Haptic Discrimination of Force Direction and the Influence of Visual Information

FEDERICO BARBAGLI and KEN SALISBURY
Stanford University
CRISTY HO and CHARLES SPENCE
Oxford University
and
HONG Z. TAN
Purdue University

Despite a wealth of literature on discrimination thresholds for displacement, force magnitude, stiffness, and viscosity, there is currently a lack of data on our ability to discriminate force directions. Such data are needed in designing haptic rendering algorithms where force direction, as well as force magnitude, are used to encode information such as surface topography. Given that haptic information is typically presented in addition to visual information in a data perceptualization system, it is also important to investigate the extent to which the congruency of visual information affects force-direction discrimination. In this article, the authors report an experiment on the discrimination threshold of force directions under the three display conditions of haptics alone (H), haptics plus congruent vision (HVcong), and haptics plus incongruent vision (HVincong). Average force-direction discrimination thresholds were found to be 18.4°, 25.6°, and 31.9° for the HVcong, H and HVincong conditions, respectively. The results show that the congruency of visual information significantly affected haptic discrimination of force directions, and that the force-direction discrimination thresholds did not seem to depend on the reference force direction. The implications of the results for designing haptic virtual environments, especially when the numbers of sensors and actuators in a haptic display do not match, are discussed.

Categories and Subject Descriptors: H.1.2 [**Models and Principles**]: User/Machine Systems—*Human information processing*; H5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—*Artificial, augmented, and virtual realities*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Evaluation/methodology; Haptic I/O*

General Terms: Experimentation, Human Factors

Additional Key Words and Phrases: Force direction, discrimination threshold, psychophysics, haptic rendering, haptic and visual interaction

F. Barbagli and K. Salisbury were supported by NIH grant LM07295-01 "Collaborative, Simulation based, Surgical Training". C. Ho was supported by scholarships from the Clarendon Fund, Oxford, and the Overseas Research Student Awards Scheme. H. Z. Tan and C. Spence were supported by a Network Grant from the Oxford McDonnell-Pew Centre for Cognitive Neuroscience. H. Z. Tan was supported by a grant from the Ford Motor Company University Research Program, a NASA award under Grant No. NCC 2-1363, and funds from the Nissan Technical Center North America, Inc. The authors wish to thank Prof. Will Provancher for many discussions and for the illustrations used in Figures 3 and 4.
Authors' addresses: Federico Barbagli and Ken Salisbury, Stanford Robotics Lab, 353 Serra Mall, Stanford, CA, 94131; emails: {barbagli,jks}@robotics.stanford.edu; Cristy Ho and Charles Spence, Crossmodal Research Laboratory, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford, OX1 3UD, England; emails: {cristy.ho, charles.spence}@psy.ox.ac.uk; Hong Z. Tan, Haptic Interface Research Laboratory, 465 Northwestern Avenue, West Lafayette, IN 47907-2035; email: hongtan@purdue.edu.

1. INTRODUCTION

With the availability of commercially available force-feedback devices, it is now possible to achieve haptic feedback in many activities, such as virtual sculpting, surgical simulation, and data perceptualization. In a typical application, the user of a force-feedback device controls the position and movements of an avatar and experiences the force variations resulting from the avatar interacting with a virtual or remote environment. The user combines the perception of the user-induced motions with that of the feedback force in order to interpret the properties of the virtual or remote objects. The realism of such haptic interactions depends on the force display, the rendering algorithm (including the environment model), and human perception. In fact, there are now many examples of how the design of both hardware (device) and software (algorithm) takes into account human sensory and motor capabilities (see, for instance, Srinivasan, Beauregard, and Brock 1996; Tan et al. 1995; Robles-De-La-Torre and Hayward 2001; Otaduy and Lin 2003). A great deal is now known about our ability to haptically discriminate linear and rotary displacement (Armstrong and Marks 1999; Clark 1992; Durlach et al. 1989; Jones and Hunter 1992), force magnitude (Jones 1989; Pang et al. 1991), stiffness or compliance (DiFranco et al. 1997; Durfee et al. 1997; Jones and Hunter 1990; Lawrence et al. 2000; O'Malley and Goldfarb 2002; Srinivasan et al. 1996; Tan et al. 1995), and viscosity (Jones and Hunter 1993), either with or without visual (or sometimes auditory) information. However, the authors are not aware of any previous study on the perception of force direction (although, see Klein 1977, for early work using a speeded-force discrimination task), presumably because it is difficult to design an experimental apparatus that can accurately administer forces in controlled directions. This is a serious omission since the user of a force-feedback device experiences both the direction and magnitude of forces while interacting with a virtual environment. Therefore, the first aim of the present study was to quantify the haptic threshold for force-direction discrimination using a force-feedback display.

