbers greater than zero that appear appropriate to you – whole numbers, decimals, or fractions. Do not think of physical units of measurement, such as grams or ounces or Newtons, and do not worry about running out of numbers, as there will always be a smaller number than the smallest you use and a larger one than the largest you use. Do not worry about numbers you assigned to previous lifts" (modified from Stevens, 1975; Zwislocki & Goodman, 1980).

2.2.7 Data Processing and Analysis

Statistical procedures involving heaviness estimates were based on Ellis and Lederman (1998, 1999). To adjust for individual differences in number scales between participants, the following conversions were made. For a given participant, each raw heaviness estimate was divided by the mean of all estimates for that participant. This value was then multiplied by the grand mean of all scores for all participants. These values were converted to common logarithms (base 10) for subsequent analyses, in order to transform the presumed power functions to linear functions (Stevens, 1961).

Movement data were collected at 100 Hz from the cube IRED. After data collection, data files were transferred to a Sun workstation for analyses using customized, in-house WATSMART (Waterloo Spatial Motion Analysis and Recording Technique) data analysis software. For files that were missing one or two frames, 3D position coordinates were linearly interpolated. Files missing more than two consecutive frames (20 ms) were rejected. Position data were then low-pass filtered at a cut-off frequency of 7 Hz with a second-order bi-directional Butterworth filter to reduce sampling artefacts. After data were interpolated and filtered, the data were translated and rotated to a meaningful coordinate system (origin near the edge of the table closest to the subject, x = forward, y = to the right, z = upward). Movement data in the x and y directions was disregarded. Motion in this plane was minimal and of little interest compared to the z position data (direction of lift). Vertical velocity profiles of the cube IRED were computed by differentiating the z position data. Vertical acceleration was obtained by differentiating the z velocity data. Start of movement was based on a criterion z velocity of 3 mm/s. The WATSMART program finds the first occurrence in a trial of a peak velocity of 100 mm/s and works backwards looking for the first occurrence of the start criterion velocity (3 mm/s), which is then defined as the start of movement. Peak vertical displacement, velocity, acceleration and deceleration were picked by the WATSMART program and reconfirmed by visual inspection of all trials.

Dependent measures included subjective heaviness reports, peak displacement, peak velocity, peak acceleration, and peak deceleration. All data was analysed using 3 (cube size: Small, Medium, Large) x 2 (environment: Natural, Augmented) x 10 (trials per cube size) repeated measures ANOVAs for each dependent measure. Planned "repeated" contrasts were used to compare levels of cube size. When the assumption of sphericity was not met, adjustments to the degrees of freedom and F values were made. Depending on the epsilon values, Huynh-Feldt or Greenhouse-Geisser corrections are reported (Howell, 1997). An a priori alpha level of α = .05 was set for all significance tests.

2.3 Results

2.3.1 Perceived Heaviness

There were no significant interactions between cube size, environment or trial. Only main effects are reported below.

2.3.1.1 Cube Size

Analysis of transformed heaviness scores yielded a significant main effect of cube size on subjective reports of heaviness ($F_{2, 38} = 69.742$, $p < .001$). Planned within-subjects contrasts indicated that, as predicted, participants' heaviness scores were significantly greater ($F_{1, 19} = 84.400$; $p < .001$) for the Small cube (mean = 1.366, SE = 0.005) than for the Medium cube (mean = 1.160, SE = 0.005), which was, in turn, significantly greater ($F_{1, 19} = 52.820$; $p < .001$) than for the Large cube (mean = 0.881, SE = 0.011). All 20 participants had heaviness reports that increased as cube size decreased, and vice versa. Cube size did not significantly interact with type of environment. As predicted, then, a visuo-haptic SWI was induced in both the Natural and Augmented environments for all participants.

2.3.1.2 Environment

No significant effect of environment on estimates of heaviness was observed. Cube heaviness was perceived similarly in both the Augmented and Natural environments.

2.3.1.3 Trial

No significant effect of trial on estimates of heaviness was observed. That is, heaviness estimates did not change significantly over time.

2.3.2 Kinematics in Vertical (z) Axis

Because each of the kinematic measures showed similar effects, they are presented together below. There were no significant interactions for any kinematic variables. Only main effects are reported below.

2.3.2.1 Cube Size

Univariate ANOVAs revealed a significant main effect of cube size on each kinematic dependent variable: peak displacement ($F_{2, 38} = 8.522$; $p = .002$), peak velocity ($F_{2, 38} = 22.431$; $p < .001$), peak acceleration ($F_{2, 38} = 61.599$; $p < .001$), and peak deceleration ($F_{2, 38} = 29.503$; $p < .001$). As seen in Table 2.1, as cube size increased, the value of each kinematic measure also increased.

Planned contrasts indicated a significant difference between each cube size for all kinematic measures.

Table 2.1 **Means for each kinematic dependent measure for each cube size. Standard errors are reported in brackets. For each kinematic measure, means are significantly different between cube sizes, as determined by planned contrasts.**

	Peak z Displacement (mm)	Peak z Velocity (mm/s)	Peak z Acceleration (mm/s^2)	Peak z Deceleration (mm/s^2)
Small (3 cm)	106 (1.8)	280 (5.7)	2067 (49.5)	-1570 (41.5)
Medium (4.5 cm)	109 (1.7)	296 (5.7)	2433 (57.6)	-1675 (43.1)
Large (6 cm)	113 (1.8)	313 (6.0)	2842 (70.6)	-1891 (49.0)

2.3.2.2 Environment

There was no significant main effect of environment for any of the z kinematic measures.

2.3.2.3 Trial

The ANOVAs revealed a significant main effect of trial for each of the kinematic measures: peak displacement ($F_{9, 171} = 7.394$; $p < .001$), peak velocity ($F_{9, 171} = 10.128$; $p < .001$), peak acceleration ($F_{9, 171} = 6.031$; $p = .001$) and peak deceleration ($F_{9, 171} = 4.28$; $p = .003$). On average, all peak z kinematic measures increased over the first 4 lifts with each cube in each environment, and then did not significantly change over the remaining 6 trials (Figure 2.4). There was no interaction between trial and cube size.

