# The Effects of Visual Information about Self-Movement on Grip Forces when Receiving Objects in an Augmented Environment.

Andrea H. Mason & Christine L. MacKenzie
*School of Kinesiology, Simon Fraser University*
*Burnaby, B.C. V5A 1S6, Canada*
*{ahm, christine_mackenzie}@sfu.ca*

## Abstract

*This work explored how the presence of visual information about self-movement affected grip forces when receiving an object from a partner. Twelve subjects either reached to grasp or grasped without reaching objects that were passed by a partner or sat on a table surface. Visual feedback about self-movement was available for half the trials and was removed for the other half. Results indicated that a visual representation of self-movement significantly decreased object transfer time between subjects. Furthermore, results showed decreased time to peak grip force and peak grip force rate when visual feedback was afforded. These results suggest that the production of grip forces on objecst as they are acquired from another person benefit from a crude graphical representation of the finger pads during the reach to acquire movement. Furthermore, these results suggest that various sources of sensory feedback cannot be studied in isolation. Instead we must consider how feedback modalities are integrated for successful interaction. Implications for the design of virtual environments and haptic feedback devices are discussed.*

## 1. Introduction

Our ability to successfully and realistically reflect haptic feedback to users of virtual environments (VE) depends strongly on our knowledge of how humans produce grip forces on objects as they perform various tasks under different environmental conditions. Armed with this knowledge, it will be possible to model and display haptic feedback that is not only stable but also resembles, with high fidelity, the feedback supplied by the real physical environment.

Our ability to sense haptic feedback is intimately coupled with the motor functions that we perform to manipulate objects. Thus, haptic perception relies on active object exploration [8]. One method for characterizing the haptic feedback received from real environments, in order to create realistic haptic models, is to actively probe the environment and measure the resulting interaction forces [9]. In the current experiment, we employ a similar technique, however, we use the human hand as the environmental probe to ask how humans receive haptic feedback from objects through the generation of grip forces.

Several factors can influence how humans interact with their environment. In the present experiment, we considered the effects of two key factors on the production of grip forces: visual feedback and task goal.

### 1.1 Visual information and object manipulation

The presence, quality and lag associated with visual feedback can have a significant impact on reaching and aiming performance before object acquisition. Several studies have been conducted to understand the effects of visual information on object manipulation in both natural and virtual environments.

In natural environments, the role of visual feedback for the performance of reach to grasp movements has received much attention. Since the seminal work of Woodworth [18], researchers have been interested in how vision is used for the control of movement in both predictable and unpredictable environments. Under normal visual control, reach to grasp movements are made with complete accuracy. It is clear that visual information about the target, gathered before movement initiation, is used to plan or program the grasp, in an anticipatory fashion, and that this information can be stored in memory for some time [3, 16]. Furthermore, some studies have shown that visual information about the movement of one's limb is important for the on-line control of reach to grasp movements [5,12].

Recently, experiments have also been conducted to assess the role of on-line visual information on human performance in virtual and augmented environments. Mandryk [10] found that when aiming to computer generated targets in a virtual environment, subjects took longer to reach for targets in conditions where a graphic

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

representation of the finger was not available, compared to when the finger was represented as a graphical pointer. Furthermore, preliminary evidence indicated that increased richness of the graphical representation, in terms of a greater number of degrees of freedom represented by the pointer improved performance. Recently, Mason et al. [11] have extended this work by studying a reach to grasp task in which visual information about hand movement was either available or removed. Their results indicated that when visual feedback about limb and hand movement was removed, subjects took significantly longer to reach to acquire a target in an augmented environment.

Thus, we have evidence that visual information about limb movement can have a significant impact on the performance of reach to grasp movements in both natural and virtual environments. However, an important question which remains to be addressed is whether on-line visual feedback can affect manipulative interaction after object contact, thus affecting the way humans produce grip forces and use haptic feedback. We asked whether on-line visual feedback obtained during the reach to acquire movement affected the production of grip forces on objects after contact was been made. Understanding how visual and haptic information are used separately and are integrated for the generation of interaction movements will be essential for the development of effective haptic displays to suit a variety of environmental conditions.

### 1.2 Object passing in virtual and augmented environments

In attempting to quantify and model interaction for the purpose of generating graphic and haptic displays, we must also consider that human interaction with physical environments is strongly related to the tasks being performed. Of particular importance and interest to the Human Computer Interaction (HCI) community is the study and implementation of efficient collaborative environments.

