Andrea H. Mason
amason@education.wisc.edu
Department of Kinesiology
University of Wisconsin-Madison
Madison, WI, 53706

Christine L. MacKenzie
christine_mackenzie@sfu.ca
School of Kinesiology
Simon Fraser University
Burnaby, BC, Canada, V5A 1S6

The Role of Graphical Feedback About Self-Movement when Receiving Objects in an Augmented Environment

Abstract

This work explored how the presence of graphical information about self-movement affected reach-to-grasp movements in an augmented environment. Twelve subjects reached to grasp objects that were passed by a partner or rested on a table surface. Graphical feedback about self-movement was available for half the trials and was removed for the other half. Results indicated that removing visual feedback about self-movement in an object-passing task dramatically affected both the receiver's movement to grasp the object and the time to transfer the object between partners. Specifically, the receiver's deceleration time, and temporal and spatial aspects of grasp formation, showed significant effects. Results also indicated that the presence of a graphic representation of self-movement had similar effects on the kinematics of reaching to grasp a stationary object on a table as for one held by a stationary or moving partner. These results suggest that performance of goal-directed movements, whether to a stationary object on a table surface or to objects being passed by a stationary or moving partner, benefits from a crude graphical representation of the finger pads. The role of providing graphic feedback about self-movement is discussed for tasks requiring precision. Implications for the use of kinematic measures in the field of Human-Computer Interaction (HCI) are also discussed.

1 Introduction

As humans, we have the exquisite ability to successfully perform a tremendous number of complex actions with seeming ease. One of the ways in which these complex movements is achieved is through the use of sensory information, gathered from the environment by exteroceptors (e.g., eyes, ears). This sensory information is gathered before the initiation of the movement, for use in generating a motor plan that will direct the performance of the complex action. In addition, sensory feedback is used on-line during the production of movements to fine-tune our actions such that success can be achieved. One of the most critical organs for providing information about objects and their movement in the environment is the eye. Visual feedback is crucial for the accurate and successful performance of many motor activities in both natural and computer-generated environments.

In natural environments, sources of visual information are rich, spatially and temporally accurate, and readily available. However, due to limitations in cur-

Presence, *Vol. 13, No. 5, October 2004,* 507–519

rent technology, it is not always possible in interactive virtual environments to provide users with rich graphic feedback about the objects with which they are interacting, and the relationship between the environment and their moving limbs. Increases in the quality and amount of information provided in the display can have a serious impact on the lag associated with interactive graphic environments. Thus, it is extremely important to discover whether the cost (in computing cycles, tracking equipment, etc.), of implementing various types of graphic feedback can be justified by performance improvements.

We can distinguish two types of graphic information that can be presented in a virtual or augmented environment. The first type of information concerns characteristics of the environment in which the user is performing. This information can include the size (depth, height, and width) of the environment, the number of objects located within the environment, the spatial location of each of the objects, and the shapes and textures associated with each of them.

A second type of graphic information concerns characteristics of the performer with respect to the environment. For example, in a natural environment, when I make a reaching movement to grasp the coffee cup located on my desk, visual information about the movement of my hand and arm is available to me as I reach toward the cup. However, this visual information may be redundant with many internal sources of sensory feedback about my limb movement, such as proprioceptive information obtained from muscle and joint receptors. Thus, an important question to resolve is whether graphic feedback about self-movement provides performance advantages when users complete tasks within computer-generated environments. Research has been conducted in both natural and computer-generated environments to address whether visual feedback about self-movement is necessary for accurate performance of simple tasks. An overview of the results of this research is presented below.

1.1 Vision and Movement in Natural Environments

Before we can effectively design and implement interactive computer simulations of the natural environment, it is crucial that we understand how movements are planned and controlled in the "real" world. A rich body of literature exists concerning the use of visual information for the guidance of simple movements in natural environments, beginning with the work of Woodworth (1899). Since Woodworth's early work, researchers have been interested in how vision is used for the control of movement in both predictable and unpredictable environments. Under normal visual control, interactive movements in natural environments 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 (Elliott, 1988; Elliott & Madalena, 1987). However, even in natural environments, it remains unclear whether on-line visual information about the movement of one's limb is important for the control of simple manipulative movements. While some studies have reported that elimination of visual feedback about limb movement has detrimental effects on the accuracy and timing of both manual aiming and grasping movements (Prablanc, Echalier, Komilis, & Jeannerod, 1979; Jackobson & Goodale, 1991; Gentilucci, Toni, Chieffi, & Pavesi, 1994), other studies have reported no differences (Jeannerod, 1981; Elliott, 1988).

In the study of manual aiming movements, Prablanc et al. (1979) noted that when visual information about the hand was removed, errors in the terminal location of aiming movements occurred. In contrast, Elliott (1988) manipulated the availability of visual information about the movement of a pointing stylus and found no difference in accuracy when vision of the stylus was removed. Based on these findings, Elliott concluded that visual information about the position of the limb is redundant with information already available through proprioception and may not be any more important than kinesthetic or feedforward sources of information.

