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Dedicated to Richard
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Thank you for being
a supportive and
encouraging advisor.

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Evaluation of a Haptic Mixed Reality System for Interactions with a Virtual Control Panel

Abstract

We present a haptic feedback technique that combines feedback from a portable force-feedback glove with feedback from direct contact with rigid passive objects. This approach is a haptic analogue of visual mixed reality, since it can be used to haptically combine real and virtual elements in a single display. We discuss device limitations that motivated this combined approach and summarize technological challenges encountered. We present three experiments to evaluate the approach for interactions with buttons and sliders on a virtual control panel. In our first experiment, this approach resulted in better task performance and better subjective ratings than the use of only a force-feedback glove. In our second experiment, visual feedback was degraded and the combined approach resulted in better performance than the glove-only approach and in better ratings of slider interactions than both glove-only and passive-only approaches. A third experiment allowed subjective comparison of approaches and provided additional evidence that the combined approach provides the best experience.

1 Introduction

One of the most promising advances for virtual environments (VEs) is the development of displays that provide force or tactile feedback during interactions with virtual objects. These displays, called *haptic* displays, can increase the realism of VEs and communicate information that improves user performance or understanding. There is a growing interest in developing haptic displays and in understanding their effect on users.

1.1 Terminology

We use the adjectives *active* and *passive* to describe haptic devices that use computer-controlled actuators and those that do not, respectively. Note that the terms are being used to describe a feedback device characteristic and not to refer to Gibson's classification of a human's mode of touching the device (Gibson, 1962, 1966).

Examples of active devices include joysticks with force feedback, pin arrays for tactile feedback to fingertips, vibrotactile devices using piezo elements or small motors, thermal displays using Peltier modules, and specialized training devices such as syringe bodies with embedded force-feedback components.

Conventional input devices encountered on a daily basis are passive. The

click of a mouse button or keyboard key is a type of passive haptic feedback that can be carefully designed to provide useful information to a user. Terms such as *passive haptics*, *static haptics*, *tactile augmentation*, and *instrumented objects* have been used to refer to approaches using rigid objects in the real world to provide tactile stimulation to users interacting with VEs (Boud, Baber, & Steiner, 2000; Hoffman, 1998; Insko, Meehan, Whitton, & Brooks, 2001; Lindeman, Sibert, & Hahn, 1999). Benefits of these approaches over active approaches include low cost and low mechanical complexity.

1.2 A Mixed Haptic Feedback Approach

We present a combination of passive haptics with an active force-feedback device. Specifically, we investigate the combined use of a glove-mounted force-feedback device and a passive panel for the virtual control panel application shown in Figure 1. The VE consists of a room and a control panel located on a table in front of the user. The panel includes sliders, buttons, and LED readouts. Figure 2 shows an external view of a user performing interactions with the virtual control panel (the specific interactions are not exactly identical to those seen in Figure 1). The user wears a head-mounted display and a force-feedback glove that provides forces of interaction for slider handles and short force pulses that indicate the reaction of buttons. The panel surface itself is felt as a result of contact with a real panel that is spatially registered with the panel in the visual display. The real table surface is also registered with its virtual counterpart.

1.3 The Mixed Approach as an Extension of Mixed Reality

We present the combination of passive haptics with an active feedback device as a form of mixed reality. It is the haptic analogue of visually mixed displays, since it can allow real and virtual components to be combined haptically. It is also a logical extension to existing mixed reality systems, which do not yet allow

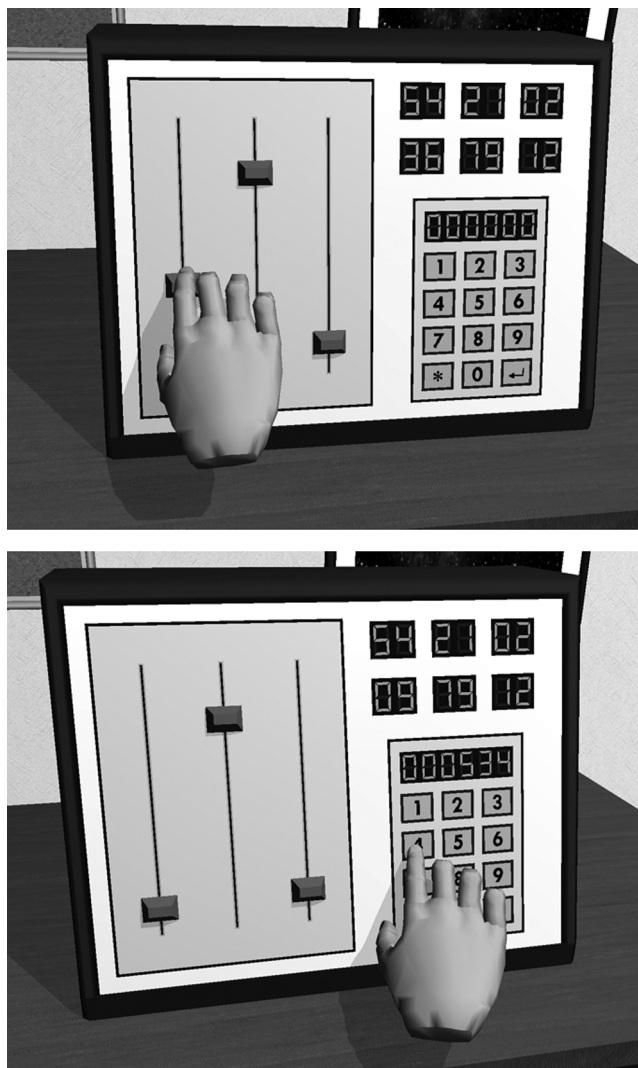


Figure 1. Virtual visual environment.

both real and virtual objects to be felt. Although we evaluated the technique with purely virtual visual feedback, it can be integrated with a visual mixed reality display in the future to produce a system that combines real and virtual elements both visually and haptically.

1.4 The Mixed Approach as an Enhancement to Other Approaches

The mixed approach overcomes some limitations of glove-only and passive-only approaches. Portable



Figure 2. User interacting with the environment.

glove-mounted devices can provide internal forces of grasping, but they have a number of limitations, as detailed in Section 3.2 (we use the term *portable*, as used by Burdea [1996], to refer to body-grounded interfaces). For our virtual control panel application, they cannot provide proper interaction forces at the virtual panel surface. On the other hand, a passive approach using static objects is promising during contact with static virtual objects such as the panel surface, but a static object does not provide feedback for contact with dynamic slider handles or for button reactions (button

clicks). A passive panel with real sliders and buttons is possible, but this increases panel complexity and does not support a highly reconfigurable virtual panel. The combination of the active and passive approaches has the potential to overcome glove limitations without requiring additional devices that limit mobility or are cumbersome for the user. The cost and mechanical complexity of introducing the passive component is minimal. The force-feedback glove can provide feedback not available with the passive approach alone.

1.5 Applications of a Mixed Approach

A mixed haptic feedback approach is useful in a variety of applications. For example, during ergonomic design of dashboards, real dashboard components could provide feedback for completed design portions while a haptic glove simulates contact with portions that only exist virtually. During engine maintenance training or practice runs, a force glove could provide internal forces of grasping for a virtual tool or part while real objects realistically constrain arm motion. A mixed approach could also be used to provide feedback in a configurable cockpit that allows the user to select from various arrangements of virtual panel components. In such a configurable cockpit, the panel itself could consist of a visual display.

2 Related Work

2.1 Passive Haptics

Past evaluations of passive haptics techniques show that they can improve a variety of VEs. For example, the use of a real plate for tactile augmentation of a virtual kitchen was considered by Hoffman (1998). A between-subjects comparison based on subjective evaluation by participants suggested that tactile augmentation improves perceived realism of virtual objects.