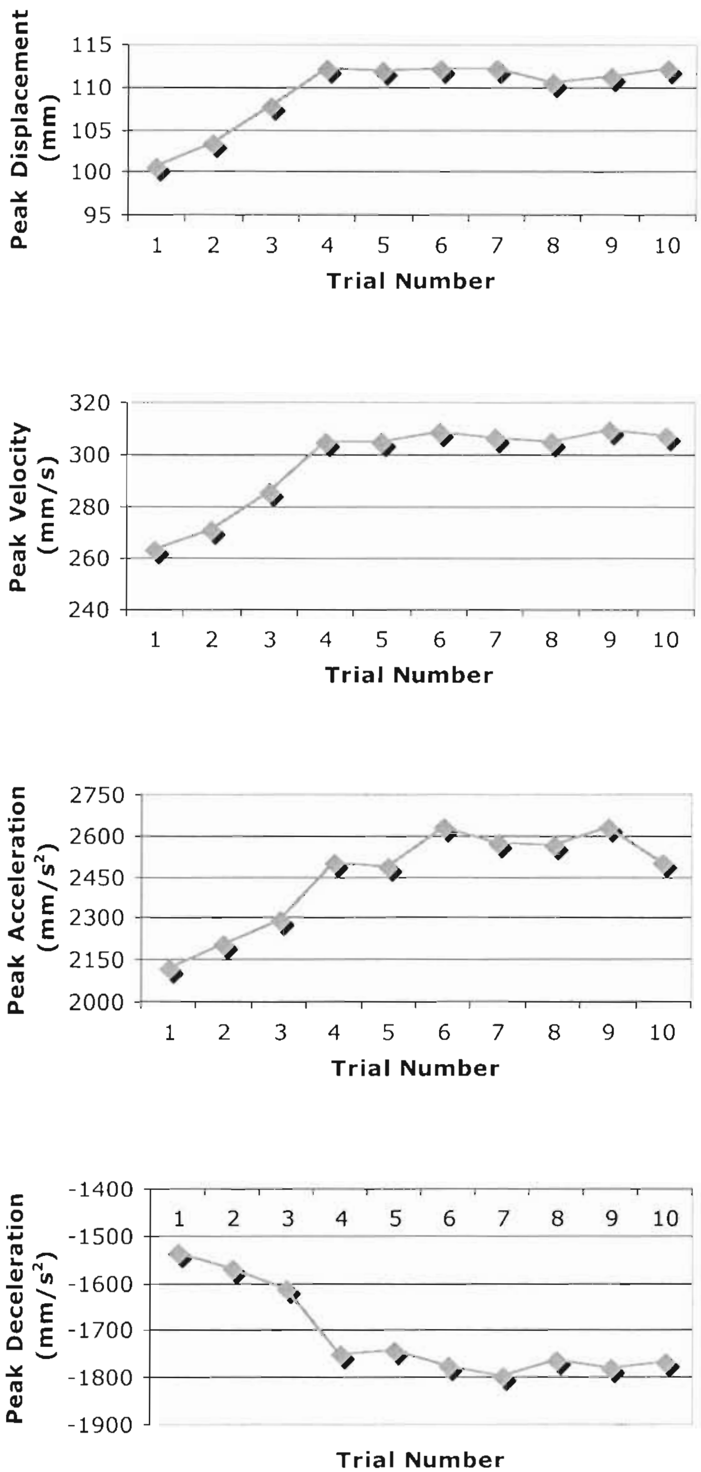

Figure 2.4 Significant main effect of trial on peak z displacement, velocity, acceleration and deceleration. Graphs show number of trials with each cube size.

2.4 Discussion

This is the first SWI experiment designed to allow analysis of movement while providing size cues from both visual and haptic modalities concurrently. Previous SWI studies investigating dynamics and/or kinematics have removed vision while providing haptic size cues (Gordon et al., 1991b) or, more often, have removed haptic size cues while providing visual size cues (Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000).

Experiment 1 has reaffirmed the robustness of the SWI, showing that it can be elicited by grasping and lifting in a natural environment that provides direct vision of the cubes, as well in an augmented environment in which computer-generated graphical cubes are superimposed upon the physical cubes. The lack of a significant size-by-environment interaction confirms that the SWI was elicited in an equivalent manner in both environments, and lack of a size-by-trial interaction confirms that the strength of the illusion did not significantly change over time, in keeping with several previous SWI studies (e.g., Flanagan & Beltzner, 2000).

In addition, Experiment 1 showed that larger cubes were reliably lifted with greater kinematics (and by inference, with greater vertical force), despite weighing the same as smaller cubes. This supports an expectation or sensory mismatch theory of the SWI (e.g., Davis & Roberts, 1976; Granit, 1972; Martin & Muller, 1899; Muller & Schumann, 1889; Murray et al., 1999; Ross, 1969), which discusses the illusion in terms of an action-perception mismatch, wherein the unexpectedly faster-lifted larger cube gives rise to a judgment of relative lightness.

In the present experiment, this difference in kinematics between cubes did not go away after repeated lifts with the objects. That is, while kinematics changed over time, they changed in the same manner for all cube sizes, contrary to the findings of some previous studies (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006) in which grip and load forces and their rates were initially scaled to the expected rather than actual weight of the cubes, but were quickly scaled to the actual weight of the stimuli after a small number of repeated lifts (i.e., 5 - 10 lifts with each cube), despite a persisting perceptual illusion. They also stand in contrast to those of Mon-Williams and Murray (2000) who found no reliable differences in load force between different box sizes; the effect of visual size cues on grip force and grip force rate diminished once an object was lifted more than once.

The present results, then, support the notion that there exists an expectation of weight that is tied to object size and that is relatively immune to experience with an object's actual weight. In this experiment, visual and haptic size cues appeared to override any sensorimotor memory based on the objects' actual (i.e., equal) weights.

The present results also highlight an action-perception dissociation, though not in the manner observed by previous researchers (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000). Here, while heaviness estimates remained constant over time, kinematics for all cubes increased over the first four lifts with each cube size, and then remained unchanged for the six lifts thereafter. It seems reasonable to assume that this pattern of movements is due to a familiarity or practice effect, wherein each subject performs relatively more cautiously at first but increases lifting speed with experience and practice, to some maximally comfortable lift rate.

It is important to note that, overall, participants judged the cubes to feel similarly heavy in the Augmented and Natural environments, despite lack of vision of the grasping/lifting hand in the Augmented environment. Many researchers point to the importance of vision of the hand as a referent for accurate visual size discrimination (Jeannerod & Decety, 1990) and some have observed that size estimates increase when sight of the hand is available (e.g., Heller, Calcaterra, Green & Brown, 1999). Since the SWI seems to depend on size cues, one might expect greater heaviness estimates in the Augmented environment due to a perception of relatively smaller cubes in that environment, arising from lack of vision of the hand. No such significant difference was observed in the present experiment; the Augmented environment employed here appears to have sufficiently simulated a Natural environment, for the purposes of grasping and lifting cubes and eliciting the SWI.

In summary, the Augmented environment employed in Experiment 1 appears to have elicited a visuo-haptic SWI in a manner akin to the Natural environment. That is, the magnitude of the perceptual illusion, as well as the kinematics observed, were not significantly different between the two environments. Therefore, the Augmented environment used here seems a worthy tool for further visuo-haptic SWI investigations. Experiment 2 used this environment in an attempt to better understand the relative role of visual and haptic size cues in the SWI during bimodal lifting.