With recent advances in computing technology and decreases in the costs associated with this technology, virtual environments have become increasingly common. Furthermore, there is substantial interest in the use of virtual and augmented environments as a medium for collaboration between remote and collocated participants [13,17] with applications in engineering, industrial design and evaluation, scientific visualization, medical diagnosis and training, medical analysis, surgery planning, and consumer devices such as 3D TV or games. However, before these collaborative applications can be effectively implemented, evaluations of human performance on simple baseline tasks in virtual and augmented environments must be performed to determine how to present sensory feedback to users to elicit optimum performance.

Studies have recently been conducted to assess the viability of collocated virtual environments as a medium for productivity and to compare collaborative VEs to real environments [17]. Widestrom et al. [17] have shown that collaboration and a sense of presence (sense of actually being) in shared virtual environments is possible. However, these authors have also shown that performance on a collaborative puzzle-solving task in a virtual environment was degraded and that participants did not collaborate to the same extent as in the "real" environment.

Recently Sallnas et al. [13] conducted a study to investigate the effects of haptic force feedback on the sense of presence in a collaborative virtual environment. Half of the participants received haptic feedback via a PHANToM, one-point haptic device while the other half received no haptic feedback. The PHANToM allowed each individual to feel and manipulate dynamic objects in a shared desktop virtual environment. The task consisted of moving cubes with a partner to form pre-determined patterns. When the two users pressed into the cube from opposing sides and lifted upward simultaneously, the cubes could be moved collaboratively. Results from this study indicated that haptic force feedback significantly improved collaborative task performance, as measured by total task completion time and also increased the subjective rating of virtual presence.

Thus, we have evidence that crude haptic feedback can be beneficial for collaborative activities in virtual environments. However, many of the collaborative tasks we perform on a daily basis, that we may wish to replicate and model in a virtual environment, require object manipulation with our hands. By measuring and understanding the grip forces produced when two people use their hands to collaboratively pass an object in a virtual environment we will be able to better model and reflect haptic feedback to users.

In the current experiment we investigated whether a crude representation of finger movement would prove beneficial when a subject reached to grasp an object that was collaboratively passed by a partner and one that was stationary on a table surface. In particular, we were interested in whether a representation of finger movement would affect the production of grasp force on the object after contact. We hypothesized that a visual representation of finger movement may permit the

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

anticipation of object contact and prove beneficial in the early stages of contact before haptic feedback became available.

## 2. Method

### 2.1 Participants

Twelve university students, ranging in age from 18 to 23 years were each paid $10 for participating in a single, one-hour experimental session. All subjects were right-handed and had normal or corrected to normal vision. Ethical approval from the Simon Fraser University, University Research Ethics Committee was obtained before testing began. Participants had no prior knowledge of the experiment and were required to provide informed consent before beginning the study.

General Procedure

Throughout the experiment each subject worked first in a collaborative pair with the experimenter and then alone for the simple reach to grasp trials. During the collaborative portion of the experiment, the experimenter always played the role of passer while the subject always played the role of receiver. The author served as experimenter and attempted to perform the passing movement as consistently as possible over all trials in the Experiment.

The task was to pass an object from passer to receiver within a designated, graphically presented interception zone. The passer's and receiver's movements were manipulated such that each partner could move toward the interception zone to pass the object or hold their hand stationary at the interception zone, for a total of four conditions (passer stationary, receiver stationary; passer stationary, receiver moving; passer moving, receiver stationary; passer moving, receiver moving).

The receiver had visual feedback of their moving hand or not. In one block of trials, graphic feedback of the receiver's limb movement was provided via small graphically presented planar circles (1 cm diameter) superimposed on infrared emitting diodes (IREDs) located on the tips of the receiver's index finger and thumb (see Figure 1, inset). In another block of trials, graphic feedback of the receiver's limb movement was eliminated. Graphic feedback of the passer's movement was provided in all conditions, as planar circles (1 cm in diameter) superimposed on the passer's index finger and thumb. Thus, the experiment for the collaborative portion was a 2 (passer movement: stationary, moving) X 2 (receiver movement: stationary, moving) X 2