Studies on the performance of reach-to-grasp (prehensile) movements have also produced contradictory findings with respect to the effects of visual feedback about the moving limb. Using an apparatus that consisted of a desktop cubicle divided horizontally into two compartments by a semireflecting mirror (an early desktop virtual environment), Jeannerod (1981) manipulated the presence of visual information about the movement of the hand and arm in a reach-to-grasp task. In the closed-loop/normal condition, subjects could see through the mirror to the table surface, and thus had vision of the target and their moving limb. In a second open-loop situation, a mask was inserted below the mirror so that the lower compartment was no longer visible. Subjects were provided with vision of the target via a virtual image of the object reflected from the top of the upper compartment into the mirror; however, vision of the limb moving in the lower compartment was removed. Jeannerod found that regardless of the presence or absence of visual information about the moving limb, subjects took the same time to reach for and grasp targets, and produced the same hand-opening (aperture) characteristics, despite small errors in terminal accuracy in the no-vision condition.

In contrast to Jeannerod (1981), while using a similar apparatus, Gentilucci et al. (1994) found that eliminating vision of the moving limb resulted in longer reach times, larger grip apertures, and longer finger-closure times. These grip-aperture results have been interpreted as reflecting a compensatory effect due to the possibility of misreaching, which thus avoids incorrectly grasping the object in the absence of vision (Wing, Turton, & Fraser, 1986).

This review of the literature on the role of visual feedback about self-movement in natural environments provides inconclusive evidence about the need for this type of sensory information. Questions remain regarding *how*, *when*, and even *whether* visual feedback about one's movements is used for the successful and timely performance of simple manipulative tasks. One goal of the current experiment was to further investigate the effects of visual feedback about self-movement on the generation of reach-to-grasp actions.

1.2 Vision and Movement in Computer-Generated Environments

The role of feedback about self-movement in computer-generated environments has received less attention. In these environments, two types of feedback about self-movement can be provided. The first type is visual feedback about one's limb movements using a see-through augmented reality system. With this type of virtual reality, graphical information is projected onto a display and overlaid onto physical objects located in the environment. When the display is see-through, users can see the natural environment and their moving limb, as well as the computer-generated graphic information. However, when the display is opaque, the user sees only the computer-generated graphic information.

Using an augmented reality system as described above, Mason, Walji, Lee, and MacKenzie (2001) explored how the availability of visual feedback about one's hand movements affected the kinematics of reaching and grasping performance. They found that when the display was opaque, movement time (MT) was longer than when visual feedback about the moving limb was available. This longer movement time was also characterized by a lower reaching velocity and longer deceleration time as users "homed in" on the target. The authors interpreted these results as an indication that users do benefit from visual feedback about their limb movements. Thus, proprioceptive feedback is not sufficient to ensure *optimal* performance.

A second method for providing users with feedback about the position of their body in interactive computer-generated environments is to represent the users' movements graphically. These graphic representations are complex, requiring high-precision 3D movement-sensing equipment. The 3D position of the user's body/limb is determined using magnetic, optoelectric, sonic, or video sensors and is used in the generation of a graphic representation of the whole body or certain body segments (i.e., the hand).

Currently, in many virtual and augmented environments, humans are represented as rigid avatars with minimal human body functionality (Slater, Sadagic, Usoh, & Schroeder, 2000). Furthermore, in conditions where complex manipulative activities must be performed (such as aiming, or reaching and grasping), the graphic representation of the hand is often 2D, rigid, and without dexterity. With current technology, it is impossible to represent interactive real-time hand movements in great detail (i.e., the movement at the individual joints in each of the five fingers) because sensing, processing, and generating graphics for such complex movements would introduce incredible lag into the interactive system. Thus, we can ask, given the limitations of impoverished graphic feedback, does a representation of self-movement provide performance advantages over no representation in computer-generated environments?

Graham and MacKenzie (1996) conducted an experiment to investigate differences in performance of a virtual aiming task when vision of the hand was provided via a see-through display versus when the finger was represented as a 2D, planar graphical pointer. Their results indicated that movement time to the target was significantly shorter when subjects could see their hand than when the hand was represented as a 2D pointer. They concluded that a more realistic 3D virtual environment may be necessary to elicit natural performance in the graphical world.

Building on Graham and MacKenzie's (1996) work, Mandryk (2000) compared aiming performance in conditions where no representation of the hand was provided, where the hand was represented as a simple 2D block arrow, and where it was represented as a 3D block arrow. Mandryk (2000) found that when aiming at the computer-generated targets, subjects took longer to reach for targets in conditions where the graphic representation of the finger was not available, compared to when the finger was represented as a 2D graphical pointer. Furthermore, preliminary evidence suggested that a greater number of degrees of freedom represented by the pointer also improved performance.

Mason & MacKenzie (2002), using the same procedures as described in the current experiment, have also provided evidence that a crude representation of one's index finger and thumb movement can have a significant effect on the timing of grip-force production when receiving a passed object. Specifically, the authors found that when a crude representation of hand movement was provided, time to peak grip-force and peak grip-force rate were reduced compared to when this graphic information was unavailable. The authors concluded that although vision is thought to become a redundant source of information once contact is made with an object, graphic feedback about limb movement prior to object contact can play an important anticipatory role for object transfer.

Thus, we have evidence that visual feedback, and even a crude graphic representation about self-movement, provides performance advantages for simple aiming and grasping tasks in computer-generated environments. Furthermore, we have evidence that graphic feedback about hand movement permits the use of anticipatory mechanisms that speed up object acquisition. In the current experiment, we were interested in further investigating the role of graphic feedback about self-movement in the performance of object-transfer tasks. To achieve this goal, we compared movements made by the receiver to grasp an object when it was passed by a partner compared to when it was stationary on a table surface. We asked whether graphic feedback about self-movement may play a greater role in more complex tasks such as receiving an object from another person compared to the simple task of grasping a stationary object.