3 EXPERIMENT 2: MODULATING THE SIZE-WEIGHT ILLUSION IN AN AUGMENTED ENVIRONMENT USING INCONGRUENT HAPTIC AND VISUAL SIZE INFORMATION

As seen in Experiment 1, the SWI occurs when people lift objects that have the same weight but different sizes. Traditionally, information about the size of the objects is attained through both the visual and haptic modalities. However, researchers have shown that the SWI may also be induced with input from either modality on its own. For instance, it has been shown that an equally strong SWI can be induced by presenting haptic size information in the absence of any visual size information (Ellis & Lederman, 1993; Pick & Pick, 1967), and that a relatively weaker SWI may be obtained by presenting only visual size information in the absence of haptic size information (Ellis & Lederman, 1993). In other words, while visual size cues appear sufficient to induce a relatively weak SWI, the combination of vision and haptic size cues generates an illusion that is not significantly different from one derived from haptic cues alone. This finding implies that visual information contributes little, if anything, to heaviness perception during bimodal lifting tasks in which we see and grasp the object, and only significantly influences perception when haptic size information is removed from the equation. In other words, when size information from both modalities is available, heaviness perception is influenced by the object's weight and haptic size cues only, and not by visual size cues.

But is this the complete story? Could it be that vision *does* influence heaviness perception during bimodal lifting tasks but that its influence is masked by the perceptual system's relative reliance on haptic size information during this type of task? If visual size cues do affect heaviness perception during bimodal lifting, then selectively varying the visual cues should produce differential heaviness estimates. The difficulty, of course, is varying the visual input independently from the haptic input, so as to avoid confounding effects. Experimenters have attempted to do this by removing haptic size cues altogether, but these studies do not fully answer the question, since the lifting task is then fundamentally different from the everyday, bimodal task. Understanding how vision affects heaviness perception in a unimodal lifting task is not necessarily the same as understanding its role during bimodal lifting.

In normal, everyday, bimodal lifting tasks, the visual and haptic modalities are providing congruent, and thus, redundant size information. It is heaviness perception under these circumstances in which vision appears to take a backseat to haptic size information. But what would happen if the two modalities were providing incongruent, and thus, non-redundant, size information? The fact that a SWI can be induced using visual size cues alone in the absence of haptic cues (Ellis & Lederman, 1993; Flanagan & Beltzner, 2000; Kawai et al., 2006; Masin & Crestoni, 1988; Mon-Williams & Murray, 2000) implies that visual size information does have *some* influence on heaviness perception. One could conceive, therefore, that under certain circumstances visual size information could modulate an otherwise haptically-induced SWI.

The present experiment tested whether visual size information could modulate the haptically induced SWI by presenting graphical size information to the visual modality that was congruent or incongruent with size information presented to the haptic modality. This incongruence of size information was created using an augmented reality environment in which graphical images of object size were manipulated independently of the physical object sizes. By directly pitting the visual and haptic modalities against one another in a bimodal lifting task, it was hoped that vision's influence on heaviness perception could better be addressed.

If the magnitude of the traditional haptic-plus-vision SWI (presumably based on haptic size information alone -- see Ellis and Lederman, 1993) is modulated in this experiment, then we would infer that it was due to incongruent visual size information. That is, visual size information is not entirely "captured" by haptic size information in bimodal lifting tasks when the two modalities are presenting non-redundant information.

3.1 Hypotheses

It was predicted that:

(a) differences in physical size (haptic size information) between cubes in the present experiment would induce a SWI. That is, the Small physical cube would feel the heaviest, followed by the Medium cube, followed by the Large cube, as in Experiment 1. This is based on previous experiments indicating that haptic size cues alone are sufficient to induce a SWI (Ellis & Lederman, 1994; Gordon et al., 1991b; Pick & Pick, 1967);

(b) the SWI induced in the present experiment would be modulated by the presentation of incongruent graphical size information. As such, each physical cube would feel heavier when paired with a smaller, incongruent graphical cube than when paired with a graphical cube that was equal (congruent) in size, and this would in turn feel heavier than when the same physical cube was paired with a larger incongruent graphical cube. Such modulation would suggest that vision can bias an otherwise haptically-induced SWI. This is based on previous experiments indicating that visual size cues alone are sufficient to induce the SWI (e.g., Davis & Roberts, 1976; Ellis & Lederman, 1993; Flanagan & Beltzner, 2000; Gordon et al., 1991a);

(c) participants would initially lift with greater peak velocity, peak acceleration and peak deceleration for larger physical cubes than for smaller ones, as in Experiment 1 and based on previous findings (Gordon et al., 1991b);

(d) participants would initially lift with greater peak velocity, peak acceleration and peak deceleration for cubes that are paired with relatively larger graphical cubes, suggesting that the motor system is influenced by graphic size in addition to physical size (e.g., Kawai et al., 2002). This follows from studies in which peak dynamic and/or kinematic values covaried with visual size cues;

(e) the motor system would adjust to the equal weights of the cubes over repeated trials despite the persistence of differences in psychophysical heaviness estimates (see Flanagan & Beltzner, 2000, Mon-Williams & Murray, 2000).

3.2 Method

3.2.1 Participants

Participants consisted of the same 20 volunteers that participated in Experiment 1. Experiment 2 occurred immediately following Experiment 1 for all participants. A honourarium of $10 was provided for the one-hour participation in both experiments.

3.2.2 Task and Materials

The procedure is similar to that described for the augmented condition of Experiment 1, except that here, the size of the graphical cube sometimes matched the physical cube size (i.e., the sizes were congruent) and sometimes did not (i.e., incongruent). Physical cubes were those used in Experiment 1. Each physical cube was paired with three different graphical cubes: one that was slightly smaller in size by 0.75 cm (Smaller), one that was the same size (Equal), and one that was slightly larger by 0.75 cm (Larger), yielding a total of nine physical-graphical size combinations (Table 3.1 and Figure 3.1). Physical-graphical size pairings were pseudo-randomly presented such that each of the nine combinations occurred 5 times and no combination occurred more than twice consecutively, resulting in a total of 45 lifts. The three-dimensional position of the cube was recorded throughout each lift. Participants provided a verbal judgment of cube heaviness at the height of each lift, using the method of Absolute Magnitude Estimation (Stevens, 1975; Zwislocki & Goodman, 1980), as in Experiment 1.

Table 3.1 **Physical-graphical cube pairings for Experiment 2. Cube labels in boldface type. Numbers represent cube face widths (cube volumes in brackets).**

Physical Cubes	**Graphical Cubes** *Smaller*	***Equal***	***Larger***
Small 3.00 cm	2.25 cm (11.39 cc)	3.00 cm (27.00 cc)	3.75 cm (52.73 cc)
Medium 4.50 cm	3.75 cm (52.73 cc)	4.50 cm (91.13 cc)	5.25 cm (144.70 cc)
Large 6.00 cm	5.25 cm (144.70 cc)	6.00 cm (216.00 cc)	6.75 cm (307.55 cc)

