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Grasping an augmented object to analyse manipulative force control

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Augmented reality allows changes to be made to the visual perception of object size even while the tangible components remain completely unaltered. It was, therefore, utilized in a study whose results are being reported here to provide the proper environment required to thoroughly observe the exact effect that visual change to object size had on programming fingertip forces when objects were lifted with a precision grip. Twenty-one participants performed repeated lifts of an identical grip apparatus to a height of 20 mm, maintained each lift for 8 seconds, and then replaced the grip apparatus on the table. While all other factors of the grip apparatus remained unchanged, visual appearance was altered graphically in a 3-D augmented environment. The grip apparatus measured grip and load forces independently. Grip and load forces demonstrated significant rates of increase as well as peak forces as the size of graphical images increased; an aspect that occurred in spite of the fact that extraneous haptic information remained constant throughout the trials. By indicating a human tendency to rely – even unconsciously – on visual input to program the forces in the initial lifting phase, this finding provides further confirmation of previous research findings obtained in the physical environment; including the possibility of extraneous haptic effects (Gordon *et al.* 1991a, Mon-Williams and Murray 2000, Kawai *et al.* 2000). The present results also suggest that existing knowledge concerning human manipulation tasks in the physical world may be applied to an augmented environment where the physical objects are enhanced by computer generated visual components.

1. Introduction

A number of apparently related methodologies have been employed in a range of studies undertaken to specify and quantify the relative contributions of visual and somatosensory information to human manipulation or perception of objects. And

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yet, some methodological constraints have prevented psychologists or motor behaviourists from reaching a definitive conclusion concerning the role of such information can be discerned to exist. That is, all information about objects cannot be successfully controlled in its entirety due to the interactive effects in the physical world.

The visual appearance of objects seems especially difficult to manipulate independently of other information. In some studies the manipulation of visual conditions has relied on the utilization of different sized objects of equal weight (Loomis 1907, Koseleff 1957, Davis and Roberts 1976, Gordon *et al.* 1991a, 1991b, Mon-Williams and Murray 2000, Kawai *et al.* 2000, 2001). However, information concerning object size was confused with that of object density (Kawai 2002a, 2002b).

While Harshfield and DeHardt (1970) used cubes of equal size and weight made of different materials (e.g. balsa wood, mahogany, aluminium, brass and steel), their study – strictly speaking – appears to have failed in maintaining the uniformity of mass distribution among the objects. Other studies employed prisms or water to distort vision (Hay *et al.* 1965, Kinney and Luria 1970) that can be understood to have affected not only the perceived size of a target object, but also the size of the apparent size of the background to the object. In addition, a study using the *Ponzo Illusion* was possibly troubled with similar problems (Brenner and Smeets 1996).

In an analysis of heaviness perception or manipulative force control in which a task requires contact with the object being perceived or manipulated, any change in weight-related information (e.g. weight, centre of gravity, mass distribution, torque, and density) accompanied by that of visual information can result in producing a major influence even if such change seems negligible at the time to the experimenter (Amazeen and Turvey 1996, Kinoshita *et al.* 1997, Jenmalm and Johansson 1997, Flanagan and Bandomir 2000). This can be attributed to the strong effects of weight-related information on manipulative force control or heaviness perception (Teghtsoonian 1971, Johansson and Westling 1984, Westling and Johansson 1984, Ellis and Lederman 1993, Lederman 1999). Most recently, Kawai (2002a, 2002b) found that the participants tend to be influenced in the process of heaviness perception by not only the factor of weight of an object but also the factor of density – not the exact density itself – by calculating from haptically perceived weight and object size. This implies that change in object weight inevitably causes variations in the factor of density even when size – as perceived haptically from a grip apparatus – remained constant between trials. Therefore, the previous studies – concerning the contribution of visually perceived size to the force programming when an object was lifted – appear to include the possibility of extraneous haptic effects (Gordon *et al.* 1991a, Mon-Williams and Murray 2000, Kawai *et al.* 2000). In consideration of this, it was thought essential to develop a study method allowing the visual information of an object to be selectively and strictly separated from other factors concerning weight.

