A Comparison of Haptic, Visual and Auditive Force Feedback for Deformable Virtual Objects

Paul Richard†, Grigore Burdea*, Daniel Gomez*, Philippe Coiffet†

† Laboratoire de Robotique de Paris
UPMC-UVSQ-CNRS
10-12 avenue de l'Europe, 78140 Velizy, France
e-mail: richard@apollon.robot.uvsq.fr

* Man-machine Interface Laboratory
CAIP Center, Frelinghuyssen Road, P.O. Box 1330
Piscataway, NJ 08855, USA
e-mail: burdea@telephone.rutgers.edu

Abstract

One of the key problems when interacting with objects in a virtual environment is the lack of haptic feedback. Being able to touch, feel, and manipulate objects in the environment, in addition to seeing (and/or hearing) them gives a sense of compelling immersion in the environment that is otherwise not possible. However, haptic feedback in the presence of time-delays can lead to instability. It is unacceptable to feed resolved force continuously back to the same hand that is operating the control (delayed feedback imposes disturbances). In that case, the visual or auditive channels could be a low-cost alternative to the haptic channel. In this study, we have investigated the effect of haptic, visual, and auditive force feedback on dextrous manipulation performance. Results showed that haptic feedback enhanced performance by about 50% for hard object manipulation. Auditive force feedback proved better when handling soft objects. This highlights the importance of reducing the friction in the feedback master.

Key words: human performance, portable master, haptic feedback, sensory transposition, dextrous manipulation, virtual object, learning.

1 Introduction

Virtual Reality (VR) is a computer generated immersive environment with which users have real-time, multisensorial interactions. These interactions involve all the human senses through visual feedback [Bohm et al., 1992], 3-D sound [Chapin and Foster, 1992], haptic feedback [Shimoga, 1992], [Burdea and Langrana, 1992], and even smell and taste [Sundgren et al., 1992].

One of the key problems when interacting with objects in a virtual environment is the lack of haptic feedback. In contrast to the purely sensorial nature of vision and hearing, only the haptic system is capable of direct action on the real environment. Being able to touch, feel, and manipulate objects in the environment, in addition to seeing (and/or hearing) them gives a sense of compelling immersion in the environment that is otherwise not possible.

Haptic interfaces have been developed in the last couple of years [Iwata, 1990], [Burdea et al., 1992a], [Stone, 1992], [Cutt, 1993], [Bouzit and Coiffet, 1993]. These interfaces enable the user to interact with the computer generated virtual environments by receiving motor action commands from the human and by displaying haptic images to the human.

In general, haptic interfaces can be viewed as having two basic functions: (1) to measure the positions and forces (and time derivative) of the user's hand (and/or other body parts) and (2) to display forces and positions (and/or their spatial and temporal distributions) to the user. Among these position and force variables, the choice of which ones are the command variables (i.e., inputs to the computer) and which ones are the display variables (i.e., inputs to the human) depends on the hardware and software design, as well as the task interface.

Many studies have quantified the benefits of force/touch feedback [Winey, 1981], [Brooks, 1988], [Patrick, 1990], [Caldwell and Gosney, 1993], [Kontarinis and Howe, 1993]. Results indicated that virtual force/touch feedback is of great importance. One possible reason for this is that force feedback may play a crucial role in the ability of an operator to satisfy constraints required by the task. Richard has shown that force feedback enhanced manipulating task performance when interacting with virtual objects by about 50% and reduced the learning time by 50% [Richard et al., 1993].

However, force feedback in the presence of time-delays can lead to instability. For some space applications it is desirable to control the space manipulator from Earth. This introduces unavoidable time-delays in the data links between master and slave systems. Ferrel [1966] showed that it is unacceptable to feed resolved force continuously back to the same hand that is operating the control. This is because the delayed feedback imposes an unexpected disturbance on the hand which the operator cannot ignore and which, in turn, forces an instability on the process. To avoid instability, a move-and-wait strategy was used. Ferrel observed that the operator makes an open loop move without waiting for feedback, then waits for confirmation before making a next (open loop) move.

Studies have investigated the effect of visually displayed force feedback on remote manipulation performance. Thus, Reger (1987) studied the effect of visually displayed force feedback in delayed and non-delayed bilateral teleoperation. Results showed that (1) delays in force feedback as short as 1.0 s severely disrupted the operator's ability to apply a low, stable amount of force during manual remote manipulation, and (2) that the additional presentation of visually displayed force feedback information improved significantly the operator's ability to apply and manage low stable forces under both real time and delayed conditions.