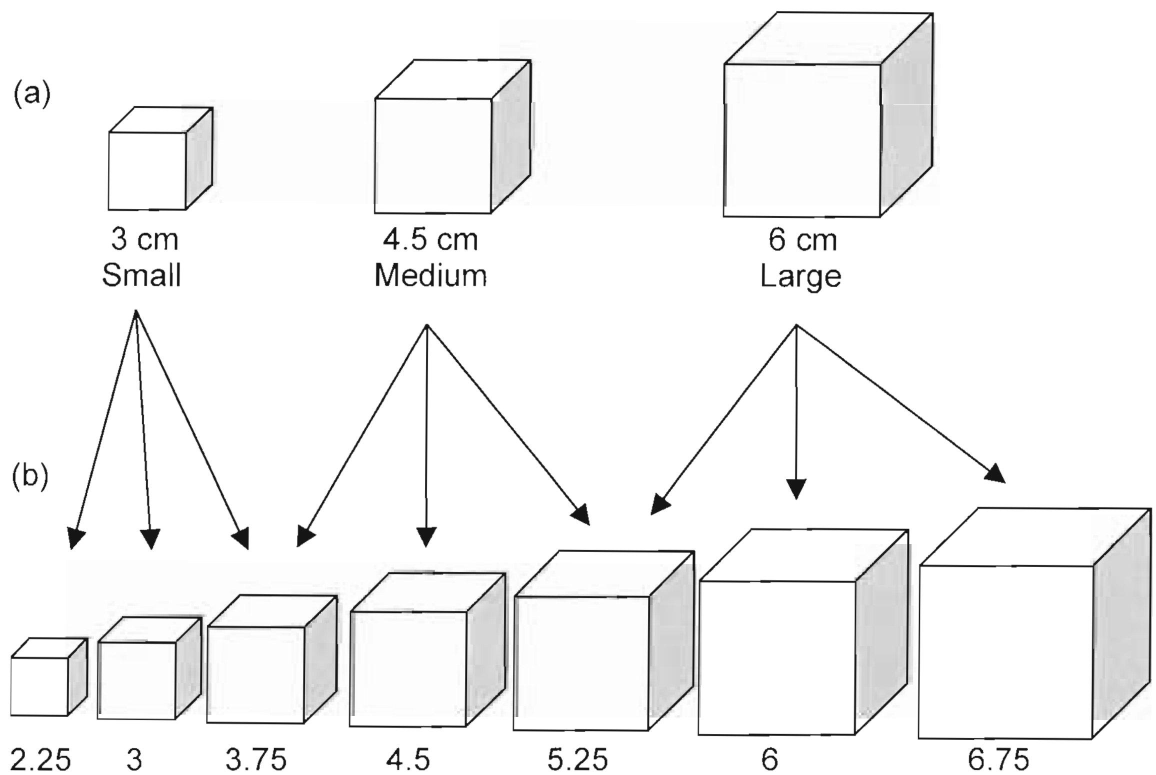

Figure 3.1 **(a) Physical and (b) graphical cubes used in Experiment 2. Lines indicate physical-graphic pairings. Face widths measured in centimetres.**

3.2.3 Experimental Apparatus

Participants performed all lifts in an augmented environment, as described in Experiment 1.

3.2.4 Instructions to Participants

"For the next phase of the experiment, you will be lifting cubes and providing heaviness estimates as before, except that we will now be using a slightly larger set of cubes. Do you have any questions?"

3.2.5 Data Processing and Analysis

Collection and pre-processing of perceptual and kinematic data followed the methods described in Experiment 1.

As in Experiment 1, dependent measures included subjective heaviness reports, peak displacement, peak velocity, peak acceleration, and peak deceleration. Each dependent measure was analysed using 3 (physical size: Small, Medium, Large) x 3 (graphical size: Smaller, Equal, Larger) x 5 (trials per physical-graphical size combination) repeated measures ANOVAs. Planned "repeated" contrasts were used to compare levels of physical and graphical sizes.

The present experimental design allowed for analysis of heaviness scores with a given physical size paired with three different graphical sizes. In addition, two *a priori* planned comparisons were conducted for heaviness estimates in which cubes of *different physical sizes* were paired the *same graphical size,* one for the 3.75 cm and one for the 5.25 cm graphical sizes (Figure 3.2). These two subsets of the data were analysed using 2 (physical size) x 5 (trials) repeated-measures ANOVAs.

For all the above analyses, when the assumption of sphericity was not met, adjustments to the degrees of freedom and p values were made. Depending on the epsilon values, Huynh-Feldt or Greenhouse-Geisser corrections are reported (Howell, 1997). Significance for all tests was based on an a priori alpha level of α = .05.

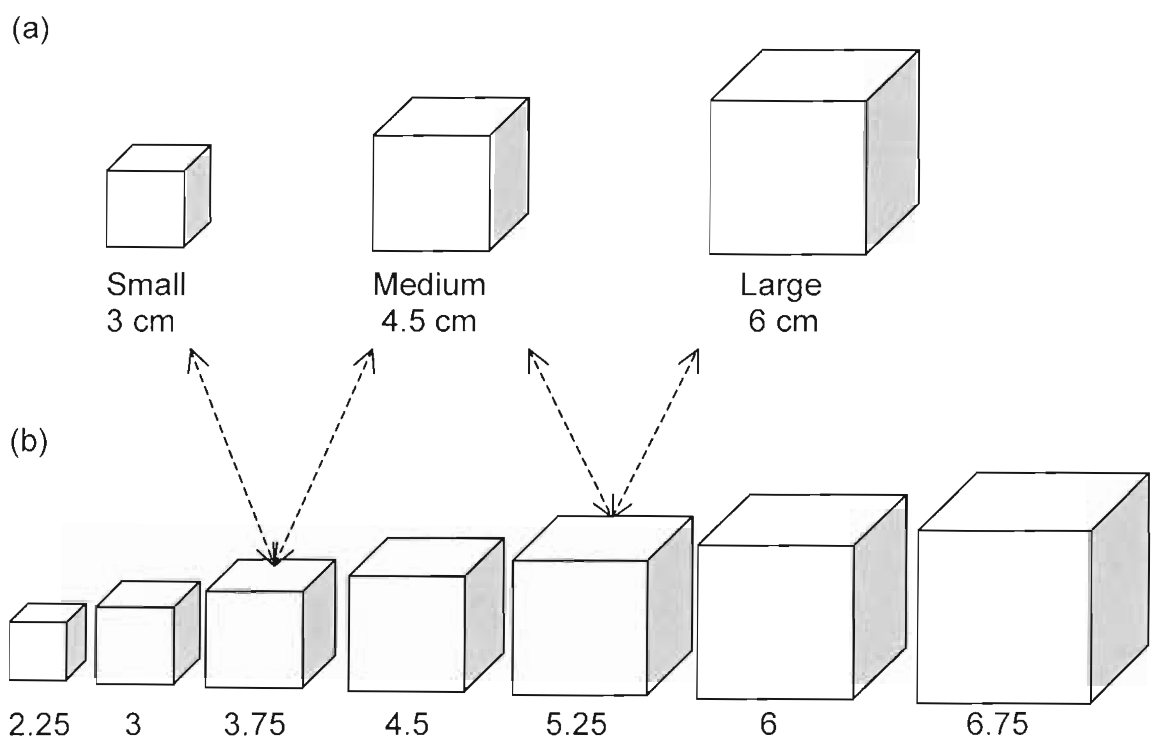

Figure 3.2 (a) Physical and (b) graphic cubes used in Experiment 2. Dashed lines indicate the two planned contrasts for physical-graphic pairings in which two physical cubes are paired with a common graphic cube.