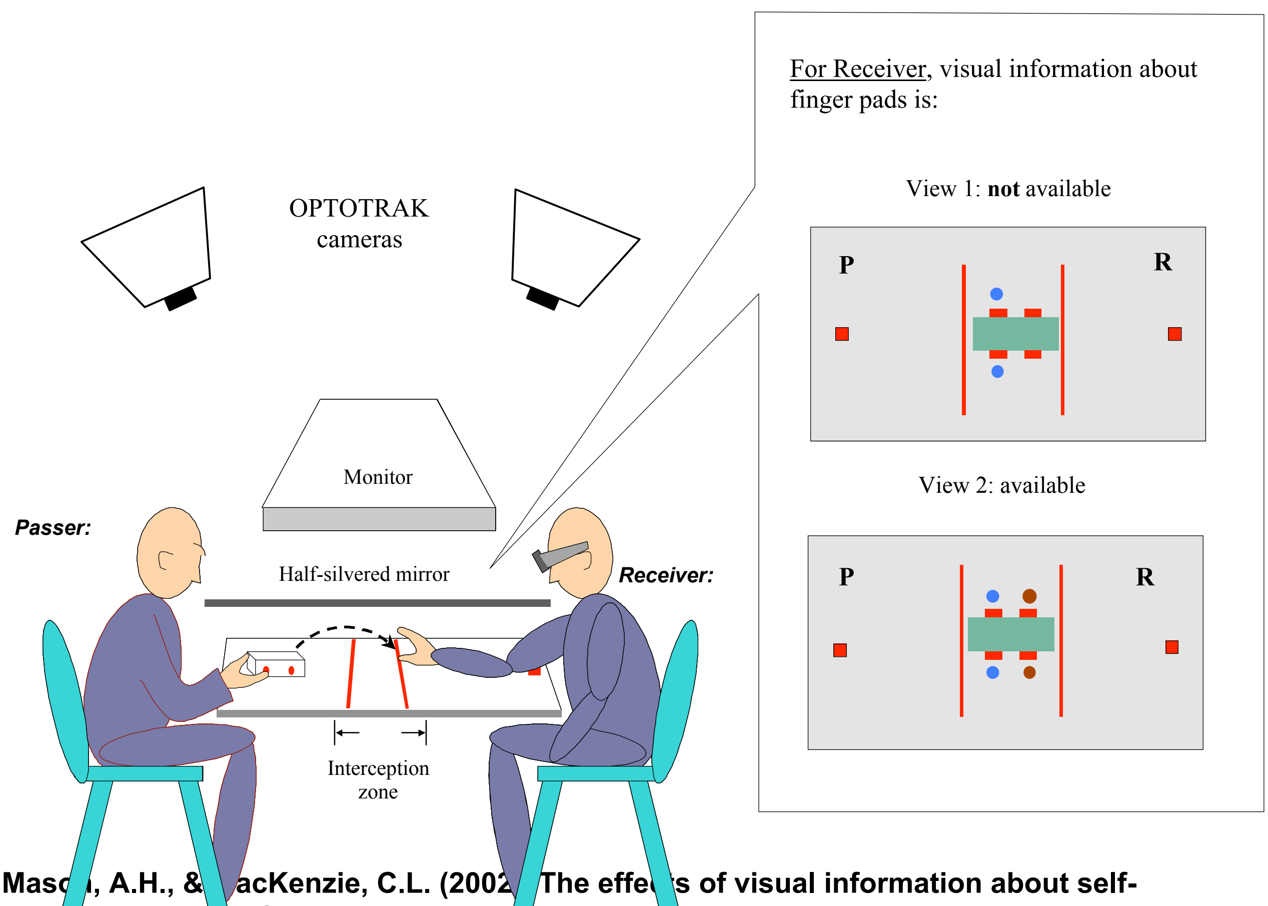





**Figure 1. Experimental apparatus.**

(receiver visual information: RV, RNV) repeated measures design. Ten trials were performed in a blocked order for each of the passer, receiver and visual conditions for a total of eighty collaborative trials. Trials were also counterbalanced using a Latin Square design.

For the simple grasp control (without passing), the subject performed trials in two visual conditions and two movement conditions. Again, for one block of trials a graphic representation of the subject's movement was provided via small graphically presented circles while for the other block of trials, this graphic representation was removed. Thus, the experiment for the simple grasp portion was a 2 (receiver movement: stationary, moving) X 2 (receiver visual information: RV, RNV) repeated measures design. Ten trials were performed in a blocked order for each of the conditions, for a total of forty simple grasp trials.

## 2.3 Experimental Apparatus

The Enhanced Virtual Hand Laboratory (EVHL) setup at Simon Fraser University was used for the current experiment. Shown in Figure 1, a graphic image produced by a Silicon Graphics Inc. (SGI) ONYX2 was displayed on a downward facing SGI RGB monitor. A half-silvered mirror was placed parallel to the computer screen, midway between the screen and the table surface. Thus, the image on the screen was reflected in the mirror and was perceived by the subjects as if it were located in the workspace below.