Lindeman et al. evaluated the Haptic Augmented Reality Paddle (HARP), which duplicated two-dimensional interface techniques in a three-dimensional environment and used a physical paddle for passive haptics (Lindeman et al., 1999). The use of passive haptics was shown to improve task speed

and accuracy. The evaluation included a selection task with similarities to button presses on our virtual control panel.

Boud et al. experimented with *instrumented objects* (IOs) consisting of grasped passive objects fitted with tracking system sensors (Boud et al., 2000). An evaluation showed that the use of IOs reduced the time needed to move puzzle pieces in a visually virtual Tower of Hanoi puzzle.

Low-fidelity passive haptics approaches have been used to provide feedback to users walking on a virtual ledge and bumping into internal walls of a virtual room (Insko et al., 2001). A haptic ledge was used with a fear-inducing environment involving a visual cliff, so physiological measures such as heart rate were useful for measuring its effects. The haptic ledge was shown to increase presence. In another experiment, use of Styrofoam obstacle mockups resulted in improved subject performance for a navigation task in which blindfolded subjects navigated a real room after exploring a virtual version of the room.

2.2 Haptics and Mixed Reality

Mixed reality systems combine real and virtual environments in a single interactive display. Milgram's taxonomy for mixed reality displays (Milgram & Colquhoun, 1999) presents mixed reality as a continuum between real and virtual environments, with augmented reality displays near the real end and augmented virtuality displays near the virtual end.

Most mixed reality research is focused on visual combinations of real and virtual environments. Development of haptic mixed reality systems has been minimal, although visual mixed reality displays are sometimes combined with haptic displays that are not mixed. Two examples of passive haptics enhancing visually mixed environments are Canesta's projection keyboard (Tomasi, Raffi, & Torunoglu, 2003) and the hybrid environments described by Lok (Lok, 2002). Canesta's system augments surfaces such as tabletops with a projected keyboard, and the surface itself provides haptic feedback important for interactions. Lok's study of hybrid environments required users to manipulate real objects in visually mixed environments, and several participants

mentioned (during debriefing interviews) that the resulting tactile feedback improved their sense of presence.

Some researchers describe the use of passive haptics with purely virtual visuals as a form of mixed reality, since a real object is experienced haptically while a virtual object is experienced visually. For example, Hoffman uses the phrase "mixed reality object," and Lindeman et al. use the phrase "haptic augmented reality." In such approaches, the mix occurs across feedback modalities rather than within a single modality. Although they are a form of mixed reality, they clearly do not constitute visual mixed reality, and similarly we do not consider them haptic mixed reality. Using Milgram's taxonomy, these approaches are perhaps best categorized as augmented virtuality, a subclass of mixed reality in which the environment still appears primarily virtual. Since development of the taxonomy was guided by visual displays, it does not explicitly address mixed reality involving haptics. We propose that Milgram's taxonomy can be extended into multiple dimensions to explicitly consider multiple feedback modalities. Development of the extended taxonomy is beyond the scope of this paper, but we note that the approaches mentioned above correspond to the virtual end of the visual dimension and the real end of the haptic dimension.

Our haptic feedback approach differs from the other approaches mentioned so far in that the haptic feedback itself is a form of mixed reality. Users interact with both haptically real components and haptically virtual components. We refer to such approaches as *haptic mixed reality* displays, even when they are not used with visual mixed reality displays.

Haptic mixed reality has previously been considered by Iwata (1999). He observed that a pen-based force-feedback device could be used to contact both real and virtual objects and coined the term *feel-through* (analogous to visual *see-through*) to refer to haptic interaction for augmented reality. Iwata's evaluation of feel-through showed that haptic feedback improves the accuracy with which users position a virtual box next to a real box, but the evaluated task did not require users to contact the real box with the pen, so the potential of haptic mixed reality was not fully considered.

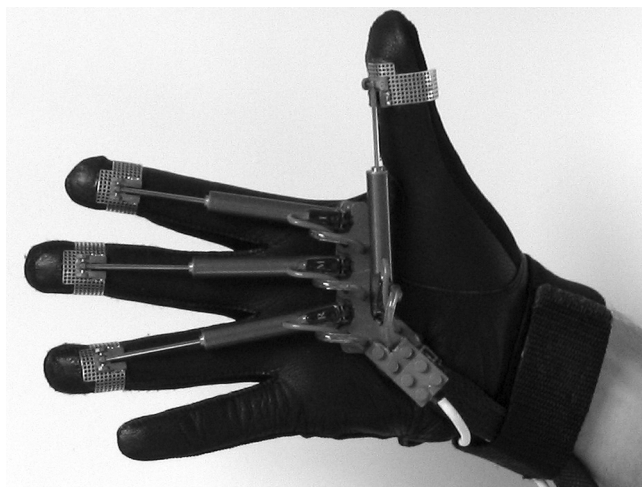


Figure 3. Force-feedback glove.

3 System Design and Technological Challenges

3.1 System Overview

The active haptic feedback component in our control panel system consists of a Rutgers Master (RM) force-feedback system (Bouzit, Burdea, Popescu, & Boian, 2002), shown in Figure 3. The RM glove uses four pneumatic pistons for feedback to the thumb and index, middle, and ring fingers, with a mechanical bandwidth at the fingertips of roughly 15 Hz (Burdea, 1996). Each piston includes sensors to measure piston displacement, piston flexion (inward bend), and piston abduction (lateral motion). A haptic control interface performs low-level pressure control and interfaces with a host PC via serial communication. Tracking of the piston base in the palm is performed using a small magnetic tracking sensor from an Ascension MiniBird system.

The passive haptic panel, seen in Figure 2, consists of shelving material with a Melamine laminate surface and is held in place by two heavy plywood supports. The virtual panel and the front portion of the virtual table are spatially registered with their real-world counterparts.

Visual rendering is performed with OpenGL. A Virtual Research V8 head-mounted display (HMD) is used

for viewing. It provides 640×480 color pixels per eye with a 60 degree diagonal field of view. Due to the resulting low pixel density, we use anti-aliasing, which our system performs using polygon smoothing. An Intersense IS-600 M2 Plus system performs head tracking. We use stereoscopic rendering and dynamic projective shadows to provide depth cues that help users understand the relative positions of the hand and the panel surface. Hu et al. have shown that stereoscopic rendering and shadows improve performance for a task requiring good perception of object-to-surface distance (Hu, Gooch, Creem-Regehr, & Thompson, 2002), and this is further supported by earlier work summarized therein.

The main application runs on a dual-processor PC using two main execution threads, which we refer to as the graphics thread and the haptics thread. The graphics thread contains the graphical rendering loop and performs related operations such as managing head tracking measures and processing keyboard input. It iterates at the graphical update rate, which depends largely on the complexity of the currently viewed scene.

The haptics thread implements force rendering and related operations. These include hand kinematics and tracking operations needed to compute fingertip positions, object dynamics to compute object positions, and a module for recording sessions for offline analysis. The haptics loop runs at 314 iterations per second and is synchronized with the RM serial communication driver to send updated force commands to the haptic controller at the same rate and with minimal latency (3.2 ms round-trip).

3.2 Force-Feedback Device Limitations

A primary motivation for our mixed haptics approach is to overcome device limitations of an existing feedback device with minimal added complexity. Portable glove-mounted devices appear well-suited to the virtual control panel application because they support a wide range of natural hand motions and apply independently controlled feedback to multiple fingers. However, Bergamasco evaluated requirements for hand feedback based on basic exploration and manipulation tasks and noted that severe technical difficulties arising in the

mechanical design of glove-based devices motivate heavily simplified models of contact areas and forces acting on them (Bergamasco, 1992).