The need for a force-direction discrimination threshold arose during an investigation on the impact of sensor/actuator asymmetry on shape perception. The term *sensor/actuator asymmetry* refers to the configuration of a haptic interface, where the number of sensors does not match that of actuators, particularly when there are more sensors than actuators (Barbagli and Salisbury 2003). In a simple example, a user controls the position of a virtual ball against a virtual wall in the $x - y$ plane and receives feedback force along the y-axis only (see Figure 1). Assuming a simple proxy-based contact model where the calculated feedback force is proportional to the penetration depth of the virtual ball into the virtual wall, it is clear that the direction of the calculated feedback force (perpendicular to the virtual wall) and the feedback force the user actually feels (along the y-axis only) differ by α, as shown in Figure 1. To the designer of the haptic interface and/or the virtual environment, the knowledge of force-direction discrimination threshold is crucial in predicting when the user will start to "notice" that the interaction has become unrealistic.

The second aim of the present study was to investigate the influence of visual information on the haptic perception of force directions. It is well known that vision can influence haptic perception (e.g., Ernst and Banks 2002; Heller et al. 1999; Hendrix et al. 1999; Klatzky et al. 1987; Lederman et al. 1986; Rock and Victor 1964; Roder et al. 2004; Soto-Faraco et al. 2002; Spence and Driver 1997; Spence et al. 2000; Srinivasan et al. 1996; see also Spence and Driver 2004, for a comprehensive summary of recent advances in our understanding of the multisensory nature of perception from developmental, neurophysiological, as well as behavioral perspectives). Since the visual display is usually an integral part of a haptic virtual environment, it is important for us to understand to what extent vision can influence our ability to discriminate force directions. Specifically, we evaluated the effect of vision by presenting visual information that was either congruent or incongruent with the haptic stimuli. The results were expected to shed light on the guidelines for designing haptic virtual environment

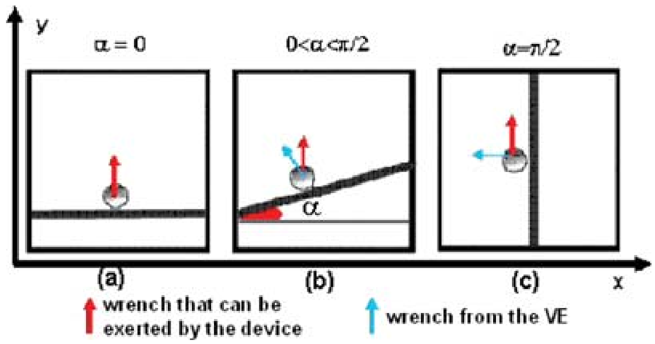

Fig. 1. A simple example of sensor/actuator symmetry where a user controls a 2-DOF (degree of freedom) virtual ball with 1-DOF feedback forces against a (a) horizontal, (b) tilted, and (c) vertical virtual wall.

systems and for understanding the integration of visual and haptic information in space (in particular, orientation) perception.

2. METHODS

2.1 Participants

Twenty participants (mean age of 26 years, age range from 21 to 39 years; 15 males and 5 females), all students at Stanford University, took part in this experiment. All of the participants had normal, or corrected-to-normal, vision, and a normal sense of touch. Seventeen of the participants were right-handed, one was left-handed, and two were ambidextrous by self-report. The participants were recruited by word of mouth and did not receive any compensation for their participation. The experiment was conducted in accordance with the Stanford University Institutional Review Board ethical guidelines and lasted for approximately 45 minutes.

2.2 Apparatus and Materials

The participants were seated in front of a 19-inch computer monitor (at a distance of 60 cm) in an experimental booth. They were instructed to insert their dominant index finger (or their right index finger for the two ambidextrous participants) into the thimble of a PHANToM (Premium 1.5, SensAble Technologies, Inc., Woburn, MA) force-feedback device, placed 30 cm away from the monitor in the direction of the participant's dominant hand, occluded from the direct view of the participants (see Figure 2). A computer keyboard was placed at a comfortable distance such that the participants could give their responses with their nondominant hand. The participants were instructed to rest their dominant arm on an armrest and to hold a squeezable gel ball gently in their dominant hand with their index finger pointing outward (i.e., away from their body). This was done to prevent participants from making excessive hand or arm movements that might have given them additional kinesthetic cues. The experiment involved a *force* being applied to the participant's finger inserted in the thimble, subtly moving the finger in the direction of the applied force until the participant provided an opposing force to maintain the finger in a stable position.