The subject (receiver) wore CrystalEYES Goggles to obtain a stereoscopic view of the images being projected onto the mirror. Three infrared markers (IREDs) were fixed to the side frame of the goggles. A two camera OPTOTRAK 3020 motion analysis system (Northern Digital, Inc.) tracked the three dimensional position of the IREDs on the goggles at 100 Hz. This information was processed by the Enhanced Virtual Hand Lab software on the SGI ONYX, with approximately 40 msec lag [14], to provide the subject with a stereoscopic, head-coupled view of the image [15].

Three IREDs were positioned on the top surface of the object. The OPTOTRAK motion analysis system monitored the position of the IREDs and relayed that information to the SGI ONYX. The movement of the physical object was used to display the movement of the graphical object, superimposed on the physical object. The graphical object had identical dimensions to the physical object. The graphic display was updated at 60Hz.

IREDs were also positioned on the index finger and thumb of both the subject and the experimenter. For the conditions where graphics of the subject's hand were displayed, IREDs positioned on the index finger and thumb were used to generate the display of corresponding graphical information. The graphic representations were small planar pink circles (1 cm diameter), which indicated the 3-D positions (X, Y and Z locations) of the tips of the index finger and thumb to the receiver as they moved through space. Graphic representations of the experimenter's index finger and thumb were presented throughout all conditions of the experiment as small, planar blue circles. The graphic representation of the receiver's fingers did not provide rotational information (i.e. 3-D position only).

Throughout the experiment, ambient room lighting was eliminated and thus it was impossible for subjects to see through the mirror to the workspace below. Note that only the subject, playing the role of receiver, viewed the workspace through the mirror. The experimenter, playing the passer role, viewed the natural workspace below the mirror. The start mark and interception zone were visually presented to the passer using phosphorescent tape positioned on the table surface. Recordings of the signals from the 10 IREDs positioned on the subject, experimenter and object were sampled at 100 Hz, to drive the graphical environment (at 60 Hz).

A second device recorded grip force data. Load cells (model ELFM-T2, Entran devices, Inc.) were imbedded 2.3 cm from each end of the black rectangular object (Length = 8.4 cm; Height = 5.5 cm; Width = 3.3 cm). Four red cylindrical buttons (Diameter = 1.4 cm) were screw mounted on either side of each load cell and served as the grasping surfaces (see Figure 2). Note that this constrained where the subjects were able to position their fingers to grasp the object. The signals from the two load cells were amplified (model PS30A-1, Entran devices Inc.), and transferred to a personal computer by means of a 12 bit analog to digital (A/D) converter (OPTOTRAK Data Acquisition Unit: ODAU). The sampling frequency for the grasp force measurements was 1000 Hz. Subsequent to completion of the experiment, the collected data were transferred to a Sun workstation for analysis

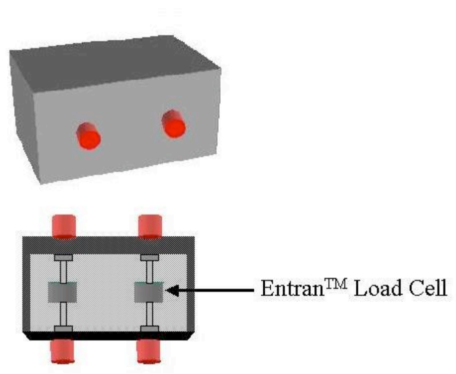



**Figure 2. Mounting of load cells within object**

### 2.4 Data Analysis

We were interested in quantifying the kinematics and grip forces produced during and after object transfer. We used transfer time (TT) to temporally quantify object transfer. The grasp forces were quantified using the absolute value of the rate of grasp force decrease by the passer and rate of grasp force increase by the receiver (GFR).