Corker et al., [1988] have developed a graphic force/torque display to present force and torque information visually to an operator during remote manipulation. Experiments have indicated a relative measure of improvement in force management with the force/torque display under real time manipulation conditions.

Ouh-young et al., [1989] studied operator's performance in a 6-D docking task using haptic and visual force feedback. They observed that even though haptic force feedback was more effective, the task could be reliably done with the visual force display alone.

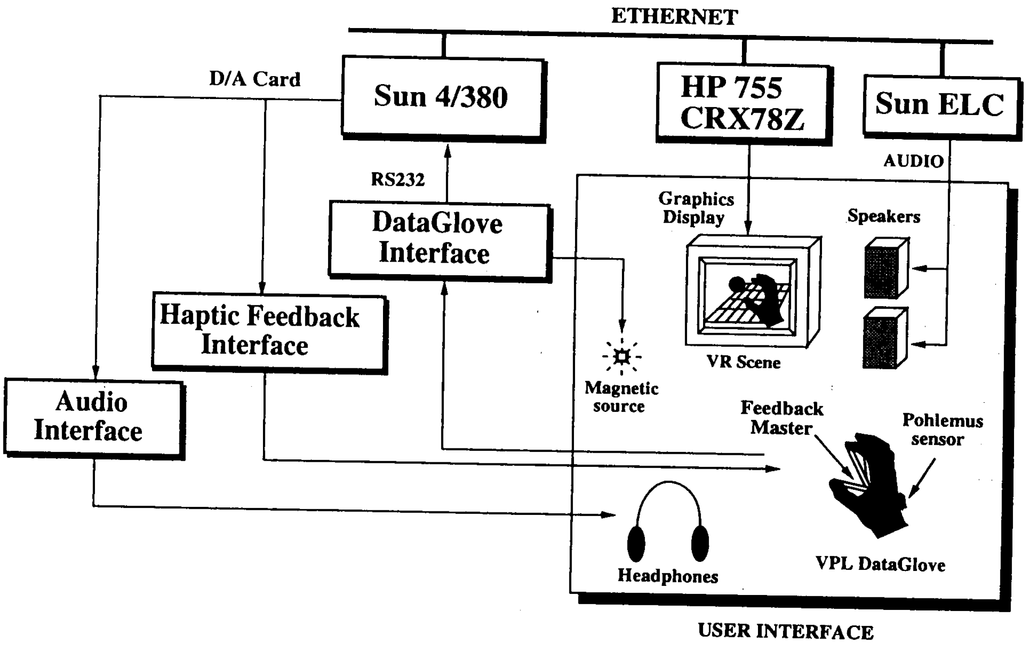

Figure 1: *The Rutgers Distributed VR System provides the users with auditive, visual and haptic force feedback cues when interacting with virtual objects [Burdea et al., 1993a].*

2 Research Objectives

This study was performed (1) to measure operators' dexterity during manipulation of virtual objects when non-delayed force feedback is presented haptically, visually, or auditorily, and (2) to determine the reliability of results when an object's compliance is modified.

2.1 Subjects

Sixty-four subjects (32 males and 32 females right-handed students), ranging in age from 18 to 27 participated in this experiment. All subjects had normal or corrected vision and had computer skills, but had never experienced virtual reality.

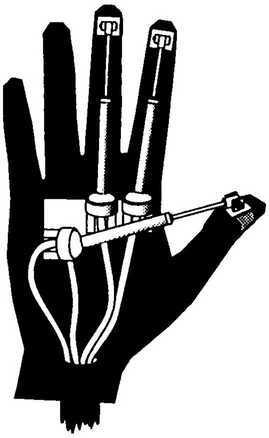

Figure 2: *The Rutgers Portable Dextrous Master [burdea et al., 1993b].*

2.2 Experimental System Set-up

The Rutgers distributed VR system was used as the experimental system. The system configuration is illustrated in Figure 1. A loosely-coupled client-server architecture allows for the distribution of computation for the simulation on three workstations [Burdea et al., 1992b]. One workstation is dedicated to reading and calibrating glove data, updating the level of feedback forces, and maintaining state information on all objects in the virtual world. An HP755 graphics workstation is dedicated to graphics rendering and display, while sound interactive processing of the VR world is provided by a Sun SLC workstation. The graphics update rate is around 28 frames per second. A 46cm-diagonal screen was used as the experimental visual display.