2 Method

2.1 Participants

Twelve healthy right-handed human volunteers, ranging in age from 18 to 23 years, participated in this experiment. Subjects had normal or corrected-to-normal vision. Ethical approval from the Simon Fraser University Research Ethics Committee was obtained before testing began. Participants had no prior knowledge of the experiment and provided informed consent. Each subject participated in an experimental session for approximately one hour, and was provided with a small honorarium.

2.2 General Procedure

Both collaborative-passing trials and simple reach-to-grasp control trials were conducted. 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 experi-

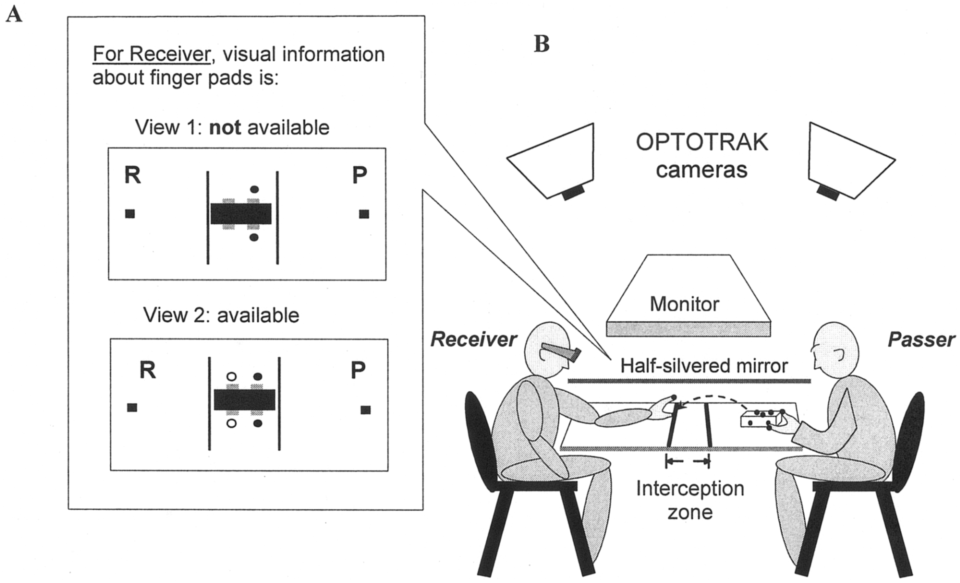

Figure 1. *(A) View reflected to the receiver from the half-silvered mirror (R = Receiver, P = Passer). Filled dots represent the graphical representation of the passer's finger pads; empty dots represent the graphical representation of the receiver's finger pads. (B) Illustration of the Enhanced Virtual Hand Laboratory experimental setup for collaborative passing. A dual OPTOTRAK camera system monitored Infrared Diodes (IREDs) located on the object and on the index finger and thumb of both the passer and the receiver. The receiver wore CrystalEyes goggles to view a stereoscopic head-coupled graphic display reflected on the half-silvered mirror.*

ment, the experimenter always played the role of passer while the subject always played the role of receiver. One author served as experimenter and performed the passing movement as consistently as possible over all trials in the experiment.

The collaborative-task goal was to transfer an object from passer to receiver within a designated, graphically presented, interception zone (see Figure 1a). The passer's role was manipulated such that she could move toward the interception zone to pass the object or hold her hand stationary at the interception zone. For the *passer moving* conditions, the passer began each trial holding the object a few centimeters above the start position located on the table surface. On the verbal "Go" signal, the passer transported the held object 18 cm from the start position toward the interception area. For the *passer stationary* conditions, the passer held the object centered within the interception zone, a few centimeters above the table, and waited for the receiver to make contact with the object. The receiver started with the right index finger and thumb pressed together over a start position located on the table. The receiver's task was to move 18 cm from the start position toward the interception zone to receive the object from the passer.

We also manipulated graphic feedback about self-movement. In one block of trials, graphic feedback of the receiver's limb movement was provided via small, graphically presented, planar circles superimposed on infrared emitting diodes (IREDs) located on the tips of the receiver's index finger and thumb (see Figure 1a). In another block of trials, graphic feedback of the receiver's limb movement was eliminated. Graphic feedback of the passer's movement was always provided—as planar circles superimposed on the passer's index finger and thumb.

For the simple grasp control (without passing), the receiver performed trials in the two visual conditions. For half the trials a graphic representation of the subject's movement was provided, while for the other block of trials this graphic representation was removed. The receiver started with the right index finger and thumb pressed together over a start position located on the table. The receiver's task was to move 18 cm from the start position toward the interception zone to grasp and lift the object from the table surface.

Thus, the experimental design was a 3 (object condition: from moving passer, from stationary passer, from table surface) $\times$ 2 (receiver graphic information: available, not available) repeated measures design. Ten trials were performed in a blocked order for the grasp and visual conditions for a total of 60 trials. Trials were also counterbalanced using a Latin square design.

2.3 Apparatus

The experiment was performed in the Enhanced Virtual Hand Laboratory (EVHL) at Simon Fraser University. Shown in Figure 1b, 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 wore CrystalEYES goggles to obtain a stereoscopic view of the images being projected onto the mirror. Three infrared emitting diodes (IREDs) were fixed to the side frame of the goggles. A two-camera OPTOTRAK 3020 motion analysis system (Northern Digital, Inc.) tracked the 3D position of the IREDs on the goggles at 100 Hz. This information was processed by the custom Enhanced Virtual Hand Lab software on the SGI ONYX with approximately 40 msec lag (Swindells, Dill, & Booth, 2000), to provide the subject with a stereoscopic, head-coupled view of the image, updated at 60 Hz (Summers, Booth, Calvert, Graham, & MacKenzie, 1999).