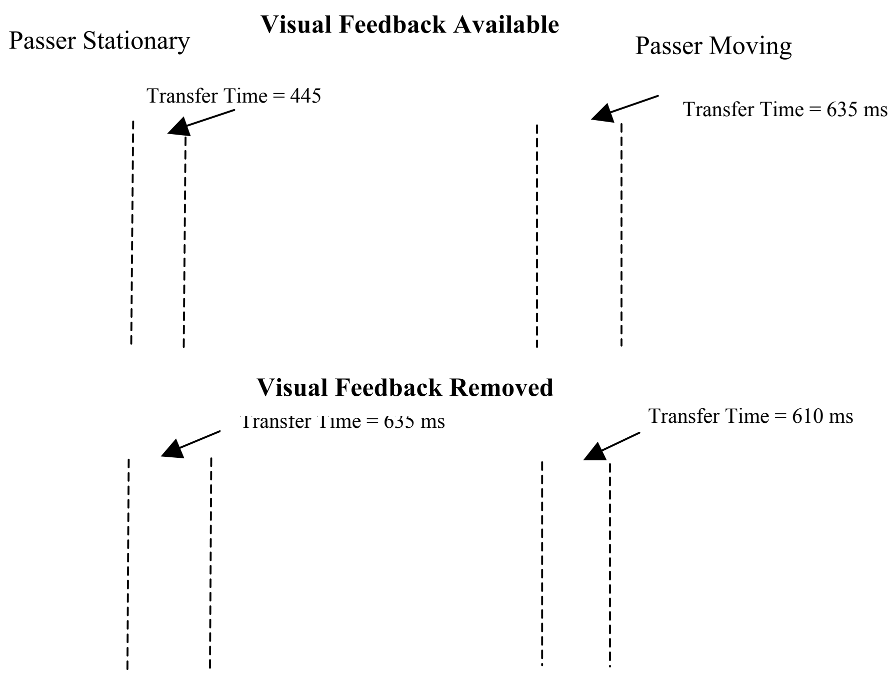
We also quantified grasp force production on the object by the receiver after the object was transferred by the passer and compared these trials to the simple grasp control trials. The dependent measures used to quantify grasp forces were receiver peak force (RPF) and time from contact to peak force (RTPF). Finally, for the collaborative trials, to investigate the coordination between the passer and receiver's grasp force production on passing trials, we quantified the time from passer object release to the receiver's peak force on the object (PR-RPF).

Data were statistically analyzed using separate repeated measures analyses of variance (ANOVAs). An a priori alpha level of $p<0.05$ was set to determine significance for all dependent measures in the current experiment. Posthoc analysis using Tukey's HSD test was performed on all significant ANOVA effects. Means and standard error measures are reported for significant results.

## 3. Results

### 3.1 Object transfer

The time taken to transfer the object from passer to receiver differed depending on visual condition ($F_{1,11}=9.9$, $p=0.009$) such that transfer time was longer when vision of the receiver's hand movement was unavailable (669 ms) than when it was available (615 ms). However, visual condition also interacted with passer movement for transfer time ($F_{1,11}=24.6$, $p<0.001$). Results indicated that transfer time was similar when the passer was moving, regardless of the visual condition, but was significantly shorter for a stationary passer when vision was available than when it was removed (see Figure 3).




**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment.**
***Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

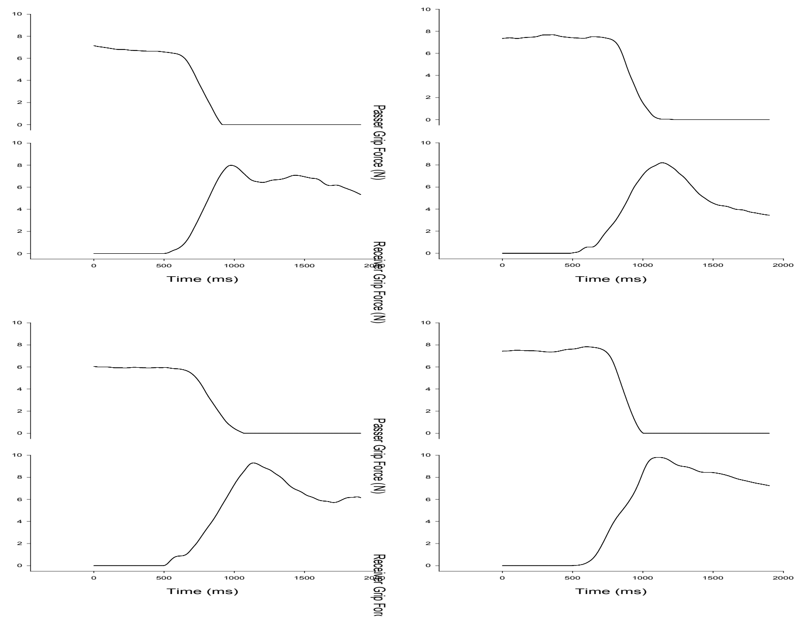



**Figure 3. Interaction between passer movement and visual condition on transfer time.**

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

The peak rate of force decrease on the object by the passer and increase on the object by the receiver during transfer was not affected by visual condition, the role (passer or receiver) being played by each partner, or partner movement ($p>0.05$). The mean rate of increase and decrease of grasping forces on the object by each partner for all conditions was approximately 35 ± 13 N/s.