Such a method became a possibility only in recent years with developments in the field of computer graphics that permit the creation of 3-D images (Iwasaki *et al.* 1996, Miyano *et al.* 1996, Summers, 1999, Summers *et al.* 1999) that have both experimental and practical applications (Suzuki *et al.* 1995, MacKenzie *et al.* 1999). The Virtual Hand Lab by Simon Fraser University and the University of British Columbia in Canada is an ideal facility for undertaking experiments involving prehension in an augmented environment (Summers 1999, Summers *et al.* 1999, MacKenzie 1999). This system enables an interaction with a virtual environment with a haptic sensation by superimposing a physical object and to analyse a visual effect on the human movement or force control by customizing visual appearance without changing a physical object. Furthermore, the difference from natural prehension is only to wear a pair of light-weight goggles unlike the other developing haptic devices (Kajimoto *et al.* 1999, Amemiya and Tanaka 1999). Such an environment is already proving to be quite valuable in achieving a better understanding of human perception and of parametric force control.

Even is such an ideal research environment, however, there remain questions. One of them is whether or not human perception of an object is the same in an augmented environment as in the physical environment. Another is whether or not human perception in an augmented environment makes use of the same strategy to program the amount of effort to be expended as in the physical environment. That is, there is a need to understand and predict if the acts of perception and manipulation in an augmented environment differ from those in the real physical world in such a way as to adversely affect the performance of critical tasks.

The purpose of the present study, therefore, was to investigate the effects of visual size information on the force programming in the process of lifting an augmented object with a precision grip. This was accomplished by comparing the results obtained in this study with those previously obtained in the physical environment (Gordon *et al.* 1991a, Mon-Williams and Murray 2000, Kawai *et al.* 2000), and then to evaluate the effectiveness of using augmented reality for the strict manipulation of visual information concerning target objects independently of tactile/proprioceptive input.

2. Apparatus

2.1. *Grip apparatus*

The grip apparatus was similar in design to that reported previously (Westling and Johansson 1984, Kinoshita *et al.* 1993, Kawai *et al.* 2000, 2001). As shown in figure 1, the grip apparatus ($30 \times 30 \times 90$ mm, 55 g) measured the grip force (Grip Force) and the vertical lifting force (denoted as Load Force) using strain gauge transducers (d.c.- 490 Hz) attached to the grip apparatus. Grip Force was the force horizontal to the grip apparatus generated by the thumb and index finger, respectively. Load Force was the force vertical to the table that the participants applied to the grip apparatus to overcome the force of the gravity. Parallel grip surfaces (30×30 mm) were situated on both sides of the upper part of this cube. A smooth, black vinyl sheet was stuck on the surface of the grip apparatus to make it invisible to the participants.

2.2. *Augmented environment*

A schematic drawing of an augmented environment set is shown in figure 2. The methodological details have been described previously (Summers 1999, Summers *et al.* 1999).

A master SGI (A: Silicon Graphics Indigo II workstation) created right and left-eye images respectively based not only on a calibration of the participant's point of view, but also for the hand workspace. These images were reflected onto the semi-silvered mirror (D) by a slave SGI monitor (B) mounted face down on a frame and superimposed on the grip apparatus (G) placed on the table surface. The strobing of the Crystal Eyes stereographic goggles (H: Stereo Graphics, Waterloo, Canada) was