Three IREDs were positioned on the top surface of the object and monitored by the OPTOTRAK cameras. The locations of the IREDs on the physical object were used, with minimal lag, to generate the graphical object. The graphical object had identical dimensions to the physical object, but was light brown in color with red buttons to provide maximum contrast.

IREDs were also positioned on the index finger and thumb of both the receiver (subject) and the passer (experimenter). In conditions where the graphic representation of the receiver's hand was displayed, IREDs positioned on the index finger and thumb were used to generate the display. The graphic representations were small pink planar circles (1 cm diameter), which indicated the 3D positions (X, Y, and Z locations) of the tips of the index finger and thumb to the receiver. The graphic representation of the passer's index finger and thumb were present in all conditions and were represented as small blue planar circles. The graphic representation of the passer's and receiver's fingers did not provide rotational information (i.e., 3D position only). Throughout the experiment, ambient room lighting was eliminated, and thus subjects were unable to see through the mirror to the workspace below. Positions of the 10 IREDs located on the passer, receiver, and object were sampled at 100 Hz, to drive the graphical environment at 60 Hz.

2.4 Data Processing and Analysis

We quantified kinematic data as the receiver reached toward and grasped the passed object. While movement time has been widely used to assess the difficulty of a task in the area of Human-Computer Interaction (HCI) (see MacKenzie & Buxton, 1992), 3D kinematic measures have long been used in human-movement studies to characterize target-acquisition movements (MacKenzie & Iberall, 1994). Measures such as peak reaching velocity, deceleration time, and peak aperture (distance between index finger and thumb) not only provide insight about the difficulty of a task, but also where within the task the difficulties lie. In the current study, we used this rich kinematic information to describe the movements made by the receiver to reach to intercept the target.

OPTOTRAK 3D position data were analyzed for specific kinematic measures that describe the transport of the hand toward the target (transport component) and the opening and closing of the fingers to acquire the target (grasp component). The transport component was quantified using Movement Time (MT), which is an overall measure of the time required to complete the task, Peak Velocity of the wrist (PV), which gives us an indication of the maximum velocity attained by the hand as it travels toward the target, and Percent Time from Peak Velocity of the wrist (%TFPV), which has been used as a measure of the precision of the movement required to complete the task (see Marteniuk, MacKenzie, Jeannerod, Athenese, & Dugas, 1987). The grasp component was quantified using Peak Aperture of the index finger and thumb (PA), which is a measure of the maximal opening of the hand before the target is acquired, and Percent Time from Peak Aperture (%TFPA), which gives us an indication of the time required to enclose the target. Finally, object Transfer Time between partners (TT) was used to quantify the length of time required to fully transfer the object from the passer to the receiver.

Before extracting the dependent measures, raw position data were interpolated, rotated into a meaningful coordinate system (x = forward movement, y = side to side movement, z = up and down movements) and smoothed with a 7 Hz low-pass second-order bidirectional Butterworth filter. A customized computer program was used to determine the start of movement based on a criterion velocity of 5 mm/s (Graham & MacKenzie, 1996). The end of the receiver's movement was determined as the point when the subject made contact with the passed object as measured by force transducers inserted within the object (see Mason & MacKenzie, 2002). The position data were differentiated using customized software that performed a 5-point central finite difference technique. Peak resultant velocity and the timing of the peak were extracted. Percent time from PV was defined as [(MT – time to PV)/MT]*100. Grasp-aperture characteristics were determined using the distance between the index finger and thumb IREDs. Percent time from peak aperture was determined as [(MT – time to PA)/MT]*100. TT was defined as the time from object contact by the receiver to object release by the passer.

Statistical procedures were performed to discover: (1) whether grasping an object from a moving or stationary passer versus simply grasping an object sitting on the table affected the receiver's transport kinematics, (2) whether a graphic representation of self-movement affected the receiver's kinematics. Separate 3 (object condition: from moving passer, from stationary passer, from table surface) × 2 (receiver graphical information: available, not available) ANOVAs were performed. An a priori alpha level of $p < .05$ was set to determine significance for all dependent measures. Post hoc analyses using Tukey's Honestly Significant Difference (HSD) test were performed on all significant ANOVA effects.

3 Results

There were no effects of visual condition or object condition (i.e., whether the object was stationary on the table or held by a stationary or moving passer) on MT or PV ($p > .05$). Average MT was 755 ms and PV was 414 mm/s for all visual and object conditions. However, grasp condition did affect percent time from peak velocity ($F(2, 22) = 15.8$, $p < .001$). Deceleration time (%TFPV) was shorter when the object was held by a moving passer than when it rested on the table or was held by a stationary passer (see Figure 2a). Figure 2b shows typical velocity plots normalized for movement time for each of the three movement conditions. First, note that a typical velocity profile for a reach-to-grasp movement has an asymmetrical bell shape (Jeannerod, 1981). Also note that PV occurs later when the object is passed by a moving passer; thus, deceleration time is shorter. Visual condition also affected %TFPV ($F(1, 11) = 6.9$, $p = .024$) such that subjects spent a greater percentage of time decelerating when graphical feedback of their moving limb was prevented (67 ± 1%) than when a graphical representation was available (65 ± 1%). The interaction between visual condition and object condition was not significant.