Hand-grounded force-feedback devices such as the RM, the Immersion CyberGrasp, and the University of Tsukuba Hand Master (Iwata, Nakagawa, & Nakashima, 1992) provide only one degree of freedom per supported finger, with attachment at the distal phalanx and a force direction best suited for normal forces during circular grasps. Additional degrees of freedom for feedback to other phalanges are provided by devices such as the LRP Hand Master (Bouzit, Richard, & Coiffet, 1993) and the EXOS SAFiRE II (EXOS, 1995). Lateral forces are not available. Therefore, friction forces are not available to anchor fingertips on object surfaces or to indicate weight of an object held at its sides, although friction and weight provide haptic cues that are important for the control of grip (Johansson, 1998). For the panel interactions seen in Figure 1, normal forces are useful during slider grasps, but the force direction at fingertips is not appropriate for simulating contact with the panel surface itself. Additionally, features such as edges and texture cannot be presented in detail, since different contact geometries are reduced to a single force value per fingertip.

Portable force-feedback gloves are grounded on the hand or wrist to provide a large workspace and freedom of motion. As a result, they cannot prevent the hand from moving through virtual walls or other earth-grounded objects. Richard and Cutkosky observed that motion will therefore not be properly constrained during virtual button presses (Richard & Cutkosky, 1997), and one of their experiments illustrated reduced human performance in detecting an earth-grounded boundary when a feedback device was finger-grounded rather than earth-grounded. Similarly, gravity cannot be properly simulated without an earth-grounded device. Bergamasco suggested the use of a complementary external robot arm (Bergamasco, 1992), and Immersion Corporation recently developed a desk-grounded armature, called CyberForce, to connect to their CyberGrasp. Unfortunately, such additions limit workspace and mobility, increase cost and complexity, and may feel cumbersome for users. Further investigation is needed to determine if the

CyberForce's attachment at the back of the hand is capable of providing reasonable earth-grounded feedback at the fingertips and to evaluate side effects that this mounting produces. Even without the CyberForce armature, the CyberGrasp produces forces on the backs of fingers as a side effect of cable guides being grounded there. With the RM device, the grounding of pistons in the palm produces forces in the palm as a side effect.

Finally, device actuators or exoskeletons can restrict motion or collide with real objects. This is especially relevant in our mixed approach due to its use of real objects. The RM glove design prevents users from grasping real objects that might be present in a mixed reality system. The CyberGrasp device would allow users to pick up real objects but not to reach into a cavity. The location of actuators or exoskeletons may therefore be the deciding factor for suitability of a glove to a mixed reality application.

As a result of these limitations, force-feedback gloves are best suited for circular grasps of lightweight virtual objects that are held in the hand and not earth-grounded. The size and apparent stiffness of objects is also restricted, particularly for actuators such as the RM pistons that have a low mechanical bandwidth and restrict finger motion range.

Despite their limitations, force-feedback gloves are potentially useful for various tasks. The forces from the RM glove have been shown to improve performance for a task requiring users to maintain constant compression of a deformable grasped object being moved to target positions (Fabiani & Burdea, 1996). Short force pulses can be useful for simulating button clicks or the initial moment of contact with a virtual wall even though realistic motion constraints are not enforceable. Since proper visual feedback can enhance the perception of haptic information (Biocca, Kim, & Choi, 2001), effects of device limitations can be reduced by good visual displays. For example, Richard and Cutkosky observed that visual feedback can reduce the problem of missing earth-grounded feedback (Richard & Cutkosky, 1997).

3.3 Technological Challenges

The successful combination of real and virtual components requires accurate spatial registration be-

tween them. For the control panel environment, a virtual panel must be accurately registered with a real panel and the virtual fingertip positions must accurately reflect the positions of the real fingertips. Otherwise, users can be distracted by spatial mismatches. For example, a user may unexpectedly encounter a misregistered haptic panel before the panel is reached visually, or glove feedback associated with sliders may occur too far from the real panel surface. The accuracy of fingertip positions depends on the accuracy of glove sensor readings, hand modeling, and hand tracking. To achieve high spatial accuracy for the mixed haptics approach, our system includes the modified RM system detailed by Borst and Volz (2003), which includes the following developments:

1. Piston sensor calibration using piecewise cubic curves.
2. Improved hand joint model with accurate kinematics system.
3. A tracker calibration system to correct for field warp in hand tracking (the tetrahedral mesh method of Borst [2004]).

The control panel environment also requires higher performance in terms of force feedback quality than other environments for which the RM system has been used successfully. The slider handles being simulated are rigid rather than compliant and are grounded on a panel rather than held in the hand. Due to the previously discussed device limitations, this complicates feedback. The problem of simulating rigid objects is also complicated by a low communication bandwidth between the haptic controller and the host machine, and this limits the achievable force update rate and introduces instabilities for stiff objects. Although the mechanical glove limitations remain, sensations have been improved with the following developments, detailed by Borst (2005) and Borst & Volz (2003):

1. A new serial communication scheme using data compression and synchronization to increase update rate (from 140 to 314 updates per second) and reduce latency (from over 14 ms to 3.2 ms round-trip).

2. Low-level pressure control loop modifications to produce finer changes at a cost of reduced maximum force.
3. Modified force rendering equations to improve force at rigid object boundaries.

4 Experiment Methods

4.1 Design

We used between-subjects experiments to compare the mixed haptics approach to the passive-only and glove-only approaches. The independent variable was the type of haptic feedback provided, and dependent variables were task performance measures and questionnaire responses. Our research hypothesis was that the mixed approach would result in improved performance and subjective evaluation when compared to passive-only or glove-only approaches.

Each human subject was randomly assigned to one of the three following groups:

M: Mixed Group. Subject received mixed haptic feedback.

P: Panel (Passive) Group. Subject contacted the real panel but glove forces were off.

G: Glove (Active) Group. Subject received glove forces but did not contact the panel.

All subjects wore the force-feedback glove and were seated near the real panel. For the P group, the glove was used to track motion, but piston forces were off. For the G group, an offset of several inches was applied to hand tracking measures so the real panel was not contacted. The glove provided only forces associated with button reactions (clicks) and slider handles. Glove forces were not used to simulate the panel surface due to device limitations described in Section 3.2.

Three experiments were performed and were presented to subjects as three sessions of one experiment. Each subject performed all three experiments in one visit. Each experiment required a subject to perform a simple control panel task repeatedly and then answer written questions. Experiment 1 was a basic comparison of the mixed approach to the other approaches in terms

of subjective ratings and task times. Experiment 2 compared the approaches for a low-visibility task requiring increased reliance on haptic cues. Specifically, the previous task sequence was repeated with progressively darkened visual feedback, and a between-groups comparison was made for task times, error rates, and subjective ratings of the interactions. The ability to perform control panel interactions with minimal visual feedback is useful in real-world environments when visual attention is focused away from the panel or when vision is obscured (e.g., by smoke). In Experiment 3, visual quality was restored and the task sequence was repeated a third time, but all subjects received mixed feedback regardless of their group assignments. This allowed us to further test for subjective differences between approaches based on subjective ratings of the change in experience.

4.2 Participants

Experiment results are reported for a total of 48 subjects, divided evenly into the three subject groups (16 per group, assigned randomly). Three additional subjects participated but encountered problems and were not included in the analysis. One experiment was halted by a subject who felt uncomfortable wearing a head-mounted display. There were physical problems with equipment in the two other cases.