The Rutgers Master [Burdea and Zuang, 1992] was designed to provide realistic simulations of natural haptic manipulation on three fingers (the thumb, the index, and the middle finger). This interface allows us to display simulated force feedback: (1) haptically (through the Rutgers Master), (2) visually through three sets of twenty LEDs located on the interface box (one set per finger) and (3) auditorily through headphones. We decided to display auditive force feedback by controlling the frequency of the audio signal, since humans are more sensitive to frequency (JND is about 2 Hz) than loudness.

The number of LEDs "on" was proportional to the level of the virtual force feedback computed by the simulation. The frequency of the audio signal was controlled by the average of the three virtual haptic feedback signals. A force feedback of 0.2 N corresponded to one LED "on" when the force feedback was displayed visually, and to a frequency of 50 Hz when the force feedback was displayed through the headphones.

The fingers' flexion was measured through a VPL DataGlove™ [VPL, 1987], while the hand position and orientation were measured using a Polhemus sensor which was mounted on the back of the glove [Polhemus Navigation, 1987]. The DataGlove measures hand gestures using optical fibers. The optical fibers change refractance according to the bending of the finger joints allowing the determination of individual joint angles. The Polhemus sensor transmits 3-D wrist position and orientation data using low-frequency

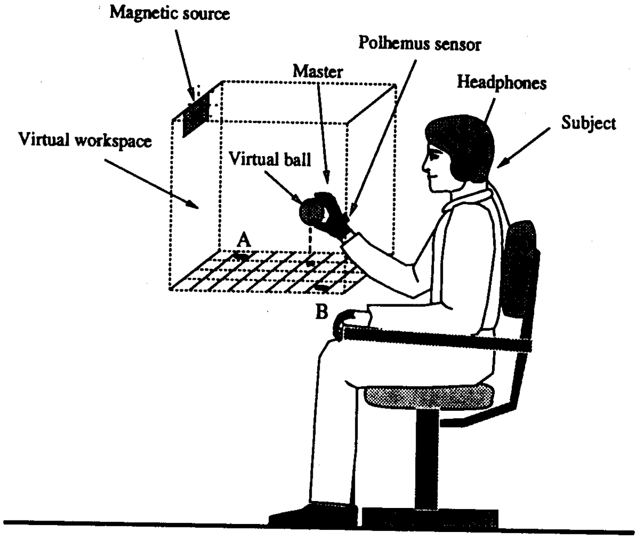

Figure 3: *Experimental System Configuration*

magnetic fields produced by a stationary source. The accuracy of the Polhemus sensor (Isotrack model) is about 2.5 mm translation, and 1^o in rotation.

3 The Rutgers Master

The Rutgers Master allows the user to "feel" virtual objects during a task involving precision grasping [Burdea et al., 1992-b]. This master is a compact feedback structure that fits in the palm of the DataGlove^{TM}. The feedback structure consists of three (more recently four) pneumatic micro-cylinders that press against the finger tips. The force applied on the finger is proportional to the force applied by a virtual hand on virtual objects. The lightness of the feedback structure is important in order to reduce operator fatigue during the simulation.

The feedback actuators are controlled by analog proportional pressure regulators (PPR) that are housed in a master interface. These regulators control air pressure to the actuators in the user's palm. The interface has its own power supply and main air pressure indicator.

A rise time of 14 ms is caused by static friction in the pneumatic cylinder and the inertia of the pressure regulator valve. The static friction is also responsible for a steady-state error of 4%, of the total force. The relaxing time of 62 ms is the bottleneck for the actuator bandwidth (of 8-10 Hz). This delay is a result of the slow rate by which air is released from the air line, since mufflers are installed to reduce noise. Tests for the Rutgers Master have demonstrated up to 4 N for each actuator [Burdea and Speeter, 1989].

4 Virtual Objects

Two different objects were used in this experiment. A "hard" ball (yellow), and a "soft" ball (red). These objects were programmed into a display list using the Starbase Graphics Library [Hewlett Packard, 1988], double buffering, and Gouraud shading with one light