Object condition affected both PA ($F(2, 22) = 12.7$, $p < .001$) and %TFPA ($F(2, 22) = 12.6$, $p < .001$). Peak aperture was smallest when the object was held by a moving partner (106 ± 2 mm), slightly larger when held by a stationary partner (108 ± 2 mm), and largest when the object was on the table surface (110 ± 2

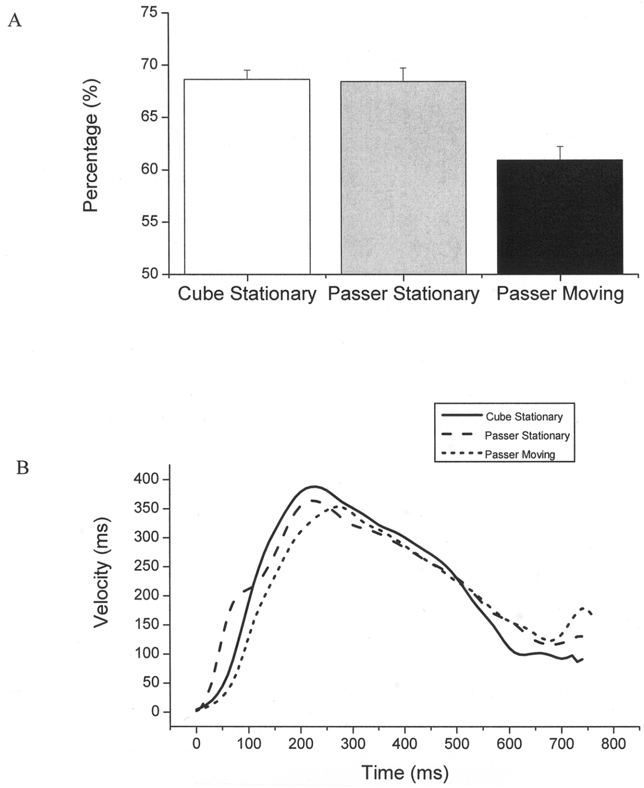

Figure 2. *(A) Main effect of object condition on Percent Time from Peak Velocity (%TFPV). Note that %TFPV is longer for grasping a stationary target than a moving target. (B) Typical velocity profiles for one receiver for trials representing the cube-stationary, passer-stationary, and passer-moving conditions. Time to peak velocity occurs earlier and deceleration time is longer for grasping a target in the cube-stationary and passer-stationary conditions than when the target was held by a moving passer.*

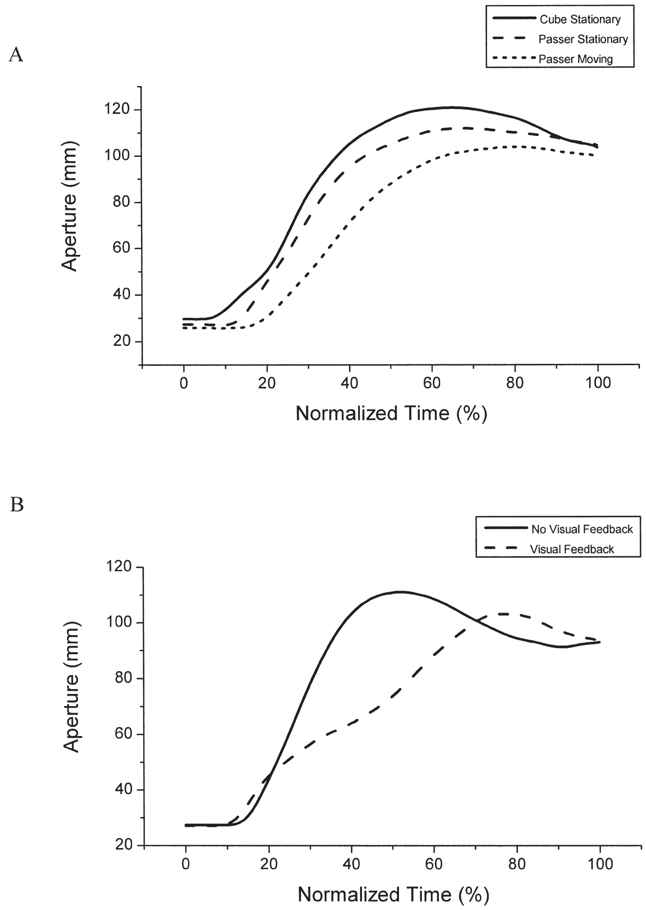

Figure 3. *(A) Typical grip-aperture profiles, normalized to 100 points, for one subject. Profiles represent grasping an object in the cube-stationary, passer-stationary, and passer-moving conditions. Peak aperture is greatest in the cube-stationary condition, slightly smaller in passer-stationary condition, and smallest in the passer-moving condition. (B) Typical aperture profiles for grasping under the visual feedback and no visual feedback conditions. Peak aperture was larger, and the percentage of time closing down on the object was longer, when vision was prevented than when a graphic representation of the receiver's fingers was available.*

mm). Post hoc analysis revealed that all means were significantly different. Figure 3a illustrates typical aperture profiles for each of the three-conditions. In contrast, only object movement affected %TFPA. Specifically, hand-closure time was longer when the object was stationary (on the table = 27 ± 2%; or in the passer's hand = 26 ± 2%) than when it was held by a moving partner (20.7 ± 2%).