Subjects were recruited primarily by flyers posted at a university campus. Each subject was compensated ten dollars for participation. Total duration for experiments was approximately one hour per subject. Due to the large size of the RM glove, advertisements listed a minimum index finger length as an eligibility requirement. Additional eligibility requirements requested right-handed or ambidextrous subjects with normal right hand function, normal or corrected vision, and no history of motion sickness.

Table 1 summarizes subjects' median age, computer experience, and video game use. The G group included one female subject; all other subjects were male (presumably due to hand size requirements). The female subject's performance measures were checked for unusual values to ensure that her inclusion was not problematic with respect to the specific conclusions reached in Section 5.

Table 1. *Subject Demographics (Median Values Are Shown)*

	M	P	G	Overall
Age (years)	22	22	23	22
Computer experience (years)	8.5	9.0	11.0	10.0
Weekly video game use (hours)	1.5	2.0	2.0	2.0

Using free-form questions, we asked subjects to describe any previous use of virtual reality (VR) equipment and to mention any other experiences with “interactive computer graphics or related technology.” Each group contained eight or nine subjects mentioning related experiences. Sixteen subjects indicated exposure to VR equipment, and other subjects mentioned related experiences while indicating no VR exposure (e.g., “full-motion flight simulator”). Reported VR equipment use was minimal in most cases (e.g., one-time use of an arcade system), so the subjects were not experienced VR users. One M-group subject had encountered VR in a geosciences lab and generated a VRML robot model. In the P group, one subject had taken a “virtual manufacturing” course but indicated no exposure to VR equipment and one subject had encountered SensAble's PHANToM haptic device but also indicated no exposure to VR equipment. Other responses refer to entertainment systems, driving simulations, 3D modeling software, and rudimentary graphics programming knowledge.

4.3 Materials and Procedure

4.3.1 Environment and Task Description.

Figure 4 shows the virtual visual environment used for experiments, and the hardware is described in Section 3. The environment included a right hand model but no model of the arm or remaining body. The virtual control panel included sliders and buttons representative of components found on many real-world interfaces. Dials and toggle switches were also considered in earlier panel designs. Dynamics of dial interactions were awkward with all haptic approaches due to the lack of lateral forces described in Section 3.2 and due to the tendency of some users to use an unsupported contact area at the

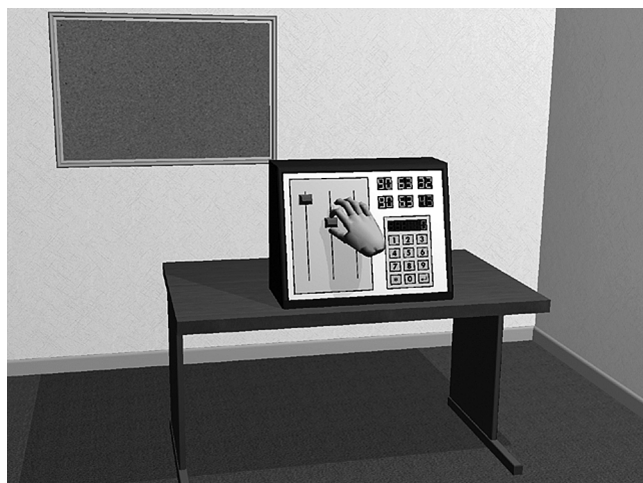


Figure 4. *Virtual room.*

side of the index finger. Toggle switch interactions were complicated by a motion limit of the index finger piston (grasping of objects smaller than our slider handles was problematic).

A closer view of the virtual panel is seen in Figure 1. The top row of LEDs was used to display target values for a task performed by participants, while the second row of LEDs displayed current position of the three sliders. Specifically, each slider was mapped to a two-digit readout displaying a value from 00 to 99 proportional to slider position. The LED readout in the button area reflected sequences of pressed buttons.

Each experiment required eight trials of a task that required subjects to move sliders to target positions and enter a sequence of digits using the buttons. The sequence of steps and the resulting panel behavior was as follows:

1. The subject pressed the asterisk button to begin a trial. As a result, the button area's LED readout was reset to show only the single digit 0 and the LED readouts in the top row of the panel were set to predetermined target values.
2. The subject moved the sliders to the target values given by the first row of LEDs. Since the values in the second row of LEDs reflected slider positions, the two rows matched when the sliders were positioned correctly.
3. Using the buttons, the subject entered the six digits seen in the top row of LEDs. The entered sequence was reflected by the six-digit readout in the button area, with new digits shifted in from the right. The subject could not erase mistakes made during entry but could continue entering digits until satisfied with the displayed digits.
4. The subject pressed the enter (\downarrow) button to end the trial. In response, the LED readout in the button area changed color until the next trial began, and the top row of LED readouts turned blank.

The sequence of target values appearing in the top row of LEDs was fixed for each experiment and for each subject as shown in Table 2. The eight trials were organized into two practice runs and two composite tasks that consisted of three trials each. The sequence of target values repeated, so the two composite tasks consisted of identical sequences.

Each trial included target values that required at least one button to be pressed twice in succession (e.g., 4-4 and 2-2 in Trial 6) and required at least one move between nonadjacent buttons. This emphasized that users must lift the finger far enough from the panel to break contact for multiple presses and to avoid accidentally triggering adjacent buttons during lateral motion. In terms of slider motion, target values in C1 and C2 required upward movements by amounts ranging from 36 to 56 and downward movements by amounts ranging from 11 to 46. More downward movements were required than upward movements, and Trials 4 and 7 required more upward movements than other trials in C1 and C2. A consequence of this is seen in Section 5.3.1.

4.3.2 Experiment I Procedure. Each subject signed an informed consent document and provided background information before beginning Experiment 1. The subject then read a written task description and entered the VE. After a system check, the subject was asked to perform the task described in Section 4.3.1. Scripted verbal instructions were given during the first trial. During the second trial, individual instruction steps were repeated if requested by the subject. The subject was then asked to perform the remaining trials. After complet-

Table 2. *Experiment Organization*

Trial	Practice runs		Composite task C1			Composite task C2		
	1	2	3	4	5	6	7	8
Targets	34,84,43	90,63,32	44,22,07	34,84,43	90,63,32	44,22,07	34,84,43	90,63,32

**Figure 5.** *Darkened virtual environment.*

ing all trials, the subject exited the VE and answered the 14-item questionnaire shown in Appendix A.

4.3.3 Experiment 2 Procedure. After Experiment 1, the subject reviewed a short written description of Experiment 2 and returned to the VE to perform eight trials. The light level in the virtual room was lowered progressively for each trial. Specifically, light levels were set to the following values, expressed as a percentage of Experiment 1 light level: 100.0, 50.0, 25.0, 12.5, 6.3, 3.1, 1.6, and 0.0%. However, virtual panel LEDs were luminous, and buttons were slightly luminous, so they remained partially visible during all trials. We included this illumination because we judged the task infeasible without it based on earlier experience with pilot subjects. Figure 5 shows a subject's view of the environment during Trial 8.

Written instructions for Experiment 2 included the statement, "It may become difficult to perform the task,

but you should continue performing it to the best of your abilities." Subjects verbally expressing difficulties received the scripted response, "If you decide a step is impossible, you may continue with the next step, but you should first try to finish the step." After eight trials were completed, the subject answered a set of questions about interactions with the darkened environment, as listed in Appendix A.

4.3.4 Experiment 3 Procedure. After Experiment 2, the subject reviewed a short written description of Experiment 3 and returned to the fully lit VE to perform eight trials. Regardless of group assignment, each subject received mixed feedback during Experiment 3. So, M group subjects experienced no changes, P group subjects experienced the addition of glove forces, and G group subjects experienced the addition of panel sensations. After all trials were completed, the subject answered a set of questions comparing the experience in Experiment 3 to that in Experiment 1, as shown in Appendix A. The subject also answered open-ended questions about the entire experience.