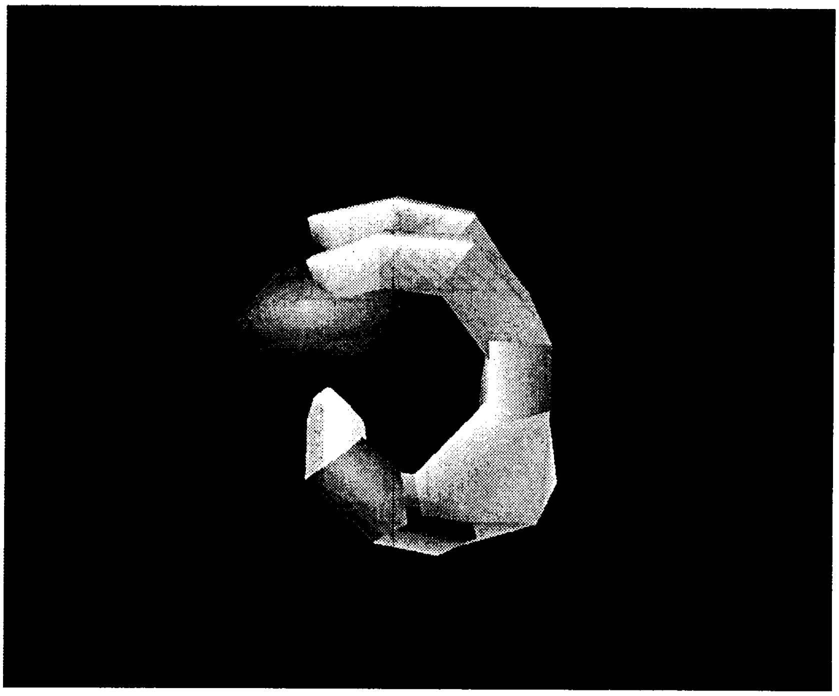

Figure 4: *The virtual hand grasping a ball*

source (adding more light sources would slow down the rendering). In the current simulation, the grasping occurs when the center of the ball is close enough to the center of the palm. These balls, depending upon their compliance, are deformed approximately as they would in the physical world. Three virtual forces were calculated individually, according to Hook's law ($F_i = k\Delta x_i$) at the contact points between the thumb, the index, and the middle finger. In this way the equation is kept simple enough for rapid computation while still retaining the ability to model objects of varying stiffnesses (k). Orientations of the contact forces were aligned with the normals of the three grasping points on the ball. When released, the spheres remained deformed (plastic deformation). The maximum deformation of the yellow sphere returned a force of approximately 4N, while the red one returned only 2N.

Winey [1981] found that artificially generated shadows projected on an imaginary horizontal floor improved the operator's performance in manipulation tasks. Kim et al., [1985] showed that by superposing in the visual display perspective grid lines, it was easier for the observer to comprehend the relative depth of the objects.

The manipulating task was performed in a square virtual room of about $1m^3$. Virtual walls and floor were constituted of grid lines, while "X" shadow of the virtual hand was displayed on the floor throughout the experiment.

5 Manipulating Task

Subjects were instructed to reach and pick up the virtual ball (red or yellow depending upon the group they belonged) at location "A" . Then, they were asked to put it in location

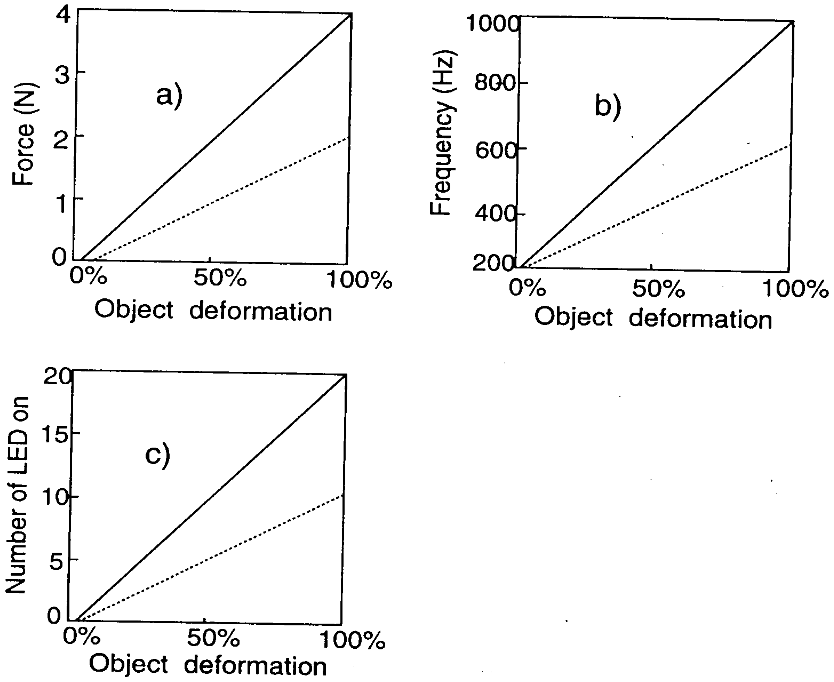

Figure 5: *Characteristics of the haptic (a), auditive (b), and visual (c) force feedback for the soft ball (–), and for the hard ball (..). Both virtual objects return forces proportional to the deformation. Note that the hard ball appears twice as hard as the soft one.*

"B" while applying low, stable amount of deformation (10% of the radius)(Figure 3). The apparent size of the ball in its initial position (A) was about 2 cm. The task had to be completed in less than 15 seconds.