Visual condition also affected grasp formation (see Figure 3b). In particular, receivers' PA ($F(1, 11) = 6.0$, $p = .032$) and %TFPA ($F(1, 11) = 44.7$, $p < .001$) were affected by the presence of a graphic representation of the movement of their reaching hand. PA was larger (110.0 ± 2 mm) and %TFPA was longer (26.9 ± 2%) when vision was prevented than when a graphic representation was available (PA = 107 ± 2 mm, %TFPA = 23 ± 2%).

The time taken to transfer the object from passer to receiver differed depending on visual condition (F(1,

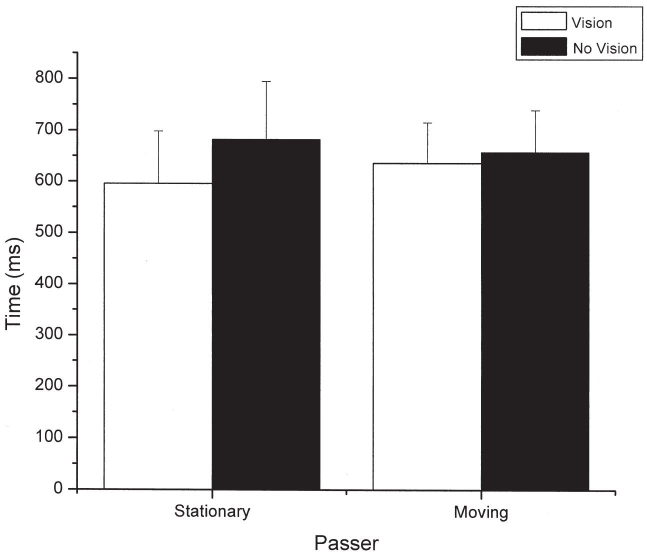

Figure 4. *Results for the visual feedback X passer movement interaction for transfer time. When the passer moved, transfer time was similar regardless of visual feedback; however, when the passer was stationary and the receiver was provided with visual feedback, transfer time was significantly shorter.*

11) = 9.9, p = .009), such that TT 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 ($F(1, 11) = 24.6$, $p < .001$). Results indicated that TT was similar when the passer was moving, regardless of visual condition, but TT was significantly faster for a stationary passer when graphic feedback about receiver self-movement was available than when it was removed (see Figure 4).

4 Discussion

In this experiment, we studied how the availability of a crude graphic representation of self-movement affected reach-to-grasp tasks in an augmented environment. Specifically, we investigated whether the presence of crude graphical information about index finger and thumb movement influenced performance in both a collaborative-passing task and a simple reach-to-grasp task. We used kinematic measures to provide a detailed description of reaching and grasping performance.

Our results indicated that removing visual feedback about self-movement in an object-passing task can dramatically affect the receiver's movement to grasp the object. Although movement time was not influenced, the receiver's deceleration time, temporal and spatial aspects of grasp formation, and the time needed to transfer the object between partners showed significant visual-condition effects. However, our results also indicated that the presence of graphic representation of self-movement had similar effects on the kinematics of reaching to grasp a stationary object on a table as for one held by a stationary or moving partner.

4.1 Implications for Understanding Interactive Human Performance: Comparison to Natural Reaching

Recent experiments on the effects of visual feedback about limb movement on the generation of reach-to-grasp movements in natural environments have provided contradictory results. While Gentilucci et al. (1994) found that the removal of visual feedback affected all aspects of the reach-to-grasp movement, Jeannerod (1981) found that reach-to-grasp movements were not affected by the presence of visual information about self-movement. In the current experiment, although no differences in movement time were observed, we found that deceleration time increased, maximum aperture was larger, and the percentage of time spent closing down on the object was longer when visual feedback about hand movement was removed.

Our results not only confirm Gentilucci et al.'s (1994) conclusions that visual feedback about limb movement facilitates both the transport and grasp phases when grasping stationary targets, but also extend these results to include transferring objects in computer-generated environments. Furthermore, given that movement time was unaffected by visual condition but that deceleration time was longer in the no-vision condition, we can conclude that in both simple grasping and in receiving objects from a partner, visual feedback information about self-movement intervenes in the control of the final phases of the movement. Our results suggest that visual feedback becomes most crucial when the image of both the hand and object is near the fovea. Further, when visual feedback is not available, a correct hand position can be achieved by relative lengthening of the deceleration phase, thus allowing time for the use of proprioceptive feedback as an error-correction mechanism, regardless of whether the object is stationary on the table surface or held by a partner.

Similar to several previous studies, peak aperture and finger-closure time (% time from peak aperture) were also found to be greater when visual feedback of the hand was unavailable (Jakobson & Goodale, 1991; Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Gentilucci et al., 1994). These results can be interpreted to signify that in the absence of vision, larger peak apertures are generated to compensate for the possibility of misreaching (Wing et al., 1986). Subsequently, a longer time must be spent closing down on the object to ensure a stable grasp.

We have also extended previous work on the effects of visual feedback about self-movement by showing that a crude, planar graphic representation of the finger pads can significantly improve performance. Thus, in contrast to Elliott (1988), we have shown that visual information about the position of the limb is not redundant with information already available, and that even a crude representation of the finger pads is superior to kinesthetic or feedforward sources of information alone. Also, in contrast to Jeannerod (1981), we have shown that grip formation in human prehension is not feedback independent, but that instead it relies heavily on visual feedback about limb position during the final stages of the transport movement for the accurate scaling of grip size, for homing in on the object, and for transferring the object between partners.