3.3 Results

3.3.1 Perceived Heaviness

As in Experiment 1, there were no significant interactions between any of physical size, graphical size or trial; as such, only main effects are reported below.

3.3.1.1 Physical Size

Analysis of the transformed heaviness scores revealed a significant main effect of physical size on adjusted subjective heaviness judgments ($F_{2, 38}$ = 52.378; p < .001). Planned contrasts revealed that the Small physical cube (mean = 1.350; SE = 0.007) was perceived as feeling significantly heavier ($F_{1, 19}$ = 50.727; p < .001) than the Medium physical cube (mean = 1.174; SE = 0.008), and the Medium cube was perceived as feeling significantly heavier ($F_{1, 19}$ = 45.457; p < .001) than the Large physical cube (mean = 0.933; SE = 0.014) (Figure 3.3).

3.3.1.2 Graphical Size

The ANOVA also revealed a significant main effect of graphical size on adjusted subjective heaviness scores ($F_{2, 38}$ = 45.235; p < .001). Collapsed across physical sizes and trials, a given physical cube paired with its Smaller graphic counterpart (mean = 1.218; SE = 0.013) was judged to feel significantly heavier ($F_{1, 19}$ = 34.477; p < .001) than when paired with its Equal graphic counterpart (mean = 1.152; SE = 0.014), and this was, in turn, felt to be significantly heavier ($F_{1, 19}$ = 39.644; p < .001) than when paired with its Larger graphic counterpart (mean = 1.087; SE = 0.014). That is, while grasping a given physical cube, concurrently viewing a Smaller graphical size elicits a greater feeling of heaviness than when lifting the same physical cube while viewing a Larger size. Viewing a congruently sized (Equal) graphic elicits a feeling of heaviness that falls between the two incongruently sized graphics (Figure 3.3).

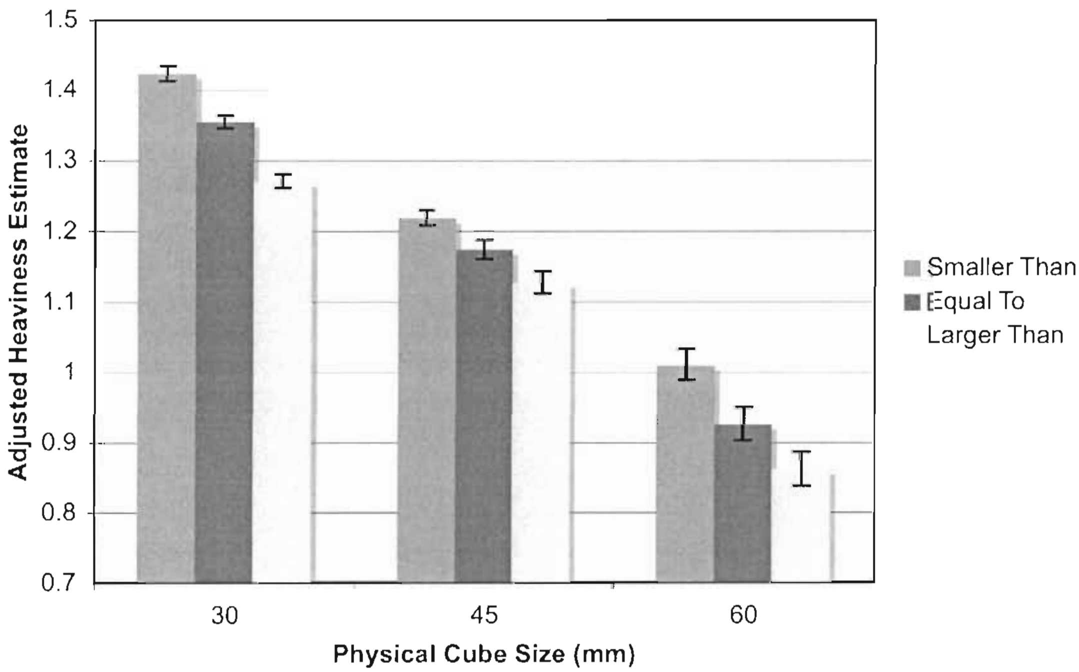

Figure 3.3 **Effect of physical and graphical size information on adjusted subjective heaviness scores. The smaller the physical size, the greater the judgment of heaviness. The same pattern exists with graphical sizes. Note: the Small Physical - Larger Graphic pairing provides the same graphic size as the Medium Physical - Smaller Graphic pairing, yet heaviness judgments are significantly different between these pairings. The same is true for the Medium Physical - Larger Graphic and Large Physical - Smaller Graphic comparison. Error bars represent standard errors of the mean.**

3.3.1.3 Different Physical Sizes with Uniform Graphical Size

The planned contrasts for cases in which a given graphical size was paired with two different physical sizes showed a significant effect of physical size on heaviness estimates. For the 3.75 cm graphic cube, the 3 cm physical cube was perceived as heavier than the 4.5 cm physical cube ($F_{1, 19} = 5.371$; $p = .032$). For the 5.25 cm graphic cube, the 4.5 cm physical cube was perceived as heavier than the 6 cm physical cube ($F_{1, 19} = 20.253$; $p < .001$). That is, despite seeing the same sized graphical cube, a smaller physical cube size elicited a perception of greater heaviness when grasped.

3.3.1.4 Trial

There was no significant effect of trial on subjective heaviness judgments, nor were there any significant interactions. That is, neither heaviness estimates nor the magnitude of the SWI elicited by physical and graphical size cues changed over time.

3.3.2 Kinematics in the Vertical (z) Axis

Because each of the kinematic measures showed similar effects, they are presented together below. There were no significant interactions for any kinematic variables. Only main effects are reported below.

3.3.2.1 Physical Size

Analysis revealed significant main effects of physical size on peak velocity ($F_{2, 38} = 12.315$; $p = .001$), peak acceleration ($F_{2, 38} = 35.608$; $p < .001$), and peak deceleration ($F_{2, 38} = 16.866$; $p < .001$) of the vertical lift, with the main effect of physical size on peak displacement approaching significance ($F_{2, 38} = 3.419$; $p = .057$). Grasping cubes of larger physical size yielded greater kinematic measures compared to cubes of smaller physical size (Table 3.2).

Table 3.2 **Means for each z kinematic measure for each physical size. Standard errors reported in brackets. Shaded cells indicate means that were not significantly different from each other, as determined by planned contrasts.**

Physical Size	Peak z Displacement (mm)	Peak z Velocity (mm/s)	Peak z Acceleration (mm/s^2)	Peak z Deceleration (mm/s^2)
Small (3 cm)	103 (2.0)	271 (6.8)	2039 (67.0)	-1451 (44.8)
Medium (4.5 cm)	104 (1.7)	289 (6.7)	2532 (79.5)	-1625 (49.0)
Large (6 cm)	108 (1.7)	308 (7.2)	2832 (88.0)	-1784 (53.4)

3.3.2.2 Graphical Size

There was no significant main effect of graphical size for any of the kinematic measures. Lift kinematics, then, were affected only by physical size.