However, the timing of peak force rate was affected by the role being played ($F_{1,11}$=5.534, p=0.002), the visual feedback condition ($F_{1,11}$=9.2, p=0.01), and receiver movement ($F_{1,11}$=7.5, p=0.02). Peak force rate was reached later by the passer (399 ms) than by the receiver (346 ms). As well, when visual feedback of the receiver's movement was removed, time to peak force rate increased (391 ms) for both partners compared to when visual feedback was available (356 ms). Peak force rate was also reached later by both partners when the receiver moved toward the interception zone (382 ms) than when the receiver waited at the interception zone (364 ms).

Finally, visual feedback condition interacted with passer movement to affect the time at which peak force rate was achieved ($F_{1,11}$=13.3, p=0.004). Specifically, when the passer moved toward the interception zone, visual feedback did not affect the time at which peak force rate was achieved, however, when the passer was stationary, peak force rate was reached sooner when visual feedback of the receiver's movement was provided to the receiver than when this feedback was prevented (see Figure 4).

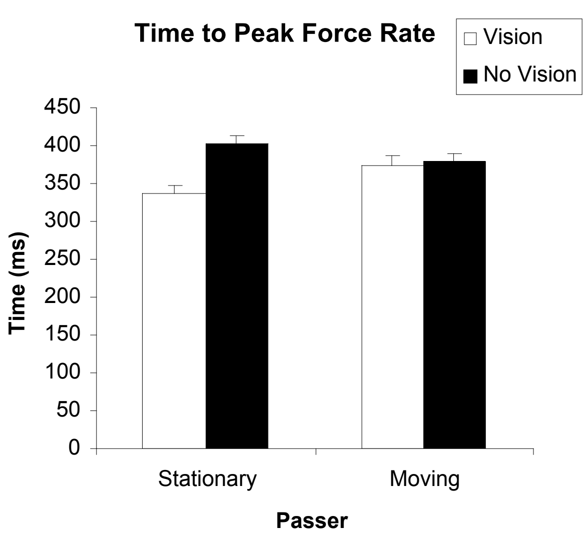



**Figure 4 Interaction between visual feedback and passer movement on time to peak force rate by both the passer and receiver.**

## 3.2 Object control by receiver

Peak grasp force generated by the receiver depended on whether the object was held by a passer or was positioned on the table ($F_{2,22}$=3.5, p=0.049). Figure 5.9 illustrates this effect. Thus, peak force was lowest for grasping an object on the table, but slightly higher when the object was held by a stationary or moving passer. However, the graphic representation of the receiver's own finger movement had no effect on the peak force generated.

The time after object contact to when the receiver reached peak grasp force was affected by visual condition ($F_{1,11}$= 9.774, p=0.01). Time to peak grasp force was longer when a visual representation of the receiver's movement was not available (814 ms) compared to when the crude representation was displayed (713 ms).

Finally, we considered only the collaborative passing conditions to better understand the coordination of passer object release and receiver peak force. Results indicated that on average, receivers reached peak force approximately 167 ms after the passer released the object. This temporal measure was not affected by visual condition or the movement of either partner.

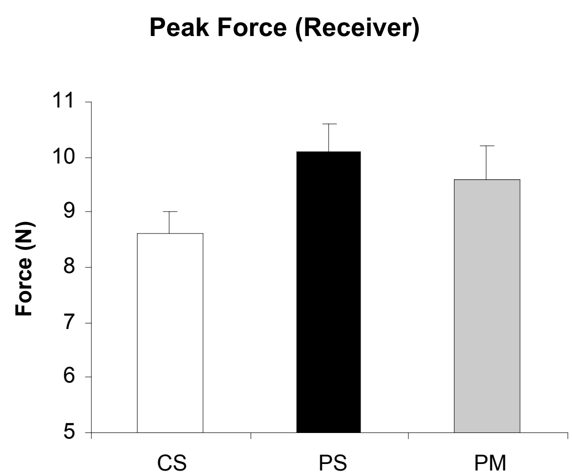



**Figure 5. Main effect for peak force generated on the object by the receiver for the cube stationary on the table (CS), passer stationary (PS) and passer moving (PM) conditions.**

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

## 4. Discussion

In the current experiment, we explored how visual feedback about one's own actions affected the production of grip forces to acquire objects from a table surface or from a partner. We were interested in understanding whether on-line visual information obtained during the reach to acquire movement would affect the timing of object transfer and grip force production. By better understanding how subjects generate grip forces on objects under various task and environmental conditions it will be possible to more accurately model haptic feedback use in haptic reflection devices.