Object condition also had significant effects on the formation of the grasp component. Effects of passer movement were found for both the size of maximum aperture and the temporal parameters associated with this measure. In particular, peak aperture was larger and deceleration time was longer for grasping a stationary object positioned on the table than for grasping an object passed by a moving partner. These results were initially quite puzzling because larger apertures have usually been associated with more complex tasks (Mason & Carnahan, 1999; Wing et al., 1986). Receiving an object from a partner should be a more complex task than grasping a stationary object from the table surface. One possible explanation for these aperture results relates to the quality of visual information provided about the target in the augmented environment. Although we presented a stereoscopic, head-coupled view of the object to the participant during all conditions, perhaps this visual feedback was most effectively used when the object was moving. The movement of the object may have provided an added dimension of visual feedback about object properties that was not present when the object was stationary, thus facilitating performance. Further studies must be conducted to replicate and clarify these aperture results, as these could have a significant impact on how we present visual feedback to users of computer-generated environments.

4.2 Implications for Human-Computer Interaction

How humans use sensory feedback for the performance of simple tasks in augmented and virtual environments has recently received some attention (Wang & MacKenzie, 2000; Arsenault & Ware, 2000; Mandryk, 2000; Mason et al., 2001; Mason & MacKenzie, 2002). Specifically, these studies have shown that sensory feedback about the environment and about oneself facilitates simple aiming, reach-to-grasp, docking, and collaborative tasks. With the results of the current experiment, we have provided further evidence for the significant role of accurate, low-lag sensory feedback. Even though the graphic feedback provided in the current experiment was crude, performance advantages were measured in both simple reach-to-grasp and complex collaborative-passing tasks when feedback about limb movement was present.

We have also shown that performance advantages are not necessarily evident only in changes in movement-completion time. Decreases in deceleration time indicate lower complexity and a less taxing movement (Marteniuk et al., 1987). Thus, when graphic information about limb movement was available, the overall complexity of the movement decreased. Because we have limited attentional resources (Norman, 1968), keeping movement complexity to a minimum is extremely important for high-precision or difficult tasks. For example, in a highly complex task such as computer-guided surgery, a visual representation of self-movement (tool movement) would be essential to keep task complexity to a minimum. However, when the complexity of the task is low, perhaps a representation of self-movement would not be necessary.

Furthermore, our deceleration results indicated that graphic feedback became most useful when the subject's limb was close to the target, such that both the target and the hand could be seen in central vision. Thus, it is possible that a visual representation of self-movement is needed only when the limb is near the target. This result could have significant implications for the design of virtual and augmented environments. If performance advantages are not found with graphic feedback when the limb is located at a distance from the target, perhaps it is necessary to provide this type of feedback only when the limb is near the target. This could significantly decrease the processing load on the computer. Further studies are necessary to determine whether this hypothesis will hold and how best to implement this type of system.

Smaller peak apertures indicate greater certainty about object acquisition (Wing et al., 1986). We found that peak aperture was significantly smaller when graphic feedback about limb position was available. Thus, a representation of self-movement would be essential for tasks that require high precision. For example, in a virtual simulation of an airplane cockpit, precise movements are required to successfully grasp and manipulate the correct control residing among hundreds on the control panel. By presenting accurate, low-lag graphic feedback about self-movement in this condition, uncertainty about object acquisition could be significantly reduced. On the other hand, in situations where precision of movement is not a factor, this type of representation may be unnecessary.

Given our results, it is logical to wonder whether richer graphic feedback about self-movement could provide even greater performance advantages. It is important to note that preliminary research has indicated that increasing the degrees of freedom represented in the graphic display does improve performance (Mandryk, 2000). If the hand were represented as a two-digit pincher with a fulcrum (like tongs), would significant performance advantages over our crude two-disk representation be found? What if the hand were rendered as a fully articulated, texturized, dexterous hand? These empirical questions must be addressed so that we can provide users with the richest virtual experience while also eliciting the best performance.

However, it is important to consider that delivering realistic, rich, computer-generated sensory information can have significant costs. Increases in lag time between the interactive movements and the presentation of the sensory results of that movement cannot become too great, or performance will necessarily deteriorate (MacKenzie & Ware, 1993; Wu & Ouhyoung, 1995; Welch, Blackmon, Liu, Mellers, & Stark, 1996). Thus, a fine balance, trading off improvements in the presentation of feedback information and performance decrements, must be delineated in an application- and task-specific fashion. For example, rich computer-generated graphical feedback about self-movement may be essential in tasks such as graphic design, equipment operation, or surgical training, which require a high degree of precision and accuracy in the manipulation of objects in the environment. However, for tasks such as architectural walk-through, simulation, or design evaluation, graphic feedback about one's own movements may be secondary to graphical information about the environment itself.

4.3 The Use of Kinematic Variables to Describe Performance in Computer-Generated Environments

Finally, we would like to further emphasize the role of kinematic analyses to study interactive human performance in computer-generated environments. Had we considered only movement time as a measure of performance in the current study, we would certainly have overlooked the valuable contributions of presenting crude graphic feedback about self-movement. More detailed measures of performance in virtual environments can lead not only to a better understanding of how the human brain controls movement (Kuhlen, Kraiss, & Steffan, 2000), but also to improvements in the way we design and implement computer-generated environments such that consistent and optimal performance can ensue.

The use of kinematic variables also has significant implications for the implementation of movement-prediction algorithms to improve the speed of graphics in interactive computer systems. By using kinematic data from human-movement studies, we may be able to mathematically model and predict the temporal and spatial characteristics of upcoming movements, leading to richer graphics and decreased lag times. Further experimentation using kinematic measures to describe performance under various conditions will be necessary to realize this goal.