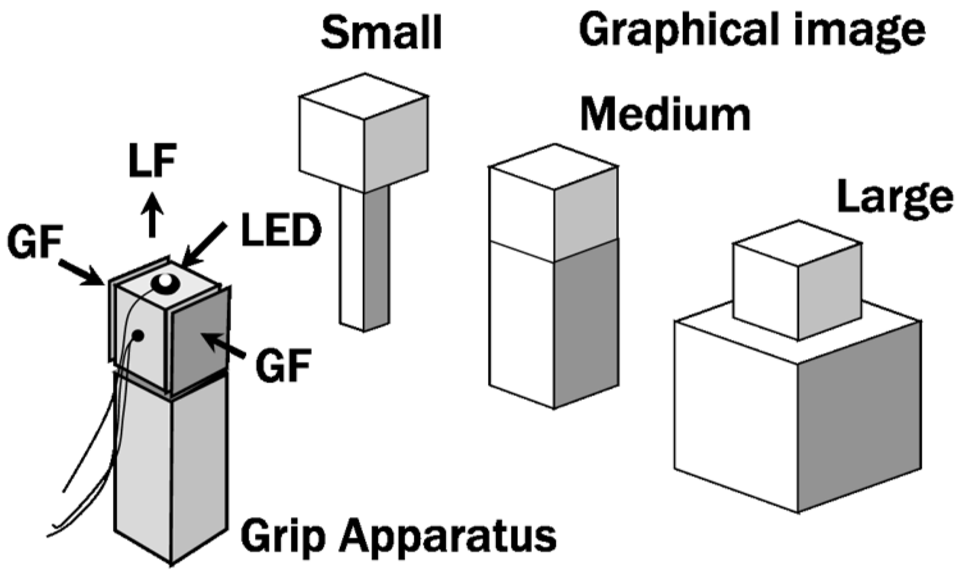

Figure 1. Grip apparatus (left) and graphical images (right).
Note: LF: load force, GF: grip force. LED: infrared light emitting diodes.

controlled by an emitter box (E) and timed with the presentation of different views of the image to give the perception of stereoscopic vision. That is, the images were rendered at 60 Hz in stereo; the goggles were shuttered at 120 Hz, giving each eye 60 images per second. An OPTOTRAK 3-D motion analysis system (C: Northern Digital Inc., Waterloo, Canada) tracked head movements through three infrared light emitting diodes (I: LED) mounted on the goggles (H).

Three different 3-D graphical images were created with original graphics software for application in an augmented environment (figure 1). The size and shapes of graphical images were identical to those of the objects that had been previously used in the physical environment (Kawai *et al.* 2000, 2001). The size of the upper part was $30 \times 30 \times 30$ mm for every image to accurately superimpose the upper part of the grip apparatus, so that the gripping aperture remained constant throughout the trials, while the lower part of the images were 10 x 10 x 60 mm for the small image, $30 \times 30 \times 60$ mm for the medium image, and 60 x 60 x 60 mm for the large image. The ratio in volume among them was 1: 9: 36. A different colour was used for each surface of the graphical image to make the edges of the image clearer.

A three OPTOTRAK camera detected 3-D position data from three LEDs mounted on the top surface of the grip apparatus and transmitted that information to the master SGI, sampling at 60 Hz. The total time required for the system to sample the LEDs' position, calculate the object's position and orientation, and draw the graphical image was no greater than 25 ms, or 1.5 frames at 60 Hz. All LED data was measured in millimetres. The size of the workspace in which both the graphical image and grip apparatus coexisted was approximately $250 \times 330 \times 200$ mm; an area that easily encompassed the lifting tasks in the present study. A small fluorescent lamp (F in figure 2) mounted under the semi-silvered mirror allowed the participants to view a graphical image and their right hands; the grip apparatus, however, was not visible.