5 Experiment Results and Discussion

5.1 Statistical Methods

To analyze ordinal data (here, questionnaire responses) and task error measures, we used the Kruskal-Wallis test followed by two Mann-Whitney pairwise comparisons. Otherwise, we used the one-way ANOVA followed by two t-tests. A protected least significant difference approach was used for the followup tests, that is, they were only performed in cases where the omnibus test detected a difference. Analysis was conducted using SPSS software.

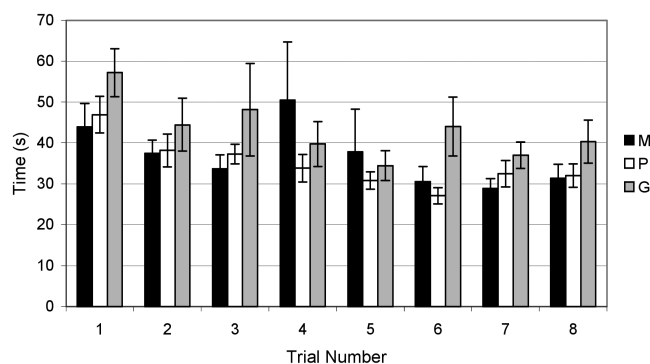


Figure 6. Experiment 1 slider time means with SE bars.

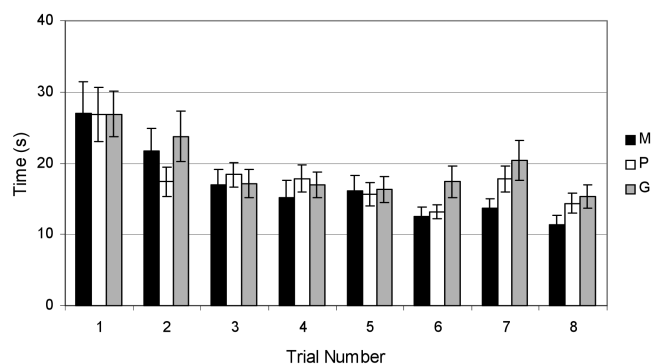


Figure 7. Experiment 1 button time means with SE bars.

We report p -values for two-tailed tests. We report p -values below .05 as demonstrations of significance. Since power was limited by a small sample size, we also mention other values below .10, referring to them as *near significant*. In the case of a near-significant omnibus test result, followup test results below 0.05 are only referred to as near significant. Sample size was limited due in part to concerns about the durability of the specialized equipment worn by subjects. Nonetheless, some effects were detected.

5.2 Experiment I Results and Discussion

5.2.1 Experiment I Performance Measures.

Performance was evaluated in terms of slider time and button time, defined as the total amount of time spent manipulating sliders and buttons, respectively. To compute these times, the workspace near the panel was divided into regions. When the fingertip closest to a button or slider was located in a region around the sliders, the subject was considered to be performing slider manipulations. When it was in a region around the buttons, the subject was considered to be performing button interactions. The resulting task times for all trials of Experiment 1 are plotted in Figure 6 and Figure 7.

Statistical analysis was based on performance measures for composite task C2, that is, the summed performance measures for the last three trials. A similar analysis was also performed for C1, but it produced no p -values be-

low .1. This was due in part to outliers that contributed to the relatively large slider times and variances of the M group for the fourth and fifth trials, as seen in Figure 6. Therefore, C1 is not considered further.

Table 3 shows the resulting performance measures and Table 4 shows the corresponding statistical test results. Significant between-group difference was detected in button time [$F(2,45) = 3.42, p < .05$] and a difference in slider time was near significant [$F(2,45) = 3.06, p = .057$].

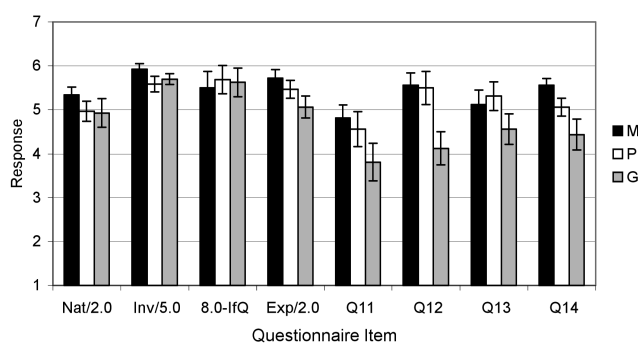
The use of the mixed approach was shown to result in significantly improved button time toward the end of the Experiment 1 when compared to the use of only the force-feedback glove [$t(45) = -2.61, p < .05$]. It has been shown elsewhere that the use of a passive panel for a selection task improves task speed when compared to the use of no haptic devices (Lindeman, 1999). In addition to providing haptic cues for surface contact, a panel physically constrains finger motion, thereby eliminating difficulties that result from the hand passing into the virtual panel during button presses. Our experiment shows that a passive panel can offer similar benefits when added to the glove-mounted force display. The portable glove alone cannot impose the motion constraints of a panel surface (see Section 3.2). Similarly, a passive panel imposes motion constraints during slider motion, and this may help users control hand position during slider interactions. A near significant difference was seen in the relatively low slider time of the M group [$F(2,45) = 3.06, p = .057; t(45) = -2.17, p = .035$].

Table 3. Experiment 1, C2 Task Time Measures

	Slider			Button		
	Mean	SD	Median	Mean	SD	Median
M	90.73	27.94	92.31	37.56	13.30	37.93
P	91.61	25.31	84.56	45.29	12.31	42.33
G	121.34	57.77	104.44	53.14	22.89	48.19

Table 4. *p*-values for Experiment 1, C2 Task Time Measures

Statistical test	Slider time	Button time
ANOVA	0.057	0.042
M vs P	0.950	0.201
M vs G	0.035	0.012

**Figure 8.** Experiment 1 question response means with SE bars.

No significant differences were detected between the M and P groups.

5.2.2 Experiment 1 Questionnaire Responses.

Figure 8 summarizes questionnaire responses from Experiment 1. The first four items are presence subscale scores from the first ten questions as described in Appendix A, transformed linearly for consistent scaling with other plotted items. Table 5 shows the results of the statistical analysis of plotted items.

No significant differences were detected for presence subscale scores. The ten presence questions were based on the more extensive questionnaire of Witmer and Singer (Witmer & Singer, 1998) and were grouped into subscales based primarily on the cluster analysis therein and secondarily on the discussion by Schubert, Friedmann, and Regenbrecht (2001). It has been shown elsewhere that this questionnaire style can fail to detect significant differences in presence even when a strong difference should exist (Usoh, Catena, Arman, & Slater, 2000). If a difference in presence exists, detecting it may require a large number of subjects or a different measurement apparatus.

Significant differences were detected for Question 12 [$\chi^2(2) = 7.81, p < .05$] and Question 14 [$\chi^2(2) = 7.95, p < .05$]. Question 12, which asked about solidity of the tabletop, was based on a question used by Hoffman to evaluate the use of passive haptics for subjects lifting a plate in a virtual kitchen (Hoffman, 1998). In our experiment, solidity was rated significantly higher by the M group than by the G group [$Z = -2.39, p < .05$]. G group subjects received no haptic feedback for contact with the virtual tabletop while the other groups could contact the real tabletop. However, it was rare for subjects to contact the virtual tabletop since the task did not require it. Therefore, we conclude that the detected difference reflects differences in belief about the tabletop that resulted from differences in feedback associated with the virtual panel. This is consistent with Hoffman's conclusion that the subjects' experience with one contacted object influences their perception of other objects in a VE.