3.3.2.3 Trial

Analysis revealed a significant main effect of trial on peak displacement ($F_{4, 76} = 3.777$; $p = .025$), peak velocity ($F_{4, 76} = 5.696$; $p = .003$), peak acceleration ($F_{4, 76} = 7.912$; $p < .001$), and peak deceleration ($F_{4, 76} = 3.734$; $p = .030$). In general, all kinematic measures increased over the course of the five trials, similar to the pattern seen for the first four trials in Experiment 1. As in Experiment 1, the lack of significant interactions indicates kinematic measures differed over time independently of physical and graphical cube size.

3.4 Discussion

Once again, as in Experiment 1, the SWI was elicited in a computer-augmented environment by having participants grasp and lift cubes of differing physical size but uniform weight. In Experiment 2, lift kinematics covaried with physical cube size such that greater peak values were associated with larger cube sizes, and this difference persisted over trials, in a manner similar to Experiment 1.

The results of Experiment 2 indicate that graphical size cues can be used to exaggerate or attenuate the SWI during bimodal lifting in the Augmented environment. That is, heaviness estimates associated with a given physical cube size can differ depending on the size of the graphical cube with which it is paired. This result suggests that heaviness estimates during bimodal lifting are not solely determined by the haptic size cues that are present, but are also influenced by visual size cues. This stands in contrast to the previous suggestion that vision is "captured" by haptics during bimodal lifting tasks (Ellis & Lederman, 1993). However, in the present experiment, the effect of graphical size is small relative to the effect of physical size, in keeping with the findings of Ellis and Lederman.

Despite heaviness estimates being affected by both haptic and visual size cues, it appears that lift kinematics were only influenced by haptic size information and not by visual size information. This contrasts with the findings of some previous studies (e.g., Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan et al., 2001; Gordon et al., 1991a, c; Kawai et al., 2002; Mon-Williams & Murray, 2000) in which differences in kinematics or dynamics were observed despite unchanging haptic size information, thus arising, presumably, by changes in visual size cues alone.

In some respects, however, the present results may be considered consistent with those of some previous researchers (Flanagan & Beltzner, 2000;

Flanagan et al., 2001; Mon-Williams & Murray, 2000). In these studies, haptic size cues were kept constant and were irrelevant, and it was found that differences in forces arising from visual size cues, when they existed at all, disappeared after the first few trials, with remaining lifts yielding essentially uniform dynamics across visual sizes. In the present experiment, too, for any given physical size (i.e., haptic size held constant) there appeared no differences in kinematics arising from visual size cues.

It is possible that the graphical sizes used in the present experiment did not differ sufficiently from one another to produce kinematic differences. A greater difference between graphical sizes may have yielded different results, as size differences here were smaller than in most previous experiments (Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan et al., 2001; Gordon et al., 1991a, c; Kawai et al., 2002). It should be remembered, however, that the differences between graphical sizes in the present experiment were, in fact, great enough to elicit a clear effect on perceptual judgments, though this effect was small relative to that of physical size.

Also of note are the SWI action-perception dissociations observed in Experiment 2. As in Experiment 1, heaviness estimates remained unchanged over trials despite all peak kinematic values increasing over trials. Also, as just mentioned, heaviness estimates were significantly affected by graphical size cues while kinematics were not. These dissociations are different, however, than those described by previous researchers (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000).

4 GENERAL DISCUSSION

4.1 Summary of Results

The main goals of the present study were to: (a) discover whether an augmented environment could be used to induce a bimodal (both haptic and visual size cues available) size-weight illusion (SWI) in a manner similar to lifting in a natural environment; (b) determine whether visual size cues mediate bimodal SWIs in which both visual and haptic size cues are present; and (c) better understand the relationship between lift kinematics and heaviness perception and the effect of repeated lifts on this relationship.

The present study is the first to analyse lifting movements in a bimodal (i.e., vision + haptic) SWI paradigm. Previous SWI studies investigating dynamics and/or kinematics have removed vision while providing haptic size cues (Gordon et al., 1991b) or, more often, have removed haptic size cues while providing visual size cues (Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Kawai et al., 2002; Mon-Williams & Murray, 2000). The present experiments were designed to allow analysis of movement while providing object size cues from both modalities concurrently.

Experiment 1 demonstrated that participants' judgments of heaviness were dependent on cube size in the manner described by the SWI, and that this pattern of judgments did not differ significantly between a natural environment and an augmented environment in which a computer-generated graphic cube is superimposed over a physical cube. Experiment 2 showed that when both haptic and visual size cues were available during lifting, heaviness estimates depended on *both* haptic and visual size cues, and not haptic size cues alone, as might be inferred from previous research (Ellis & Lederman, 1993). Finally, in both experiments, larger physical cubes were lifted with greater peak displacement, velocity, acceleration and deceleration than smaller cubes, despite the fact that all cubes had the same physical weight. This association between kinematics and physical size rather than weight persisted despite presumably ample opportunity to adjust to the cubes' actual weight (i.e., 60 lifts over two environments in the first experiment and another 45 lifts in the immediately subsequent experiment, all with the same weight). However, all kinematic measurements increased over time for all cubes in both environments, and in both Experiments 1 and 2, despite relatively unchanging heaviness perception, suggesting a dissociation between action and perception.

4.2 SWI Investigations Using Augmented Environments

As stated previously, the present study is the first to analyse lifting movements in a bimodal (i.e., visuo-haptic) SWI paradigm. We believe it is also the first instance in which the SWI has been elicited while providing both haptic and visual size cues while at the same time eliminating vision of one's hand. Despite seeing neither one's grasping and lifting hand, nor the physical object being lifted (two seemingly large departures from natural, everyday lifting tasks), the SWI still occurred as expected. The Augmented environment used here elicited a bimodal SWI; neither the magnitude of the illusion nor the kinematics involved in lifting significantly differed between the Augmented and Natural environment. Because augmented environments allow information to be presented to different modalities concurrently and independently of one another, such environments promise to be useful tools for SWI and other multisensory integration investigations.

One of the benefits of being able to perturb graphical size cues independently of physical cues, as was done in Experiment 2, is that it helps to rule out the possibility that the SWI is simply a product of rotational and torque differences arising from differences in density and distribution of mass between cubes. The fact that the SWI in Experiment 2 was modulated by graphical size cues negates this possibility as the only cause of the SWI, since the physics involved in lifting a given physical cube do not vary with changing graphics. The augmented environment allows graphical cues to vary independently of the physical properties of the object, a feat that is not easily accomplished in experiments in the real world.

The present findings are in keeping with those of Kawai et al. (2006) in which the SWI was induced while lifting the same physical object paired with differing graphics, and with vision-only SWI experiments in which cubes are lifted while suspended from a tether (Ellis & Lederman, 1993) or lifted with a tether and pulley system (Masin & Crestoni, 1988). Experiments such as these suggest that there is more to the SWI than can be explained the properties and mechanics of interacting with the physical objects (cf., Amazeen & Turvey, 1996).