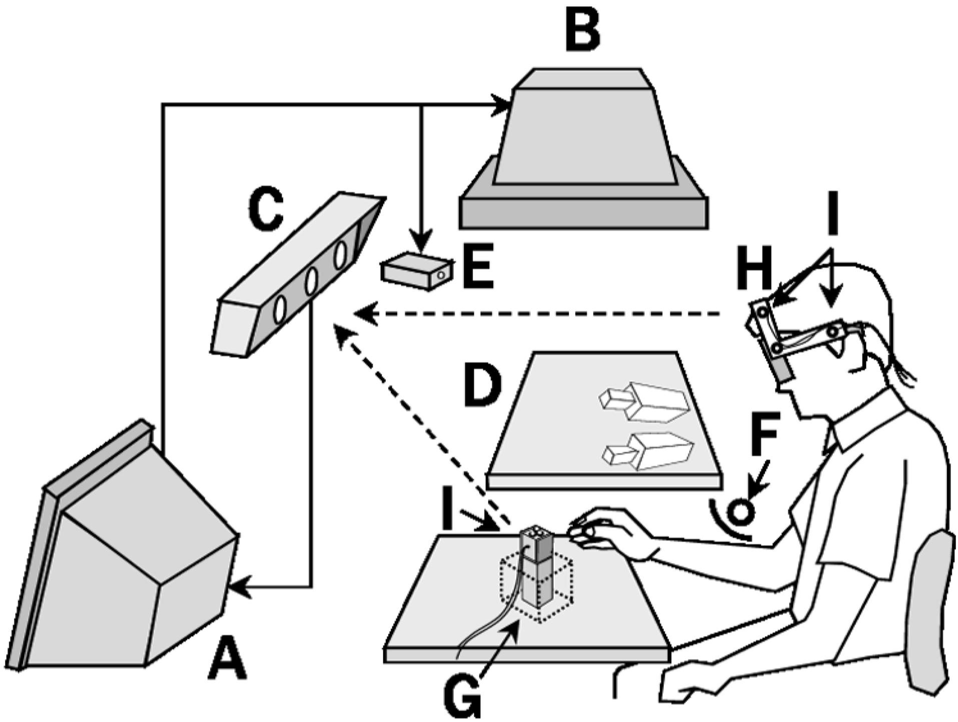

Figure 2. Schematic drawing of an augmented environment set.
Note: A: master SGI, B: slave SGI monitor, C: three OPTOTRAK cameras, D: semi-silvered mirror, E: emitter box, F: fluorescent lamp indirectly illuminating a participant's right hand, G: augmented object with grip apparatus covered in black vinyl (solid object) and a graphical image (a large image) (dotted line), H: liquid crystal shutter goggles, I: infrared light emitting diodes (LED). A virtual image (a large image) reflected onto the semi-silvered mirror (D) was seen by the participants as superimposed on the grip apparatus (G) (dotted line).

3. Materials and methods

3.1. *Participants*

Twenty-one healthy adults (11 women and 10 men), aged from 18 to 38 years (M = 23.7 yr., SD = 5.0) participated in the present study. All of them provided informed consent prior to participating. All participants were right-handed, and vision was either normal or corrected to normal. None of them had previous experience with the experimental tasks, nor were they familiar with the hypothesis being tested. Concerning the ethics of this study, approval was obtained from the local institutional ethics committee.

3.2. *Procedures*

Participants were seated in a height-adjustable chair facing an augmented environmental apparatus. After putting on the liquid crystal shutter goggles shown in figure 2, the laboratory was darkened to calibrate the each participant's point of view and hand workspace. Following that, participants confirmed that they could fuse the stereo display into a 3-D image, and that a 3-D image existed upon the table surface.

A careful explanation of the procedure was provided to each of the participants. That is, participants were told to grasp the augmented object (grip apparatus + graphical image) with the thumb and index finger of the right hand when the virtual image appeared in the workspace. The participants then lifted – by flexing the elbow – the augmented object vertically with a single flowing movement to a predetermined height 20 mm above the table surface. After holding this position for 8 seconds, a 2-D replacement target appeared on the table surface to which the augmented object was replaced. The participants then replaced the augmented object on the table surface and released it.

Following a few practice lifts with each of three images, the participants repeated 10 lifts of the augmented object for one of three graphical images to minimize participant's visual fatigue (Repeated Condition). That is, the 21 participants were randomly divided into three groups: seven participants performed 10 repeated lifts for the small image, seven for the medium, and seven for the large. Following each Repeated Condition, the size of the graphical image was pseudorandomly changed for all participants, with the only restrictions being that all blocks of three trials contained each graphical image (Random Condition). Each possible order of the three graphical images was presented to each participant. In total, 30 trials (10 blocks) – 10 trials for each size – were performed in the Random Condition for each participant. The inter-trial interval was approximately 10 seconds, during which participants saw nothing in the physical workspace.

A master SGI controlled the experiment. During the trials, the experimenter observed whether the participants were grasping the centre of the gripping surface with the appropriate fingers. Care was taken to minimize the effects of sweat on the pads of the thumb and index finger by keeping the laboratory cool (20°C) and wiping the hand with a paper towel between trials. Participants were not informed of forces measured by the grip apparatus during the experiment.

3.3. *Data acquisition and data analysis*

Force signals from the grip apparatus were recorded by a PCM data recorder (RD101T, TEAC, Tokyo, Japan). All force data were amplified (AS1202, San-Ei, Tokyo, Japan) and digitized using a personal computer (PC-9801DA, NEC, Tokyo, Japan) via a 12-bit A/D converter (ADX-98E, Canopus, Kobe, Japan) sampling at 200 Hz. High frequency noise was removed from the sampled signals using a second order Butterworth filter with a cut-off frequency of 10 Hz.