Question 14 asked in a direct manner about the overall quality of the sense of touch. The M group was

Table 5. *p* Values for Experiment 1 Questionnaire Responses

	Nat	Inv	IfQ	Exp	Q11	Q12	Q13	Q14
Kruskal-Wallis	0.510	0.306	0.946	0.242	0.213	0.020	0.311	0.019
M vs P	—	—	—	—	—	0.799	—	0.059
M vs G	—	—	—	—	—	0.017	—	0.009

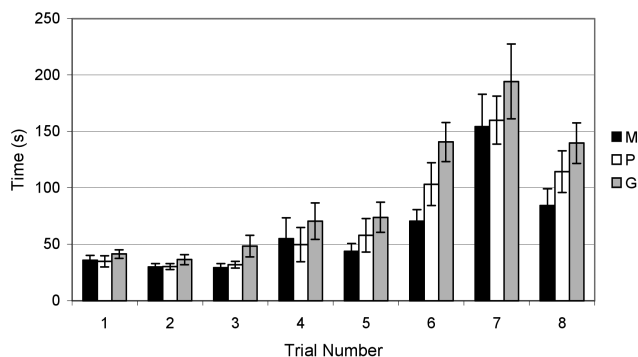


Figure 9. Experiment 2 slider time means with SE bars.

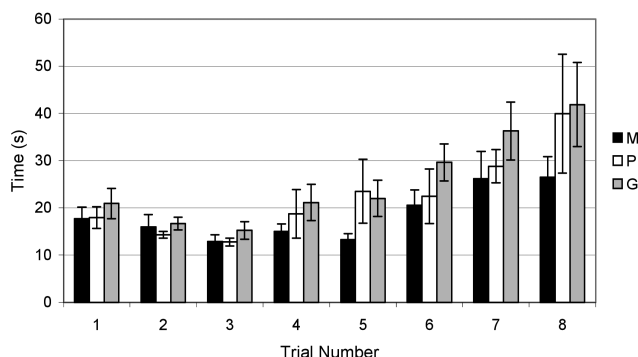


Figure 10. Experiment 2 button time means with SE bars.

found to provide significantly higher ratings than the G group [$Z = -2.61, p < .01$]. A near significant difference was seen in higher ratings from the M group than from the P group [$Z = -1.89, p = .059$].

5.3 Experiment 2 Results and Discussion

5.3.1 Experiment 2 Performance Measures.

Figure 9 and Figure 10 show the task times for all Experiment 2 trials, which were performed with the virtual lighting conditions described in Section 4.3.3. Task error measures were also considered for Experiment 2 and are shown in Figure 11 and Figure 12 (errors were not analyzed for Experiment 1 because they were rare for all groups until visual feedback was degraded). Slider error is the sum of absolute values of the differences between the target positions and the actual final slider positions. Button error is a measure of difference between the six target digits and the digits entered using buttons, defined as the smallest number of operations needed to transform the entered digit sequence into one in which

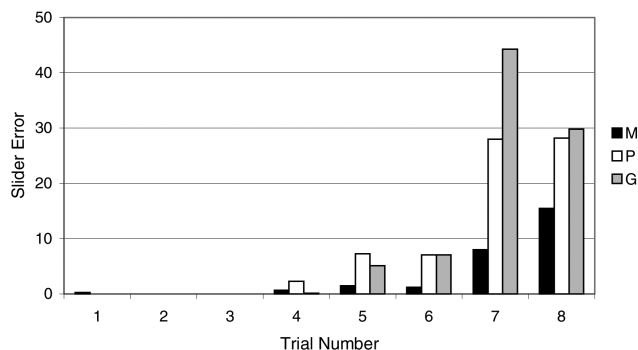


Figure 11. Experiment 2 slider error means.

the rightmost six digits match the desired target (an operation is insertion, deletion, or replacement of one digit).

Errors were rare for light levels of 25% and above. One subject made a small magnitude slider error during Trial 1. One button error was made in each of the first three trials, two of them being single digit errors. No other errors were made during the first three trials.

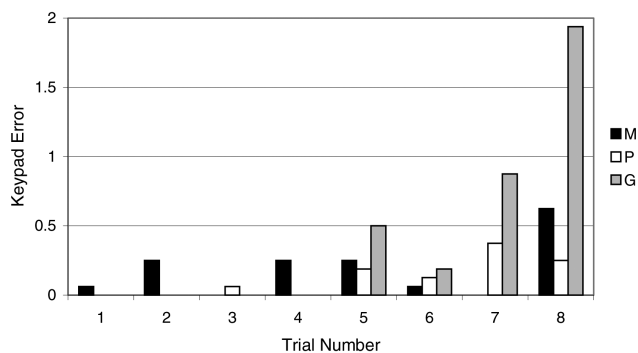


Figure 12. Experiment 2 button error means.

Large increases in task times and error rates were observed as the virtual room was darkened. However, slider manipulation was faster in Trial 8 than in Trial 7. This resulted from the particular choice of target values, which involved less upward motion for Trial 8. Subjects had more difficulty with upward motion than downward motion, because they used multiple fingers to search for and manipulate sliders during downward motion, but typically only the thumb for upward motion.

Most subjects manipulated control panel elements until the panel state correctly matched target values, so any difficulty these subjects had performing interactions was reflected in high task times rather than task errors. However, 30% of trials in C2 ended with nonzero slider error, and 17% ended with nonzero button error. We computed correlations between C2 task time and C2 task error for the set of all subjects and found significant positive correlations between these measures for slider interactions (Spearman's $\rho = 0.360$, $p < 0.05$) and for button interactions (Spearman's $\rho = 0.553$, $p < 0.001$). Two G group subjects were found to have small task times but large error values during Trial 7 as a result of the hand moving into the button area and suddenly triggering multiple buttons, including the one that ended the trial. This illustrates the difficulty of button interactions without good visual feedback or motion constraints.

Table 6 summarizes performance measures for Experiment 2, and corresponding p values are shown in Table 7 and Table 8. As for Experiment 1, the analysis was for

task C2, which also corresponded to the portion of the experiment during which visual feedback was severely degraded (virtual light levels of 3.1, 1.6, and 0.0%).

For interactions during severely degraded visual feedback, the mixed haptic approach was found to produce significantly improved performance for both slider and button interactions when compared to the glove-only approach. For slider interactions, a significant task time reduction was detected, $F(2,45) = 3.71$, $p < .05$; $t(45) = -2.71$, $p < .01$. For button interactions, significantly reduced error was detected, $\chi^2(2) = 10.77$, $p < .01$; $Z = -2.77$, $p < .01$. This further supports our discussion from Section 5.2.1. A passive panel can help a user position the hand during searching or manipulation for slider tasks, thereby reducing task time. During button interactions, a properly registered passive panel prevents the user from moving the hand too far into the virtual panel.

5.3.2 Experiment 2 Questionnaire Responses.

Figure 13 summarizes the Experiment 2 question responses and Table 9 shows the corresponding statistical test results. For both questions about the quality of slider interactions, ratings from the M group were significantly higher than those from either the P group or the G group [Question 1a: $\chi^2(2) = 7.03$, $p < .05$; M vs P, $Z = -1.99$, $p < .05$; M vs G, $Z = -2.40$, $p < .05$; Question 2a: $\chi^2(2) = 7.13$, $p < .05$; M vs P, $Z = -2.34$, $p < .05$; M vs G, $Z = -2.26$, $p < .05$]. This indicates that subjects receiving mixed haptic feedback perceived the highest quality of slider interaction. A difference was not detected for questions asking subjects to rate their ability to find objects.