4.3 Heaviness Perception During Bimodal SWI Tasks Depends on Both Haptic *and* Visual Size Cues

Past experiments have suggested that the influence of visual size cues on heaviness perception in bimodal SWI paradigms is negligible compared to the influence of available haptic size cues (Ellis & Lederman, 1993). Experiment 2 showed that when both haptic and visual size cues were available during lifting, heaviness estimates depended on *both* haptic and visual size cues, and not haptic size cues alone. The SWI in this bimodal lifting paradigm was exaggerated with smaller, and attenuated with larger, graphical size cues, suggesting that such cues are not negligible as had been thought, and vision is not "captured" by haptics in this type of task (cf., Ellis & Lederman, 1993). However, it should be noted that heaviness estimates were more strongly influenced by haptic size cues than by graphic ones, consistent with Ellis and Lederman.

4.4 Action and Perception and the SWI

Davis and Roberts (1976) observed, during sequential lifting with two objects in which weight and haptic size cues were uniform and visual size cues differed, that when the SWI occurred, the larger object was usually lifted with greater force (as inferred from lift kinematics: acceleration, deceleration and velocity) and yet judged to feel relatively lighter than the smaller object. This "inverse" action-perception relationship was also observed in grip and lift forces and vertical lifting acceleration by Gordon et al. (1991a, c), who varied visual size cues while maintaining haptic size cues. Varying haptic size cues while removing vision yielded similar results (Gordon et al., 1991b). In the present study, too, larger kinematic values were seen during lifts of larger cubes, and these cubes were judged to feel lighter than smaller cubes. These results support the suggestion that size cues lead to an expectation of object weight, and that the SWI is due to a mismatch between the forces used for an object's expected weight and those required for its actual weight.

4.5 Sensorimotor Memory and Adaptation of Lift Dynamics

Despite the previous findings (Davis & Roberts, 1976; Gordon et al., 1991 a - c), it has been suggested that repeated lifting of an object should create a sensorimotor memory of the object's actual weight, and this memory should quickly lead to an appropriate scaling of forces for subsequent lifts (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Johansson & Westling, 1988). This memory, after all, should provide a more accurate estimate of an object's actual weight than should size cues. While Gordon et al. (1991a) observed no such force scaling over lifts, their experiment used only a small number of lifts (i.e., 18: six trials with each of three cube sizes). Flanagan and Beltzner (2000) attempted to show the effect of sensorimotor memory by having subjects make relatively more lifts with each of two cubes, and they observed that while the SWI persisted, grip and lift forces and their rates scaled to the actual (i.e., equal) weight of objects within the first 5 - 10 lifts of each. This sensorimotor adaptation to object weight has since been replicated (Flanagan et al., 2001; Grandy & Westwood, 2006) and suggests that the perceptual SWI cannot be explained in terms of a sensory-motor mismatch generated by inappropriately applied forces.

4.6 Lack of Kinematic Adaptation to Object Weight Over Lifts

In contrast to the adaptation of lift dynamics observed in the aforementioned studies (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006), lift kinematics observed in the present study did not scale to the actual (i.e., equal) weight of cubes, despite there being presumably ample lifts on which to create such a sensorimotor memory. In Experiment 1, participants lifted each of the three cubes 10 times, in each of the Natural and Augmented environments. Subsequently, each physical cube was grasped and lifted another 15 times in Experiment 2. As such, participants lifted the exact same weight 105 times within one hour. Based on the results of previous studies (Flanagan & Beltzner, 2000; Flanangan et al., 2001; Grandy & Westwood, 2006), one would expect to see some adaptation of kinematics to actual weight given this number of lifts.

Several factors may have contributed to this lack of adaptation in the present study. Flanagan et al. (2001) describe sensorimotor adaptation in terms of the motor system, via development of a weight-based sensorimotor memory, learning to suppress or overcome the natural size-weight association that has been elicited by available (erroneous) size cues. In their study and others showing this adaptation (Flanagan & Beltzner, 2000; Grandy & Westwood, 2006), only visual size cues required such suppressing, since haptic size cues were not available in their paradigm. It seems reasonable to imagine that any cue-derived size-weight association might be stronger and/or more difficult to suppress given the presence of relatively more size cues. After all, SWI tasks providing haptic size cues alone and those providing visual size cues alone both induce size-related force and kinematic differences between cubes (e.g., Gordon et al., 1991a, b), so some manner of additive effect when both modalities are concurrently providing size cues does not seem unrealistic. As such, lifting in a bimodal SWI paradigm, like the one used here, in which both visual and haptic size cues are available during lifting, may require a relatively longer period of time to achieve such suppression/adaptation, if such adaptation occurs at all. Future studies could compare adaptation during bimodal and unimodal SWI tasks to determine if such an additive effect exists. One could imagine, for instance, comparing the time required for sensorimotor adaptation to occur while lifting two cubes with visual size cues only (as in previous experiments, e.g., Flanagan & Beltzner, 2000) with that required while lifting two cubes with both visual and haptic size cues available. If there is some manner of additive effect as proposed, motor adaptation should occur earlier in the former condition than in the latter.

The number of different objects to be lifted may also impact the rate of motor adaptation to object weight. Adaptation may be more difficult when encountering more sizes of object, despite maintenance of uniform weight. Akin to the previous suggestion, ease of suppression may depend on the amount of competing size information. In the present study, more stimuli were employed (i.e., three cubes in Experiment 1 and nine in Experiment 2) than in previous studies showing adaptation using two stimuli (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; though see Mon-Williams &

Murray, 2000). Recall that while Flanagan and Beltzner and Flanagan et al. saw adaptation within 5 - 10 lifts of their equally weighted two cubes (i.e., within 10 - 20 total lifts with that particular weight), Gordon et al. (1991a) did not see adaptation within 6 lifts of their three equally weighted cubes (i.e., within 18 total lifts with that particular weight), nor did we with many more lifts of three cubes. Future studies might investigate this proposed inverse relationship between number of stimuli and rate of sensorimotor adaptation. It should be noted, however, that Mon-Williams and Murray (2000) used three objects and reported adaptation of grip force upon the second lift of a given size.

Another factor that possibly affects rate of sensorimotor adaptation is the order in which the stimuli are presented. Gordon et al. (1991b) observed that applied forces differed between cube sizes (A, B) only when presented randomly and not when the same boxes were lifted consecutively (A, A, ... B, B...). Most studies showing adaptation have presented two cubes in a sequential manner, with participants repeatedly lifting one cube and then the other (A, B, A, B...). In the present study, cubes were presented in a pseudorandom order such that participants never knew beforehand which cube would be presented next. It may be that size predictability/uncertainty between lifts influences the rate at which the motor system suppresses size cues; the more ordered the presentation, the more easily cues are suppressed.

Continuing discussion of the impact of stimulus uncertainty, it should be noted that participants in the present study were explicitly told that they would be lifting cubes of various sizes *and* weights and were shown a large number of different cubes prior to the experiments. In other studies, participants were not explicitly told that cubes would have different weights, nor were they led to believe that many different cubes would be lifted. In most cases, subjects could clearly see that there were only two objects to be repeatedly lifted (e.g., Flanagan & Beltzner, 2000). It is possible that the expectation of different cubes and different weights in the present study persisted and prevented suppression of size cues.