Force parameters analysed in this study are shown in figure 3. Temporal parameters were preload and loading phases respectively as defined by Johansson and Westling (1984). Preload Time was the period from the initial increase in Grip Force to the onset of an increase in Load Force. Loading Time was the period from the onset of an increase in Load Force to the onset of vertical movement of the object lift-off. Spatial parameters were Peak Grip Force, Peak Load Force, Peak Grip Force Rate and Peak Load Force Rate. Peak Grip Force and Peak Load Force were the peak values of Grip and Load Force, respectively. Using a five point numerical differentiation, Grip and Load Force Rate were computed from Grip Force and Load Force, respectively. Ten trial records for each image size in Random Condition were averaged for each participant.

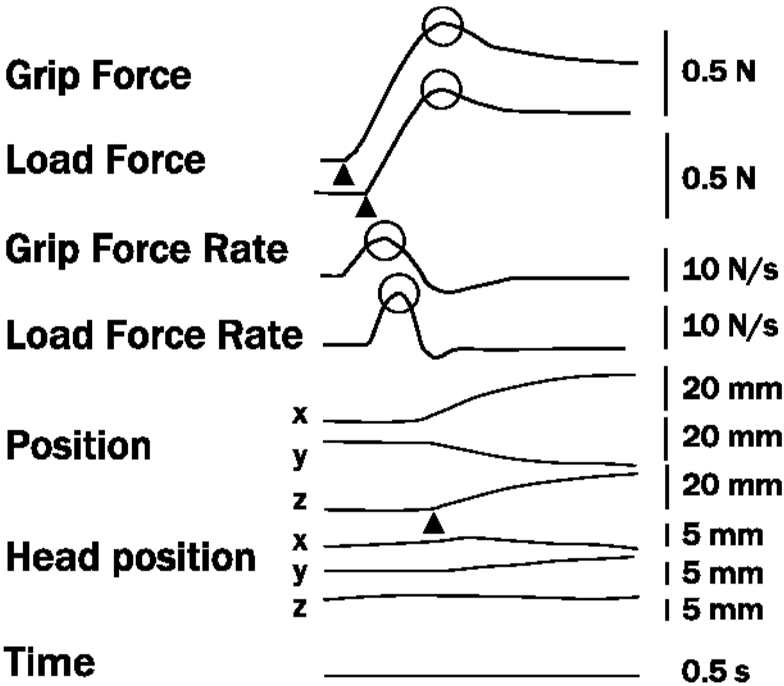

Figure 3. Grip force, load force, grip force rate, load force rate and the position of the grip apparatus in relation to the participant's head as a function of time.
Note: Each circle indicates a peak for each force parameter. Each triangle indicates an onset of grip force, load force, and vertical movement of the object, respectively.

4. Results

4.1. *Condition reports from the participants*

None of the participants complained of visual or physical discomfort (e.g. sickness, visual fatigue or dizziness) caused by the liquid crystal goggles. Neither was there any failure to grasp the augmented object in any of the trials, nor was any delay perceived between the movement of the hand and that of the graphical image. All of the participants easily perceived the augmented object to be stereoscopic, to be touchable, and as having heaviness, and reported feeling as if they were manipulating the graphical image itself rather than the grip apparatus actually being grasped.

4.2. *Repeated lifts with graphical images of constant size*

Figure 4 illustrates the adaptive profiles of group means and standard deviations of the Peak Grip Force Rate (upper) and Peak Load Force Rate (lower) as a function of trial in the Repeated Condition, where the participants repeated the lifts of the object of the same image size. A 3 x 10 (Size x Trial) ANOVA with repeated measures revealed that the main effects for size ($F(2, 18) = 1.18$ and 0.49) and trial ($F(9,162) = 0.373$ and 0.53), and the size x trials interaction ($F(9, 162) = 1.42$ and 1.20) were not significant in Peak Grip Force Rate and Peak Load Force Rate, respectively. The mean values in the initial trials, however, seemed to have a greater spread than those in the last few trials. Thus, force