This experiment was divided into four sub-experiments. Each group of 16 subjects performed the manipulating task using: (1) only graphics feedback , (2) graphics and visual force feedback, (3) graphics and auditive force feedback, and (4) graphics haptic force feedback. The graphics update rate was about 28 frames per second. The virtual world complexity was held constant (the operator's virtual hand, one sphere and walls). The characteristics of each force feedback modality are illustrateded Figure 5. The Rutgers master was integrated with the DataGlove^{TM} throughout the experiment. This allowed a true comparison between visual, auditive, and haptic force feedback, since friction and the master's weight were always present.

6 Procedure

The subjects were seated in front of the screen of the graphics workstation (the eye-display distance was approximately 60cm) and the Rutgers Master integrated in the DataGlove^{TM} was fitted to their right hand (all the subjects were right-handed). Then a calibration of the subject's hand was made. For a given session, subjects performed with a 20-sec rest period between trials (12 trials). Each subject was given a detailed explanation of the nature of the different devices and displays they had to use in this experiment. Room

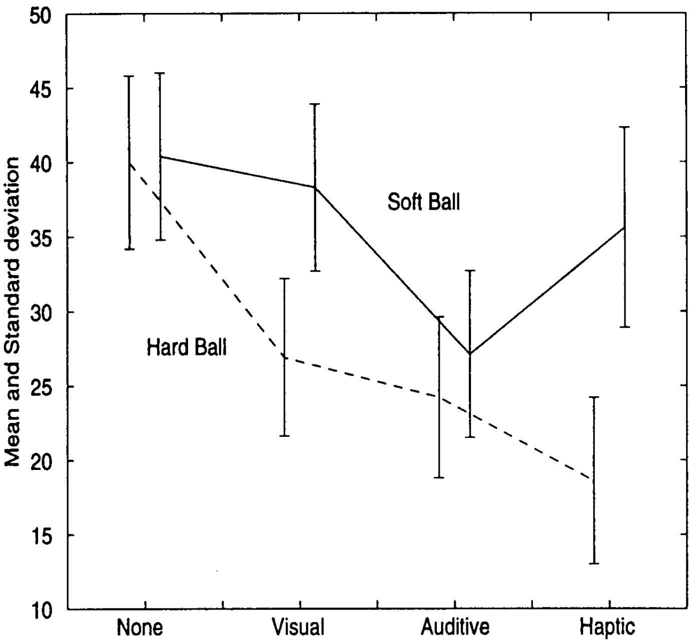

Figure 6: *Mean performance and standard deviation when performing the manipulating task using visual, auditive, haptic or no force feedback; with the soft ball, and with the hard ball.(in % of the radius)*

illumination was maintained low in order to increase the contrast between the display and the immediate surroundings. The maximun amount of deformation applied by the subjects on the ball was recorded after each trial.

Performance of the first three trials (BT), and the last three trials(ET) was averaged. This procedure allowed us to assess the learning process associated with each force feedback mode.

7 Results

Results showed that when no force feedback cues were present (only graphics), subjects deformed both the hard and the soft ball by the same amount of about 40 % of the radius (the required amount of deformation was of 10%) (Figure 6) . This is not surprising since in both cases, deformation was assessed visually from the screen-image.

We observed that haptic and auditive force feedback led to the best performance. Haptic force feedback was best when interacting with the hard ball (Figure 6). Performance was increased by about 45 % at the begining of the training session (BT) and by about 65% at the end of the training session (ET) as compared with the graphics only feedback case. However, haptic force feedback was relatively ineficient when interacting with the soft ball. In this case, auditive force feedback proved the most efficient. Performance associated with haptic and visual force feedback dropped off when performing with the soft ball while the