Significant differences were not found for questions about button interactions, although a near significant difference was seen between groups M and G for the Question 2b about button naturalness, $\chi^2(2) = 5.16$, $p = .076$; $Z = -2.10$, $p = .036$.

Based on inspection of Figure 13, button interactions were rated higher than slider interactions. One possible reason is that slight illumination was provided for buttons but not for sliders. Free-form question responses discussed in Section 5.5.2 give further insight into the low ratings of slider interactions.

Table 6. Experiment 2, C2 Performance Measures

		Slider			Button		
		Mean	SD	Median	Mean	SD	Median
Task time	M	308.83	160.56	293.25	73.18	43.14	62.30
	P	377.59	159.30	336.93	91.20	64.91	70.27
	G	474.52	196.21	480.11	107.80	60.51	84.93
Task error	M	24.69	52.02	0.00	0.69	1.74	0.00
	P	63.25	133.68	0.00	0.75	1.73	0.00
	G	81.13	94.01	39.50	3.00	2.85	2.50

Table 7. *p* Values for Experiment 2, C2 Task Times

	Slider time	Button time
ANOVA	0.032	0.239
M vs P	0.267	—
M vs G	0.009	—

Table 8. *p* Values for Experiment 2, C2 Task Errors

	Slider error	Button error
Kruskal-Wallis	0.169	0.005
M vs P	—	0.715
M vs G	—	0.006

5.4 Experiment 3 Results and Discussion

5.4.1 Experiment 3 Performance Measures.

Objective performance data were not analyzed for Experiment 3 since the experiment was included to allow subjective comparisons to Experiment 1 and performance analysis would not address the research hypothesis. Experiment 3 performance measures are tabulated in Borst (2002).

5.4.2 Experiment 3 Questionnaire Responses.

Figure 14 summarizes the Experiment 3 question responses, and the corresponding *p* values are shown in

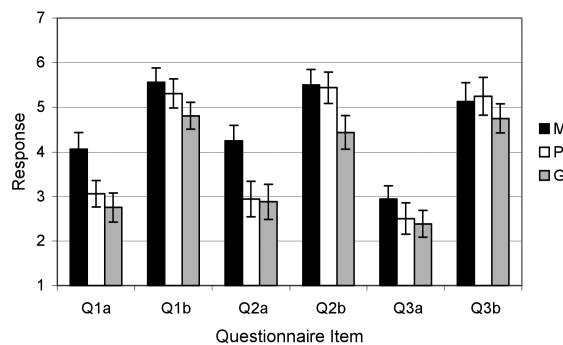


Figure 13. Experiment 2 response means with SE bars.

Table 9. *p* Values for Experiment 2 Questionnaire Responses

	Q1a	Q1b	Q2a	Q2b	Q3a	Q3b
Kruskal-Wallis	0.030	0.242	0.028	0.076	0.342	0.480
M vs P	0.047	—	0.019	0.907	—	—
M vs G	0.016	—	0.024	0.036	—	—

Table 10. Significant between-group differences were detected for the two questions about haptics [Question 2a: $\chi^2(2) = 13.57, p < .01$; Question 2b: $\chi^2(2) = 16.12, p < .001$], and for the question about overall quality [Question 3: $\chi^2(2) = 10.01, p < .01$].

On average, all groups tended to give ratings above 4, suggesting a possible perceived increase in haptic and

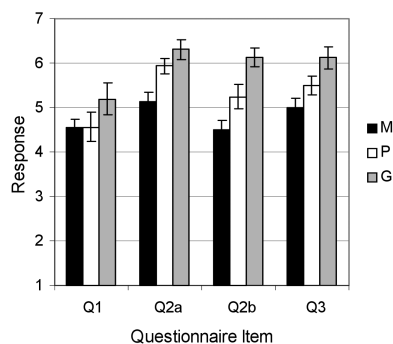


Figure 14. Experiment 3 response means with SE bars.

Table 10. *p* Values for Experiment 3 Questionnaire Responses

	Q1	Q2a	Q2b	Q3
Kruskal-Wallis	0.455	0.001	0.000	0.007
M vs P	—	0.007	0.047	0.077
M vs G	—	0.001	0.000	0.003

visual quality even though there were no visual changes from Experiment 1 and no haptic changes for group M. Subjects may have perceived improvements because they learned to interact with the environment more effectively or because their memory of Experiment 1 was biased by the degraded experience in Experiment 2. The fact that the questions asked for comparisons may also have caused some subjects to believe there was a change even when there was not.

No significant difference was detected for the question about visual quality (question 1), and by design there was in fact no difference in rendered visual quality. For the questions about haptic quality of sliders and buttons, both groups P and G reported haptic improvement that was significantly larger than that reported by group M [Question 2a: M vs P, $Z = -2.69$, $p < .01$; M vs G, $Z = -3.29$, $p < .01$; Question 2b: M vs P, $Z = -1.99$, $p < .05$; M vs G, $Z = -3.91$, $p < .001$]. For the question about overall quality, a significant difference was found between the M and G groups, and a near significant difference was seen between groups M and P

[Question 3: M vs P, $Z = -1.77$, $p = .077$; M vs G, $Z = -2.93$, $p < .01$]. These results provide further evidence that the mixed approach provides the best experience.

5.5 Responses to Open-Ended Questions

Responses to open-ended questions following Experiment 3 provided further insight into the value of haptic feedback and helped us identify difficulties encountered by some subjects. Responses included comments specific to certain experiments as well as comments describing the overall experience. A complete list of responses is tabulated in Borst (2002).

5.5.1 Most Beneficial System Aspects. Forty-five subjects responded to the question asking them to identify the most beneficial system aspects. Approximately half of them referred to haptic feedback. When subjects clearly identified a specific haptic component, the one mentioned most frequently was the active force feedback for sliders. One-fourth of P group subjects clearly identified the additional glove forces in Experiment 3 as the most beneficial system aspect. For example, one subject wrote, “On the final session the sliders felt more realistic; made it much easier to control.” Other comments referred to both the real panel and the active force feedback for button interactions. So, comments about haptics indicate that subjects judged both active and passive components to be useful. Some comments mentioned buttons or sliders without specifying haptics, such as the comment, “The pushbutton pad was perfect.” Six subjects included comments on visual aspects such as shadows, and two commented positively on hand modeling.

5.5.2 System Aspects Needing Improvement. Forty-five subjects responded to the question about system aspects needing improvement. Twenty-one of the responses directly referred to sliders. Several of these referred to properties such as “sensitivity” or lack of “resistance” for sliders. Often, subjects spent substantial time making minor adjustments to almost-correct slider positions because they found it difficult to move a slider

by only a small amount. This can result from jitter in motion tracking, an overly sensitive object dynamics system, or actual limitations of human control of hand motions. A simple solution to the problem is to provide a coarser-grained LED readout (e.g., 25 increments instead of 100). Precise slider control is also a problem in 2D interfaces due to limited device resolutions, and this has led to the augmentation of 2D scroll bars with arrow buttons and to the development of techniques such as the AlphaSlider (Ahlberg & Shneiderman, 1994). The limited graphical resolution contributing to the problem in 2D interfaces is not the cause of the problem in our 3D environment, since slider increments are produced by a dynamics model that is independent of graphical resolution.

Several comments reflected mechanical limitations of the glove. Subjects mentioned that their sense of touch was limited and that properties such as “texture” were not felt. Three subjects mentioned the glove’s limited finger motion range, and other comments about grasping appeared to be related to the limited motion range or to a difficulty in grasping sliders that resulted from the lack of tangential forces of friction needed to keep fingers anchored on a slider. The inability of the device to completely prevent a user from moving a finger into a virtual object was also noticed by one subject who wrote, “At times I found my thumb would pass through the slider if I squeezed on it.” One M group subject and one G group subject reported noticing delays in device reaction. Overall, the comments suggest that the device limitations described in Section 3.2 remain distracting to users. The comments about sliders also help explain the low slider ratings that were observed in Experiment 2.