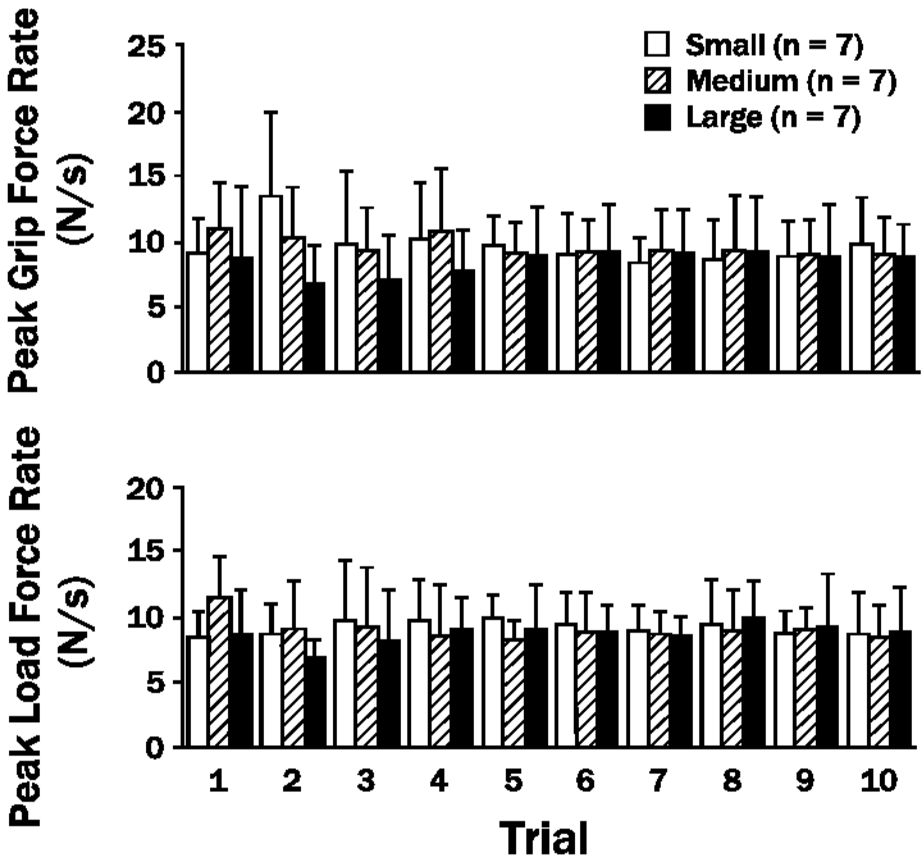

Figure 4. The means and standard deviations of the peak grip force rate (upper) and the peak load force rate (lower) as a function of trial and size of graphical image for the Repeated Condition.
Note: The mean values for each size were obtained from seven participants, respectively.

stability was obtained within 10 trials, and significant differences of absolute values were not observed among graphical size. A significant size effect was not observed for the other dependent measures. The adaptive profiles in the augmented environment were similar to those in the physical environment previously reported (Kawai *et al.* 2000).

4.3. *Size effects of graphical images*

Table 1 shows the means and standard deviations of the dependent measures as a function of image size in the Random Condition. A one-way ANOVA with repeated measures was performed on each dependent measure for all of the participants. The main effects for size were significant in Peak Grip Force ($F\ (2,40) = 36.81$, $p < 0.01$), Peak Load Force ($F\ (2,40) = 17.39$, $p < 0.01$), Peak Grip Force Rate ($F\ (2,40) = 42.39$, $p < 0.01$), and Peak Load Force Rate ($F\ (2,40) = 11.22$, $p < 0.01$). However, significant differences were not found in Preload Time ($F\ (2, 40) = 0.481$) and Loading Time ($F\ (2, 40) = 3.20$).

Table 1. Mean and standard deviations (parentheses) of dependent measures as a function of size of graphical image for the Random Condition.

	Size		
Dependent measures	Small	Medium	Large
Peak grip force (n)	1.36 (0.35)[a,b]	1.53 (0.45)[b]	1.80 (0.57)
Peak load force (n)	0.70 (0.06)[b]	0.71 (0.06)[b]	0.73 (0.06)
Peak grip force rate (n/s)	9.53 (3.62)[a,b]	11.16 (4.04)[b]	13.70 (5.23)
Peak load force rate (n/s)	10.74 (3.61)[a,b]	11.85 (3.18)[b]	12.77 (4.28)
Preload time (ms)	48.0 (25.8)	49.0 (29.6)	52.2 (30.9)
Loading time (ms)	130.0 (43.7)	118.8 (41.9)	114.4 (40.5)

Tukey's HSD procedure was performed at the 0.05 level for all ANOVAs which yield a significant main effect for size. a: significantly different from a medium image, b: significantly different from a large image.