2.3 Stimuli

The haptic stimuli were generated by the force-feedback device. Five reference force vectors were used. They included the normal vectors corresponding to the top, right, and left sides of a cube, and the normal vectors corresponding to the upper-front two faces of an octagonal prism (see Figure 3a). The

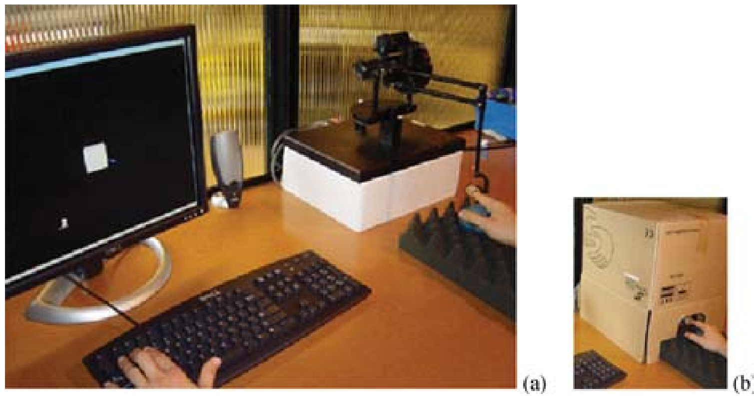

Fig. 2. Experimental setup. (a) Participant rests the palm of the dominant hand on a gel ball and inserts the dominant index finger into the thimble of the PHANToM device. (b) During the experiment, the PHANToM and the participant's dominant index finger were hidden from direct view.

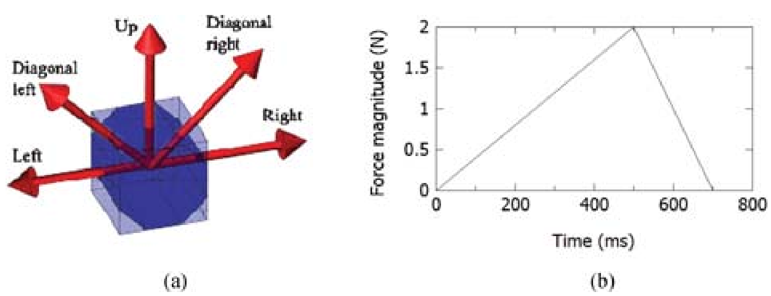

Fig. 3. (a) An illustration of the five reference force directions. (b) A profile of the force magnitude.

magnitude of the force vectors were always presented in the same way throughout the experiment (see Figure 3b). The force vector was ramped up from 0 to 2 N over 500 ms, and then attenuated down to 0 N over the next 200 ms. The maximum force of 2 N was clearly perceptible to all participants—indeed, forces on the order of 1 N are typical in interactions with haptic virtual environments. The ramping of the force vectors was necessary in order to keep the haptic device stable; it also gave the participant time to adjust to the applied forces while maintaining their finger position.

The visual stimulus consisted of a white cube (size $3.5 \times 3.5 \times 1.0$ cm) positioned at the center of the screen. An arrow was displayed to indicate the direction of the force vector (see Figure 1). The length of the arrow changed in synchrony with the force magnitude; i.e., it appeared to shoot out from the center of the cube until it reached its maximum length of 3.5 cm, and then shrank back to the center of the cube. The cube was opaque and only the portion of the arrow outside of the cube was visible. The numbers "1," "2," or "3" were clearly displayed in large font 20 cm below the cube to mark each of the three different force intervals (see Procedure). The instruction "Please press 1, 2 or 3" was displayed 20 cm below the cube to signal response selection at the end of a trial. Both interstimulus intervals featured the white opaque cube displayed during each interval with no arrows shooting out of it as well as no numbers nor instructions.

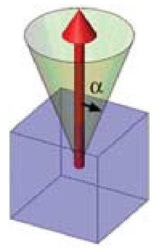

Fig. 4. An illustration of the relationship between the reference and target force directions (i.e., α).