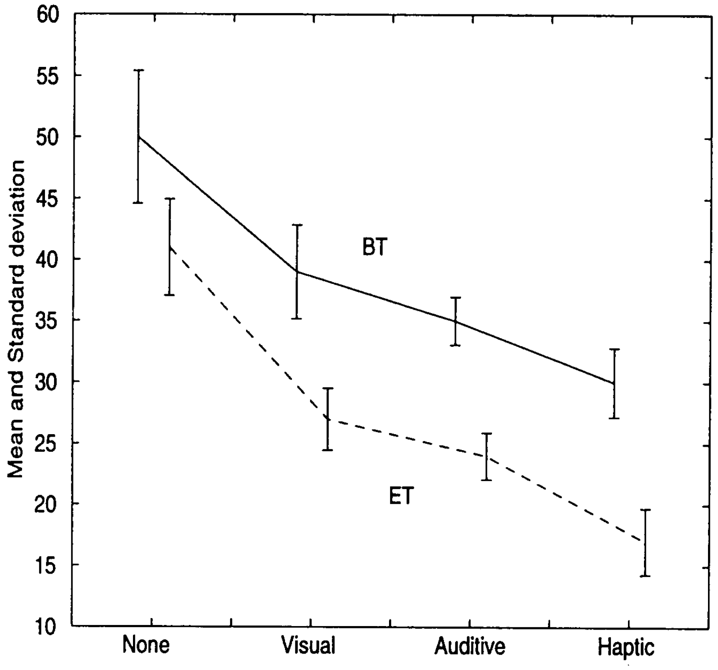

Figure 7: *Mean performance and standard deviation obtained at the beginning of the training period (BT), and the end of the training period (ET), with the hard ball, for different force feedback modalities.(in % of the radius)*

one associated with auditive force feedback remained almost the same (Figure 6).

Visual force feedback was shown to be unefficient especially when interacting with the soft ball (38.3 % of deformation vs. 40.4% in the graphics-only feedback case). It is believed that this is due to an overload of the visual channel. Subjects had to look back and forth to the LEDs and the screen. This affected the task by increasing the completion time. Results are summarized in Table 1.

A learning process was observed even when no force feedback cue was available: performance was increased by about 20% (Figure 7). The learning process associated with the haptic force feedback was best when interacting with the hard ball (50% vs. only 34% when interacting with the soft ball). The learning process associated with the auditive force feedback increased the performance by about 34% when using both the hard and the soft ball (about 35%), while that associated with the visual force feedback increased the performance by about 22% when using the soft ball and 34.5 % when using the hard ball.

8 Discussion

Results showed that force feedback increased subjects' dexterity when interacting with objects in a virtual environment. However, performance is far from the 10% deformation required. In fact, we measured operators' dexterity in a position feed-forward force feedback

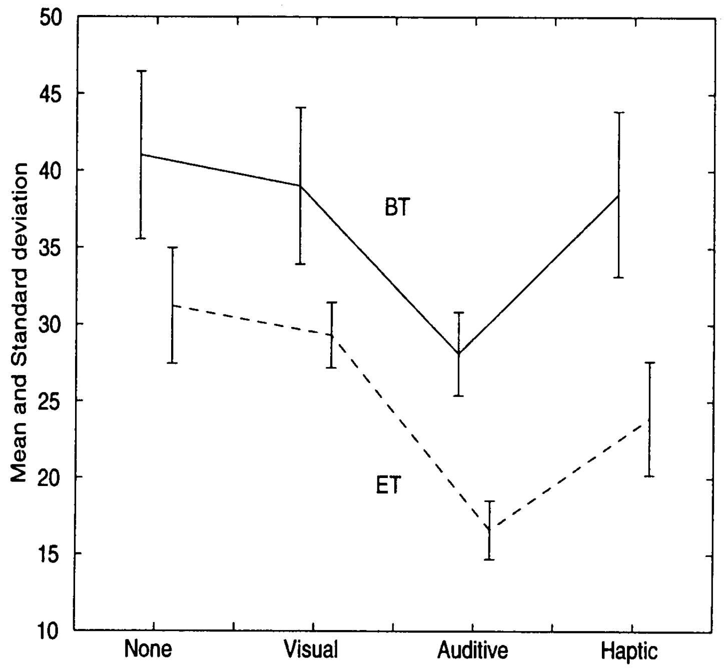

Figure 8: *Mean performance and standard deviation obtained at the beginning of the training period (BT), and the end of the training period (ET), with the soft ball, for different force feedback modalities. (in % of the radius)*

loop. Results are affected by the poor accuracy of the VPL DataGLove. Even a perfect force feedback interface can lead to bad performance if the hand device that is measuring the fingers' flexions is not accurate.

Haptic force feedback increased the performance for sof ball by only 5.2 %, while auditive force feedback increased the performance by 28 % .This fact highlights the potential for interactions between a beneficial source of information and mechanical limitation. Haptic stimuli were masked by friction present in the micro-cylinders.