Another possible factor may be the length of time that participants spend holding the objects. In the present study, participants were told to hold the cube at the top of the lift for approximately 1 s, or whatever felt comfortable, before replacing it; few held it longer than 1 s. Previous studies have had participants hold the object at the top of the lift for between 2 - 8 s (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Gordon et al., 1991a - c; Kawai et al., 2002; Mon-Williams & Murray, 2000), thus allowing more continuous exposure to the actual weight of the objects and, perhaps, more time to develop a sensorimotor memory that would influence subsequent lifts.

The weight of the stimuli was also significantly different between studies. Previous studies (Davis & Roberts, 1976; Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Gordon et al., 1991a - c; Mon-Williams & Murray, 2000) have used much heavier stimuli (250 - 1200 g) than the present study (57 g), though density was similar between studies. Perhaps a sensorimotor memory that would influence subsequent lift forces to a noticeable degree requires heavier stimuli, with lighter stimuli making suppression of size cues relatively more difficult. It should be noted, however, that the perceptual SWI has been reported not to be dependent on object weight (e.g., Ellis & Lederman, 1993).

The size/volume difference between cubes in previous studies (e.g., Flanagan & Beltzner, 2000) was much larger than in the present study. As such, size cues would likely cause a greater initial difference in movement parameters between cubes, since the difference in expected weights would be larger in those studies. Attenuation of those forces over time might, therefore, be much easier to observe than any attenuation that might occur in the present study. Future investigations into sensorimotor adaptation should take this into account.

4.7 Action-Perception Dissociations and the SWI

While some researchers have reported actions covarying with heaviness perceptions in SWI experiments, such that larger objects are lifted with greater force and acceleration despite being reported to feel lighter than smaller objects (Davis & Roberts, 1976; Gordon et al., 1991a - c), several researchers have observed dissociation between action and perception during SWI experiments (Flanagan & Beltzner, 2000; Flanagan et al., 2001; Grandy & Westwood, 2006; Mon-Williams & Murray, 2000). As stated previously, lift forces and movements often adapt to the actual weight of objects despite heaviness perception remaining unaltered.

In the present study, heaviness perception and lift kinematics were seen to covary in the manner observed by Davis and Roberts (1976) and Gordon and colleagues (1991 a - c), and lift kinematics did not adapt to the actual weight of objects. However, an action-perception dissociation was nonetheless observed. In the present experiments, all measured kinematic values were smallest for the first lift with each cube size and subsequently increased over lifts (up to the fourth lift in Experiment 1). Heaviness perception, however, remained constant over the same course of time. Actions changed but perceptions did not. It would appear, therefore, that processes underlying heaviness perception are independent of those controlling lifting actions.

Other researchers have suggested such a distinction. It has been proposed that heaviness perception reflects density rather than weight, that it is a function of *both weight and volume together*, a product of sensory information integration (Anderson, 1970; Cross & Rotkin, 1975). Changes in density, independent of changes in mass, have been shown to affect judgements of heaviness (Kawai, 2002; Ross, 1969; Ross & DiLollo, 1970). Grandy and Westwood (2006) suggest that relative density is more salient than actual mass under SWI (and possibly broader) lifting conditions, and so the perceptual system might be more strongly biased toward the relative density of the objects being lifted rather than their absolute weights. They have likewise proposed that the sensorimotor system, in contrast to the perceptual system, must rely on the absolute properties of objects, such as absolute size and weight, rather than relative differences within a set of objects, in order to appropriately plan and execute actions. The sensorimotor system does not need to take into account relative differences between object weights or densities to ensure that lift forces are applied accurately.

The action-perception dissociation observed in the present study seems, in part, consistent with this notion. While the motor system did not appear to adapt to the absolute weight of the cubes, kinematics did still change over the course of the experiments. Relative density of the cubes, however, remained constant throughout, as did heaviness perception and the SWI. Also, while kinematics increased over the course of lifts, they did so in an equivalent fashion for all cube sizes. That is, the relative difference in kinematics between cube sizes remained. Absolute kinematic values changed, but relative differences did not. The SWI may have persisted throughout each experiment due to this relative difference and despite the absolute changes.

4.8 Future SWI Investigations

The generalizability of the present results might be strengthened by replicating and extending the design to include more than one level of weight. As well, if the graphic cubes used here reduce the magnitude of the SWI between physical cubes, one could perform the experiment with different relative size differences between physical and graphic cubes in such a way as to possibly eliminate the SWI altogether. For instance, a small physical cube presented with a large graphic cube might be perceived as being a medium-sized cube. The SWI might be made to disappear or reverse under certain conditions despite a difference in haptic size remaining.

Future studies might also further investigate sensorimotor-based kinematic adaptation. Previous studies have shown adaptation of grip and lift dynamics, but the present experiments showed no such kinematic adaptation. It would be interesting to learn the necessary and sufficient factors for such adaptation, be it based on number of trials, number of stimuli, stimuli parameters such as absolute or relative size and/or weight, or some other unknown variable. A better understanding of the relationship between action (e.g., kinematics) and heaviness perception is required to understand the SWI and to resolve the wide variety of results of past SWI experiments.

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6 APPENDIX: RATIONALES

6.1 Rationale for Number and Size of Physical Cubes

1. Three cubes provide more heaviness comparisons than only two (even though two cubes are sufficient to see a SWI; e.g., Flanagan & Beltzner, 2000). Limiting the number to three is also easier than creating and comparing four or more cubes. Ellis and Lederman (1993) used sets of seven different cube sizes, each with sides about 2.5 cm different from one another, and found that the SWI was consistent across the range of volumes.

2. It is desired to have participants' grasp configuration remain uniform for all cubes. Sizes smaller than the smallest physical cube (3 cm) would be difficult to grasp using a precision grip without vision of the hand/fingers (i.e., individuals may be prone to missing the cube or may have difficulty grasping the middle of the cube faces). Sizes larger than the largest physical cube (6 cm) would be difficult for many people to grasp with the same grasp configuration. Ellis and Lederman (1993) used a larger range of sizes but many of the cubes were too large to grasp with one hand and with a precision grip. The medium-sized cube (4.5 cm) in the proposed experiment was chosen to fall directly between the smallest and largest. The medium and large cubes were chosen to have side sizes that were multiples of the smallest cube's sides (i.e., medium = 1.5 x small; large = 2.0 x small).

3. Other studies have used larger and heavier objects, but participants grasped a grip apparatus/handle; the required grip aperture was thus limited to a smaller, comfortable size.

6.2 Rationale for Weight of Physical Cubes

1. Created so that the medium cube has a 1 kg/L density, which Gordon et al. (1993) state is the density of commonly manipulated objects (cited also by Flanagan & Beltzner, 2000). The other cube densities are then determined by the weight of the medium cube.

2. Other studies have mostly used heavier objects because they often used larger objects; however, our selected cube sizes are limited by the width of a person's grip aperture. It is reasonable to have grip aperture limit object size and corresponding weight (i.e., super-dense cubes are not desired here).