5. Discussion

5.1. *Coincidental inputs facilitated reality for an augmented object*

The participants seemed cognizant of the fact that the graphical overlay was superimposed on the actual object since no visual effects such as lighting or texture – except for the stereoscopic effect – were added to the graphical image. All of the participants, however, reported perceiving realism when interacting with the augmented objects. This may be because, first, the participants were able to obtain haptic information from the grasped apparatus at the same time they obtained visual information from the virtual reality. The importance of somatosensory afferent signals has been emphasized not only for the explorative functions of the hand, but also for the refined manipulation (Morberg 1962, Rothwell *et al.* 1982). Morberg (1962) reported that the patients with impaired finger sensibility complained about motor deficiencies regardless of the fact that they still had normal peripheral nerves. The experiments with local anaesthesia on cutaneous finger afferent nerves indicated that afferent information critically involved in the automatic adjustment of pre-programmed muscle commands and updating of motor programs (Johansson and Westling 1984, Westling and Johansson 1984).

Second, the participants were able to manipulate the augmented object in exactly the manner they intended to move it. They were even able to see the bottom surface of the augmented object when they tipped it. As far as the augmented object was manipulated in the workspace, the OPTOTRAK camera and a master SGI never failed to follow the position of the grip apparatus and superimpose the graphical overlay on it precisely. Consequently, the participants did not perceive any delay between their movements and the augmented object's movement in the present conditions. Therefore, the coincidental inputs from different modalities between participant's action and object movement probably enhanced the realism of the augmented objects and convinced the participants of their existence.

5.2. *Forces increased as visually perceived size increased*

The initial Grip and Load Forces for lifting an augmented object were significantly scaled on the basis of graphical size in the Random Condition although the participants were not informed of forces measured by the grip apparatus during the experiment. This result was apparently due to the effects of visually perceived size since these effects were not observed in the Repeated Condition where the size of an augmented object was constant (figure 3), and since all haptic information from the grip apparatus was totally constant during the experiment.

Gordon *et al.* (1991b) and Mon-Williams and Murray (2000) suggested – using physical objects in the normal environment – that the participants used size cues acquired visually for weight estimation through size-weight associations for classes of related objects. Brenner and Smeets (1996) indicated the similar fact that the increase in visually perceived size – caused by using the *Ponzo illusion* – influenced the force to lift the object in spite of constant weight. Kawai *et al.* (2000) also supported the contribution of visually perceived size to the scaling of fingertip forces – when lifting physical objects of matched size with the graphical images as used in the present study – although the effect of size was weaker when using smaller objects than when using larger objects (Gordon *et al.* 1991b). Though the present findings appear similar to those arrived at in the previous studies, it is important to note that – unlike previous studies in which the possibilities of other haptic effects such as those contributed by the factor of density remained – the results of the present study were derived solely from the effect of visually perceived size.

Recently, the neural substrates as part of the visual control of object-oriented manual actions in humans (the dorsal stream) have been reported to be quite distinct from those underlying visual perception (the ventral stream) (Goodale and Milner 1992, Dijkerman *et al.* 1996). This indicates a necessity for investigating whether or not the augmented environment can properly affect object perception among humans (Gordon *et al.* 1991a, 1991b, Mon-Williams and Murray 2000). However, the present results suggest that the augmented environment used here may produce an effect to the visuomotor control or the force programming systems at least, and that the graphical image itself apparently provides a strong source of feedforward information to identify and recognize objects, while automatically retrieving relevant information to parameterize motor commands prior to the lift (Gordon *et al.* 1991a).

5.3. *Validity of the virtual environment for grip force analysis*

Lederman (1999) and MacKenzie (1999) emphasized the importance of haptic feedback for human dexterous manipulation, and suggested the additional development of a haptic interface to a visual interface in the teleoperation and virtual environments.

The application of augmented reality may be a powerful method for better understanding parametric force control mechanisms in a precision grip, since virtual environments can offer a technique for strictly manipulating the visual cues of target objects (e.g. size, shape, colour, texture and appearance) independently of weight-related information. In addition, this system allows for faster experiments and a reduced amount of labour while providing no inadvertent cues such as sound when objects are changed. In addition, this technology offers a method for performing manipulations that may be impossible in the real world such as that made possible by superimposing a smaller graphical image on a larger physical object as was done in this experiment (figure 1). The current results suggest that augmented reality may allow a replacement of the visual appearance of physical tools with one generated under computer control to obtain consistent human performance.

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