### 4.1 Grasp Forces During Object Transfer

After object contact by the receiver, haptic feedback becomes the dominant source of information for sensorimotor control, and the presence of visual information about limb movement becomes a redundant source of information. However, in the current experiment, visual feedback about limb movement prior to object contact played an important role during object transfer. Although force rate remained unaffected by visual condition, transfer time was longer and time to peak force rate was reached later when visual feedback was removed than when this information was available.

The difference between transfer times in the full vision condition and the no vision condition was only 50 ms and the increase in time to peak force rate was only 45 ms. It has been shown that the sensorimotor loop for haptic feedback takes on average 60-70 ms [2,6]. Thus, our results indicate that a graphic representation of the receiver's hand movement was used in a feedforward fashion to anticipate the time to object contact, before haptic feedback became available to the receiver. The receiver may have anticipated object contact using a visual feedback based comparison of the target position and their own position [12] and used this comparison to anticipate the time at which their hand would reach the interception zone. Thus, in the early stages of object transfer, before haptic feedback about object contact became available, the receiver used the anticipated contact time as a signal to increase grip force production on the object, accelerating force rates and subsequently shortening overall transfer time.

We also found that the shortest transfer times and earliest peak transfer rates occurred when the object was held by a stationary passer in the full vision condition. The visual representation of self movement was most useful when the receiver was not also required to monitor the movement of the object and passer. These results provide evidence that when the object was being passed by a moving passer, receivers focused their visual attention on monitoring their partner's approach and relied more heavily on kinesthetic feedback about their own movement to anticipate contact time. Thus, the presence or absence of visual feedback about finger position did not affect the time needed to transfer the object. However, when the passer was stationary, the receiver could focus visual attention on their own hand movement. Subsequently, when visual feedback was unavailable, transfer time and time to peak transfer rate were significantly longer.

### 4.2 Grasp Forces After Object Transfer

To maintain a stable grasp on an object, it has been shown that humans initially make contact with the object, increase their grasp force to a peak and then release grasp forces to a value slightly higher than the minimum necessary to prevent the object from slipping [7]. We measured peak force and the time to peak force for the receiver during both the collaborative and simple reach to grasp trials.

During the collaborative trials, the receiver always reached peak force after the passer had completely released control of the object and the task of maintaining object stability had been transferred solely to the receiver. During the simple reach to grasp trials, peak force was reached while the receiver lifted the object toward the target area. Visual condition significantly affected time to peak force for the receiver. On average, the receiver reached peak force approximately 713 ms after they made contact with the object when vision of their limb was provided. However, when no visual representation was available, the receiver took 814 msec to reach peak force. As discussed early, this extended time to peak force in the no vision condition may be accounted for by the delay in reaching peak force rate. That is, in the no vision condition, the receiver could not anticipate making contact with the object based on visual information, and had to wait for haptic feedback to confirm that contact had been made. This in turn delayed the increase in grip force rate on the object, which in turn delayed peak force. Thus, we can conclude that a representation of self-movement facilitates the production of grasp forces on objects by allowing for an anticipatory visually-based mechanism to be used to judge the time of object contact before haptic feedback becomes available for use.

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

### 4.3 Implications for the design of computer-generated environments and haptic display devices

How humans use sensory feedback in performing simple tasks in augmented and virtual environments has recently received some attention [1,4,10,11,13] Specifically, these studies have shown that visual and haptic feedback facilitate simple aiming, reach to grasp, docking and collaborative tasks. However, the experiment presented here has shown that these sources of information are used not only to provide feedback about past environmental conditions but are also used in an anticipatory fashion to predict the consequences of motor actions and ready the system for subsequent events.

Furthermore, our results have shown that we cannot study these sources of sensory feedback independently if we wish to design optimized systems. We have shown that sources of visual feedback are heavily used in the production of grip forces and thus anticipation of haptic feedback. Thus, when designing haptic feedback systems, it is imperative that we consider the sources of visual (and perhaps auditory and olfactory) feedback that will also be available in the system and consider all sources of sensory feedback as an integrated system.

Our results also showed that humans rely heavily on feedforward information when performing simple and collaborative tasks. When available, visual feedback was used as the primary source of feedforward information to anticipate object contact. Thus, it is imperative that veridical visual information about hand movements be provided to facilitate the use of this form of movement control.