It is believed that the good results associated with the auditive force feedback resulted from a better resolution of the auditive information. Application of small amounts of deformation resulted in large changes in the frequency. This allowed for finer judgments regarding the amount of deformation applied on the ball.

We observed that subjects working with haptic and auditive force feedback moved their hand continuously in space while trying to apply the minimum amount of deformation on the ball, whereas subjects working with visual force feedback decomposed their activities into deformation minimization and motion in space. Ouh-young observed a similar behavior in a 6-D simple docking task [Ouh-young, 1989]. Subjects working with visual force display alone decomposed their acitivities into 3-D force minimization and 3-D torque minimization whereas subjects working with force display moved continuously in 6-space to find the minimum.

		None	Visual	Auditive	Haptic
Hard Ball	Mean	40.0	26.9	24.2	18.6
	STD	5.8	5.3	5.4	5.6
Soft Ball	Mean	40.4	38.3	27.1	35.6
	STD	5.6	5.6	5.6	6.7
Average	Mean	40.2	32.6	25.7	27.1
	STD	5.7	5.4	5.5	6.2

Table 1: *Mean and standard deviation (% of the radius) of the average amount of deformation applied by the subjects on the balls when using the visual, auditive, and haptic force feedback.*

			None	Visual	Auditive	Haptic
Soft Ball	BT	Mean	46.0	43.9	33.2	43.6
		STD	5.4	5.1	2.7	5.4
	ET	Mean	36.3	34.3	21.7	28.8
		STD	3.8	2.1	1.9	3.7
Hard Ball	BT	Mean	45.6	33.9	29.8	24.8
		STD	5.4	3.8	2.0	2.8
	ET	Mean	36.4	22.1	19.2	12.6
		STD	3.9	2.5	1.9	2.7

Table 2: *Mean and standard deviation (% of the radius) of the performance at begining of the training period (BT), and at the end of the training period (ET). Deformation required: 10% of the radius of the virtual balls*

9 Conclusion

We have investigated the effect of haptic, visual and auditive force feedback on dextrous manipulation performance when interacting with virtual objects. Haptic force feedback was found to be the best modality when interacting with a hard object. However, auditive force feedback was revealed to be the best one when interacting with a softer object. This highlighted the importance of reducing friction in the master. We believe that auditive force feedback can be a low-cost, efficient alternative to haptic force feedback in dextrous manipulation of virtual objects, especially when time delays occur. In that case auditive force feedback allows us to continuously receive force feedback cues without inducing instability.

Visual force feedback was revealed to be inefficient, especially when interacting with the soft ball. It is believed that this is due to an overload of the visual channel.

We are working on a new portable master called "RUTGERS MASTER 2". This low friction master will be tested once it is integrated into the simulation.We will also repeat the above tests in stereo display in order to determine what is the advantage of this modality.

Acknowledgments

Work reported here was supported by grants from the Centre Robotique Integree d'Ile de France (CRIIF), from the AT&T Foundation and by the generous support of the Center for Computer Aids for Industrial Productivity (CAIP) at Rutgers - The State University of New Jersey, USA.

References

Bohm, K., Hubner, and W., Vaanaen, (1992). "GIVEN: Gesture driven Interactions in Virtual Environments. A Toolkit Approach to 3D Interactions", *Proceedings Interfaces to Real and Virtual Worlds,* Montpellier, France, March, pp:243-254.

Bouzit, M. and Coiffet, P. (1993) "The LRP Dextrous Hand Master" *Rapport Interne*, Laboratoire de Robotique de Paris, France.

Burdea, G., and Speeter, T., (1989). "Portable Dextrous Force Feedback Master for Robot Telemanipulation (PDMFF)", *Proceedings of NASA 1989 Coference on Space Telerobotics*, NASA pasadena CA, Vol:2, pp: 153-161.

Burdea, G., and Zuang, J., (1992) "Actuator system for providing force feedback to a dextrous Master Glove", US Patent 5,143,505, September 1, 1992.

Burdea, G., Lagrana, N., Roskos, E., Silver, D., and Zhuang, J., (1992a). "A Portable Dextrous Master with Force Feedback, *Presence-Teleoperators and Virtual Environments"*, MIT Press, Vol.1 (1), (pp.18-28).

Burdea, G., Roskos, E., Silver, D., Thibaud, F., Wolpov, R., (1992b). A Distributed Virtual Environment with Dextrous Force Feedback, *Proceedings of Interface to Real and Virtual Worlds Conference*, (pp.255-265), Montpellier, France.