Some subjects in the G and P groups mentioned the (intentionally) lacking feedback in earlier experiments. For example, a P group subject wrote, “The first session needs more touch sensations.” This further suggests that subjects found both components of the mixed approach to be valuable. Three subjects indicated that visual feedback was not realistic enough, one commenting: “There is still this feeling of a virtual world.”

5.5.3 Additional Comments. Thirty-four subjects responded to the free-form question asking for

additional comments. Approximately half of these subjects commented positively on the experience, describing the system as natural, realistic, and user-friendly. Other responses tended to be similar to those for the preceding questions. One M group subject wrote, “I was able to tell when I was interacting with [objects] without looking directly at them,” suggesting that the haptic feedback enhanced interactions performed outside of the field of view. Two M group subjects reported motion sickness, although one added, “but I got used to it.” One of these two subjects consistently had task times well below average, but neither made any task errors and no unusual trends were seen in their questionnaire responses.

6 Summary and Observations

When significant differences were detected using objective performance measures, they consistently favored the mixed approach over the use of only glove feedback. This supports the hypothesis that the mixed approach improves performance compared to the glove-only approach. No significant task time differences were demonstrated between the mixed approach and the use of only passive haptics, but this should be investigated further. We speculate that cues from a haptic glove are potentially useful for finding objects in a darkened virtual room, and that the mixed approach may offer improvement over a passive-only approach for other task types. For example, an improvement can be expected if a passive object constrains hand motion while a user performs grasping tasks for which the glove has already been shown effective (Fabiani & Burdea, 1996; Richard et al., 1996). Based on our experiment, we would not anticipate meaningful task time improvements over the passive approach in the well-lit environment of Experiment 1.

The analyses of questionnaire responses from Experiments 2 and 3 support the hypothesis that the mixed approach results in an improved subjective experience when compared to either passive-only or glove-only approaches. The Experiment 1 analysis detected significant improvement only over the glove-only approach. Re-

sponses to open-ended questions further indicate that both passive haptics and glove forces contributed positively to the perceived quality of interactions with the mixed approach. Improvements to realism or naturalness can relate to higher-level goals of VEs (e.g., training effectiveness) even if they do not manifest themselves as reductions in task times or error rates.

Slider interactions were difficult for some subjects due to glove limitations. Users with small hands and those who tended to grasp (pinch) sliders tightly reached the limit of motion for index finger movement. One subject described the problem as follows: “I often needed to keep my hand loose in order to feel the reaction.” This may be remedied by forthcoming RM designs or by other designs. One promising approach is the use of small vibrotactile elements to provide haptic cues without complex mechanical structures. This approach improves comfort and finger motion range, but would lack the ability to simulate contact with rigid virtual objects or to constrain finger motion during grasping. Although the force feedback provided by the RM glove can aid control of grasp forces (Fabiani & Burdea, 1996), no current glove design supports friction forces to anchor fingers on the virtual slider handles of our control panel. Grasp on slider handles was easily lost in Experiment 2, and this helps explain why significant slider time reductions were not found when the mixed approach was compared to the passive-only approach. Interaction without good visual feedback remained difficult for all evaluated approaches. One possible software-based improvement is to use “sticky” slider handles that constrain virtual hand model motion once a slider is grasped. However, this could complicate the intentional release of a grasp or introduce other unrealistic artifacts.

7 Conclusion

An approach to combining active and passive haptic feedback devices has been presented and evaluated. It provides an improved sense of touch for VEs by combining the strengths of both techniques, and it results in a haptic mixed reality system for future integration with visual mixed reality displays.

The introduction of passive haptics into a glove-based force-feedback system overcomes some limitations of portable glove designs with minimal added cost and without requiring additional devices that are mechanically complex or uncomfortable. Glove forces remain useful for improving perceived haptic quality and provide haptic feedback for portions of the environment not supported by passive haptics.

In the future, this work can be extended to consider other device types or other interaction types. A glove design using vibrotactile feedback rather than force feedback may produce interesting results since its capabilities and limitations are different. Further work with the mixed approach can include other interaction types as suggested by the applications in Section 1.5. Finally, the system will benefit from further technological developments to improve glove-based interactions. For example, hand modeling can better support a wide range of users with a parameterized model and an efficient method of determining parameters to match an arbitrary user’s hand.

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Appendix A

This appendix describes experiment questionnaires. Subjects responded to each question by circling a number from 1 to 7, or with a free-form response in the case of an open-ended question. Semantic anchors, indicated below in parentheses, were placed near the num-

bers 1 and 7. For Experiment 3, an additional semantic anchor, “similar,” appeared below the number 4.

The first ten questions following Experiment 1 were grouped into four presence subscales. A Naturalness (Nat) score was computed by summing scores from questions 1 and 5. Involvement/Control (Inv) was computed as a sum from questions 2, 3, 4, 6, and 9. Interface Quality (IfQ) was the Question 10 score, and Exploration (Exp) was a sum from questions 7 and 8.

Questionnaire Following Experiment 1

1. How natural did your interaction with the environment seem? (Not Natural to Very Natural)
2. How well were you able to control the environment? (Not Well to Very Well)
3. How responsive was the environment to actions you initiated (or performed)? (Not Responsive to Very Responsive)
4. How much did the visual aspects of the environment involve you? (Not Much to Very Much)
5. How consistent did your experience in the virtual environment seem with your real-world experiences? (Not Consistent to Very Consistent)
6. How well were you able to anticipate what would happen in response to your actions? (Not Well to Very Well)
7. How well could you actively search or survey the environment using touch? (Not Well to Very Well)
8. How well could you move or manipulate objects in the virtual environment? (Not Well to Very Well)
9. How quickly did you adjust to the virtual environment? (Not Quickly to Very Quickly)
10. How often did you encounter uncomfortable or distracting sensations? (Never to Very Often)
(a pagebreak occurred between items 10 and 11)
11. How solid did the objects with which you interacted seem in the virtual world? (Not Solid to As Solid As Real)
12. How solid did the tabletop seem in the virtual world? (Not Solid to As Solid As Real)
13. How solid did the walls of the virtual room seem? (Not Solid to As Solid As Real)

14. Overall, how realistic was the sense of touch provided by the system? (Very Poor to Very Good)

Questionnaire Following Experiment 2

1. How well were you able to perform the interactions when the display was darkened?
 - a) For the sliders: (Not At All to Very Well)
 - b) For the pushbutton pad: (Not At All to Very Well)
2. How natural did your interactions seem when the display was darkened?
 - a) For the sliders: (Not Natural to Very Natural)
 - b) For the pushbutton pad: (Not Natural to Very Natural)
3. How easy was it to find objects when the display was darkened?
 - a) For the sliders: (Not Possible to Very Easy)
 - b) For the pushbutton pad: (Not Possible to Very Easy)

Questionnaire Following Experiment 3

1. In terms of visual display, the final session was: (much worse than the first, similar, much better than the first)
2. The sense of touch experienced in the final session was:
 - a) For the sliders: (much worse than the first, similar, much better than the first)
 - b) For the pushbutton pad: (much worse than the first, similar, much better than the first)
3. In the final session, the overall quality of the experience was: (much worse than the first, similar, much better than the first)

Open-Ended Questions (Also Given After Experiment 3)

- Which aspects of the system did you find most beneficial?
- Which aspects of the system need the most improvement?
- Please mention any additional thoughts you have about your experience.