Furthermore, designers should strive to reduce latency to its minimum in order to facilitate anticipatory control strategies. For example, if visual information about the receiver's interception movement lags too far behind the receiver's actual movement, it will be impossible to effectively predict when object contact will be made. Thus, the receiver's control strategy for increasing grip forces will be dependent on haptic feedback, and thus be significantly delayed.

Finally, we found that the presence of visual information about the receiver's movement affected force generation on the object, and ultimately the object transfer process. Thus, intersensory integration processes were evident in collaborative passing. These results speak strongly to the need to accurately synchronize haptic and graphic (and other modalities, i.e. auditory) feedback displays in collaborative computer-augmented environments. Environments where sensory feedback modalities are not synchronized will cause latencies in sensory feedback processing and integration. Ultimately this will degrade human performance.

## 5. References


[1] R. Arsenault, and C. Ware, "Eye-Hand co-ordination with force feedback." *Proceedings of the Conference on Human Factors in Computing Systems CHI '00,* ACM Press, 2000, pp. 408-414.

[2] K.J. Cole, and J.H. Abbs, "Grip force adjustments evoked by load force perturbations of a grasped object." *Journal of Neurophysiology,* 1988, pp. 1407-1423.

[3] D. Elliott. " The influence of visual target and limb information on manual aiming." *Canadian Journal of Psychology*, 1988, pp. 57-68.

[4] H.G. Hoffman, "Physical touching of virtual objects using tactile augmentation enhances the realism of virtual environments." *Proceedings of IEE VRAIS,* 1998, pp. 59-63.

[5] L.S. Jakobson, and M.A. Goodale, "Factors affecting higher-order movement planning: A kinematic analysis of human prehension." *Experimental Brain Research*, 1991, pp. 199-208.

[6] R.S. Johansson, and G. Westling, "Signals in tactile afferents from the fingers eliciting adaptive responses during precision grip." *Experimental Brain Research,* 1987, pp. 141-154.

[7] R.S. Johansson, and G. Westling, "Afferent signals during manipulative tasks in man." In O. Franzen & J. Westman (Eds.). *Somantosensory Mechanisms,* MacMillan, London, 1991, pp. 25-48.

[8] S.J. Lederman and R.L. Klatzky. "Extracting object properties through haptic exploration. *Acta Psychologica,* 1993, 84:29-40.

[9] K.E. MacLean. "The haptic camera: A technique for characterizing and playing back haptic properties of real environments.

[10] R. Mandryk, *Using the finger for interaction in virtual environments*. M.Sc. Thesis, School of Kinesiology, Simon Fraser University, Vancouver, B.C., Canada. 2000.

[11] A.H. Mason, M.A. Walji, E.J. Lee, and C.L. MacKenzie. "Reaching Movements to Augmented and Graphic Objects in Virtual Environments." *Proceedings of the Conference on Human Factors in Computing Systems CHI 2001.* ACM Press, 2001.

[12] C. Prablanc, J.F. Echalier, E. Komilis, and M. Jeannerod. " Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatiotemporal characteristics of eye and hand movements and their relationships when varying the amount of visual information." *Biological Cybernetics,* 1979, pp. 113-124.

[13] E-L Sallnäs, K. Rassmus-Gröhn, C. Sjöström, "Supporting presence in collaborative multimodal environments by haptic force feedback.", *2nd International Workshop on Presence*, Wivenhoe, Essex, April 6-7. 1999.



**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**

[14] C. Swindells, J.C. Dill, and K.S. Booth, "System lag tests for augmented and virtual environments." *Proceedings of the ACM conference on User Interface Systems Technology*, 2000, pp. 160-170,.
[15] V.A. Summers, K.S. Booth, T. Calvert, E. Graham, and C.L. MacKenzie, "Calibration for augmented reality experimental testbeds." *ACM Symposium on Interactive 3D Graphics*, 1999, pp. 155-162.
[16] D.A. Westwood, M. Heath, and E.A. Roy, The effect of a pictorial illusion on closed-loop and open-loop prehension. *Experimental Brain Research,* 2000b, pp. 456-463.
[17] J. Wideström, A.-S. Axelsson, R. Schroeder, A. Nilsson, I. Heldal, Å. Abelin, "The collaborative cube puzzle: A comparison of virtual and real environments." *ACM* 2000. pp. 165-171
[18] R.S. Woodworth. "The accuracy of voluntary movement." *Psychological Review Monograph,* (Suppl. 3).

**Mason, A.H., & MacKenzie, C.L. (2002). The effects of visual information about self-movement on grip forces when receiving objects in an augmented environment. *Proceedings of the IEEE Conference on Virtual Reality, Haptics Symposium.* 105-112**