Burdea, G., and Langrana, N., 1993a, "Virtual Force Feedback - Lessons, Challenges and Future Applications", *Journal of Robotics and Mechatronics*, Vol. 5, No. 2, Japan, pp.178-182.

Brooks, F., (1988). Grasping reality through illusion: interactive graphics serving science. In Proceedings of SIGGHI-88, May:1-11.

Caldwell, D. G., Gosney C., (1993). "Tele-Taction for Enhanced Tele-Manipulator Control". *Proceedings of 1993 JSME International Conference on Control advanced Mechatronics*

Chapin, W., S., Foster, (1992). "Virtual Environment Display for a 3D Audio Room Simulation", *Proceedings of SPIE Stereoscopic Display and Applications*, 12pp.

Corker, K.M., Bejczy, A.K., and Rappaport, B., (1985). "Force/Torque Display for Space Teleoperation Control Experiments and Evaluation" *Proceedings of the 21st Annual Conference on Manual Control* (pp.465-477). Los Angeles, CA: Oct 15-17.

Cutt, P. (1993). "Tactile Displays: Adding the Sense of Touch to Virtual Environments" *Proceedings of Virtual Reality Systems'93 Conference*, PP:120-122, New-York.

Ferrel, W. R., (1966). Delayed force feedback. *Human Factors*, October, pp:449-455.

Gharaybeh M., (1992) "Dextrous Master with Force Feedback Using Shape Memory Metals". Master Thesis, Department of Electrical and Computer Engineering, Rutgers - The State University of New Jersey, Piscataway, NJ.

Gibson, J. J., (1962). Observations on active touch. *Psychological Review*, Vol:69, PP:477-490.

Gomez, D., Burdea, G. (1993). "The Grabber" *Proceedings of Virtual Reality Systems'93 Conference*, New York.

Hewlett Packard Co., (1988). Starbase Graphics Techniques; HP-UX Concepts and Tutorials, Volumes 1-3, December.

Iwata H.(1990) "Artificial Reality with Force Feedback: Development of Desk-top Virtual Space with Compact Master Manipulator. *Computer Graphics*, Vol:24, PP:165-170.

Kontarinis, D. A., Howe R. D., (1993). Tactile Display of Contact Shape in Dextrous Telemanipulation. *Proceedings of Haptic Interfaces for Virtual Environment and Teleoperator Systems*, ASME Winter Annual Meeting, New Orleans.

Kim, W., Ellis, S. R., Tyler, M., and Stark, L., (1985). Visual Enhancement for Telerobotics. *In Proceeding of 1985 International Conference on Systems, Man and Cybernetics*, Tuscon, AZ.

Kramer, J., (1991). PhD thesis in progress, Stanford University.

Massinimo, M., Sheridan, T. B., (1989). Variable force and visual feedback effect on teleoperator man-machine performance.

Ouh-Young, M., Beard, D.V., Brooks,Jr., F.P., (1989). "Force Display Performs better than Visual Display in a simple 6-D Docking Task. *Proceedings of the IEEE Robotics and*

Automation Conference

Patrick, N., (1990). Design, Construction, and Testing of a Fingertip Display for Interaction with Virtual and Remote Environment, Master Thesis, M.I.T., 1990.

Polhemus Navigation Science Division, (1987). *Space Isotrack User's Manual,* Colchester, VT.

Richard, P., Burdea, G., and Coiffet, P., (1993). Human performance in Tasks involving Virtual Objects with Force Feedback, *Proceedings of Interface to Real and Virtual Worlds Conference*, (pp.229-238), Montpellier, France.

Reger J., (1987). "Visually Displayed Force Feedback in Delayed and Non-Delayed Bilateral Teleoperation" *SID International Symposium - Digest of Technical Papers*, New Orleans.

Shimoga K., (1992). "Finger Force and Touch Feedback Issues in Dextrous Telemanipulation", *Proceedings of NASA-CIRSSE International Conference on Intelligent Robotic Systems for Space Exploration*, Troy, NY, 20pp, September.

Stone, J. R., (1992). Virtual Reality: A Tutorial *Proceedings of MICAD 1992,* pp.2-16, Paris, France.

Sundgren, H., F.,Winquist, and I., Lundstrom, (1992). Artificial Olfactory System Based on Field Effect Devices, *Proceedings of Interfaces to Real and Virtual Worlds,* Montpellier, France, pp:463-472, March.

VPL Research Inc. "DataGlove model 2 Operating manual",(1987), Redwood City, CA.

Winey, C. M., (1981). Computer Simulated Visual and Tactile Feedback as an Aid to Manipulator and Vehicle Control. SM thesis, MIT, June.