5 Conclusions

In sum, our results suggest that performance of goal-directed movements, whether to a stationary object on a table surface or to objects being passed by a stationary or moving partner, benefit from a crude graphical representation of the finger pads. We found that our simple graphic representation of the finger pads provided performance advantages over no graphic representation. A richer graphic representation may have provided even further performance advantages. However, one difficulty with improved graphics is increased lag inherent with increased computer processing demands. Thus, we suggest that a compromise between the richness of the graphic representation and the ability to decrease movement-dependent graphic latency to a minimum must be made to optimize performance on a task-by-task basis. Further research is required to determine what the optimal compromise will be for various tasks and applications.

Acknowledgments

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada. Thank you to Colin Swindells and Frank Henigman for software support.

References

Arsenault, R., & Ware, C. (2000). Eye hand co-ordination with force feedback. *Proceedings of the 2000 ACM Conference on Human Factors in Computing Systems (CHI 2000),* 408–414.

Berthier, N. E., Clifton, R. K., Gullapalli, V., McCall, D. D., & Robin, D. (1996). Visual information and object size in the control of reaching. *Journal of Motor Behavior, 28,* 187–197.

Elliott, D. (1988). The influence of visual target and limb information on manual aiming. *Canadian Journal of Psychology, 42* (1), 57–68.

Elliott, D., & Madalena, J. (1987). The influence of premovement visual information on manual aiming. *Quarterly Journal of Experimental Psychology, 39A,* 541–559.

Gentilucci, M., Toni, I., Chieffi, S., & Pavesi, G. (1994). The role of proprioception in the control of prehension movements: A kinematic study in a peripherally deafferented patient and in normal subjects. *Experimental Brain Research, 83,* 447–482.

Graham, E. D. & MacKenzie, C. L. (1996). Physical vs virtual pointing. *Proceedings of the 1996 ACM Conference on Human Factors in Computing Systems (CHI 1996),* 292–299.

Jackobson, L. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: A kinematic analysis of human prehension. *Experimental Brain Research, 86,* 199–208.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long & A. Baddeley (Eds.), *Attention and Performance IX* (*pp. 153–169*). Hillsdale, NJ: Erlbaum.

Kuhlen, T., Kraiss, K. F., & Steffan, R. (2000). How VR-based reach to grasp experiments can help to understand movement organization within the human brain. *Presence: Teleoperators and Virtual Environments, 9*(4), 350–359.

MacKenzie, C. L., & Iberall, T. (1994) *The grasping hand.* Amsterdam: Elsevier Science.

MacKenzie, I. S., & Buxton, W. (1992). Extending Fitts' law to two-dimensional tasks. *Proceedings of the 1992 ACM Conference on Human Factors in Computing Systems (CHI, 1992),* 219–226.

MacKenzie, I. S., & Ware, C. (1993). Lag as a determinant of human performance in interactive systems. *Proceedings of the ACM International Conference on Computer Human Interaction,* 488–493.

Mandryk, R. L. (2000). *Using the finger for interaction in virtual environments.* Unpublished masters thesis, Simon Fraser University, Vancouver, British Columbia, Canada.

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenese, S., & Dugas, C. (1987). Constraints on human arm trajectories. *Canadian Journal of Psychology, 41,* 365–378.

Mason, A. H., & Carnahan, H. G. (1999). Target viewing time and velocity effects on prehension. *Experimental Brain Research, 87,* 407–420.

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

Mason, A. H., Walji, M. A., Lee, E. J., & MacKenzie, C. L. (2001). Reaching movements to augmented and graphic objects in virtual environments. *Proceedings of the 2001 ACM Conference on Human Factors in Computing Systems (CHI 2001),* 426–433.

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychological Review, 75,* 522–536.

Prablanc, C., Echalier, J. F., Komilis, E., & Jeannerod, M. (1979). 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, 35,* 113–124.

Slater, M., Sadagic, A., Usoh, M., & Schroeder, R. (2000). Small-group behavior in a virtual and real environment: A comparative study. *Presence: Teleoperators and Virtual Environments, 9*(1), 37–51.

Summers, V. A., Booth, K. S., Calvert, T., Graham, E., & MacKenzie, C. L. (1999). Calibration for augmented reality experimental testbeds. *Proceedings of the 1999 ACM Symposium of Interactive 3D Graphics,* 155–162.

Swindells, C., Dill, J. C., & Booth, K. S. (2000). System lag tests for augmented and virtual environments. *Proceedings of the 2000 ACM Conference on User Interface Systems Technology,* 160–170.

Wang, Y., & MacKenzie, C. L. (2000). The role of contextual haptic and visual constraints on object manipulation in virtual environments. *Proceedings of the 2000 ACM Conference on Human Factors in Computing Systems (CHI 2000),* 532–539.

Welch, R. B., Blackmon, T. T., Liu, A., Mellers, B. A., & Stark, L. W. (1996). The effects of pictorial realism, delay of visual feedback and observer interactivity on the subjective sense of presence. *Presence: Teleoperators and Virtual Environments, 5*(3), 263–273.

Wing, A. M., Turton, A., & Fraser, C. (1986). Grasp size and accuracy of approach in reaching. *Journal of Motor Behavior, 18*(3), 245–260.

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review Monograph,* 3 (Whole No. 13).

Wu, J., & Ouhyoung, M. (1995). A 3D tracking experiment on latency and its compensation methods in virtual environments. *Proceedings of the 1995 ACM Conference on User Interface Systems Technology* 41–49.