2.4 Design

Each participant was tested with one of the five reference force directions, which were counterbalanced across participants (i.e., four participants for each reference-force direction). The experimental session consisted of one practice block and one experimental block of trials. The practice block consisted of ten trials. The same randomly selected reference-force direction was used in both blocks of trials. Both the practice and experimental blocks consisted of trials from three conditions: haptic cues only (H), haptic cues with congruent visual cues (HVcong), and haptic cues with incongruent visual cues (HVincong). The three conditions differed only in the way in which the visual information was presented. During the H condition, the visual display consisted of the cube but no arrows. During the HVcong condition, the visual display included an arrow whose direction (and magnitude) always agreed with the applied forces. During the HVincong condition, the direction of the visual arrow was no longer consistent with the direction of the haptic force vector at all times (see Procedure, for more details). Participants were always presented with valid haptic cues at all times during the experiment.

2.5 Procedure

A three-interval one-up three-down adaptive procedure was used (Levitt 1971). On each trial, the participant was presented with three stimuli (three intervals) under one of the five reference-force directions (fixed within a block of trials) and one of the three experimental conditions (randomly chosen for each trial). A test force direction was presented during a randomly selected one of the three intervals, while the reference force direction was presented during the remaining two intervals. The interstimulus interval between intervals 1 and 2 and between intervals 2 and 3 was 600 ms. The independent variable was the angle between the reference and target force directions, denoted by α (see Figure 4). Given a value of α, the target force could lie anywhere on the cone with the reference force vector as the axis and with an angle of α (in other words, the orientation of the plane formed by the reference and target force vectors was randomly selected with the constraint that the angle formed by the two vectors was exactly α).

Within a given experimental block, three separate threads of adaptive procedure were run for the H, HVcong, and HVincong conditions. The initial value of α was 40° for each of the three conditions. The value of α was increased after each incorrect response, and decreased after three consecutive correct responses. Initially, the magnitude of α changed by increments of 8°, and then by 2° after the first three initial reversals. A reversal occurred when α changed from increasing to decreasing, or vice versa. Each thread of the adaptive procedure would terminate after twelve reversals at the 2° step size (i.e., after fifteen reversals). Each condition typically contained about 80 trials. An experimental block terminated after all three threads were completed.

Each trial began with the force-feedback device gently pulling the participant's dominant index finger to an initial start position. The beginning and the end of the pulling were indicated by single and double

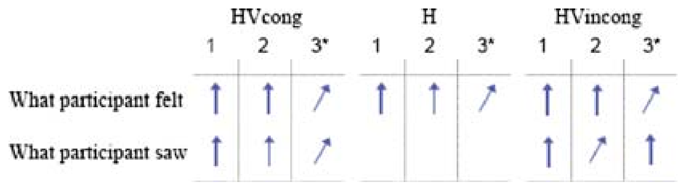

Fig. 5. An illustration of a sample trial in each of the three conditions (where test force direction occurred in interval 3, indicated by*).

auditory beeps, respectively, presented at a clearly audible level from two computer loudspeakers placed on either sides of the monitor. Three stimulus intervals immediately followed. The target force direction was presented in a randomly chosen interval, and the reference force direction was presented during the other two intervals. Figure 5 shows a sample trial where the test force direction occurred in interval 3. In the HVincong condition, it can be seen that inconsistent haptic and visual stimuli were presented. The odd visual arrow (corresponding to the direction of the target haptic force direction shown in interval 3, Figure 5) was displayed during one of the two intervals when the reference force direction was presented haptically (interval 2, Figure 5). In the remaining two intervals where one reference force direction and the target force direction were presented haptically (intervals 1 and 3, Figure 5), the visual display would depict an arrow going in the same direction as the reference haptic force direction.

The participants were instructed to indicate the odd (i.e., target) haptic force interval by pressing the numeric key 1, 2, or 3 on the keyboard (corresponding to interval one, two, and three, respectively). The participants were explicitly informed prior to the start of the experiment that the visual stimulus might sometimes be misleading, and that they should always base their responses on the *haptic* sensations. The instructions also emphasized that they had to look at the computer monitor during the presentation of the stimuli. No feedback on the correctness of participants' performance was provided.

In the HVincong condition, inconsistent haptic and visual stimuli were presented. The odd visual arrow (corresponding to the direction of the target haptic force direction) was displayed during one of the two intervals when the reference force direction was presented haptically (interval 2 in the example depicted in Figure 5). In the remaining two intervals where one reference force direction and the target force direction were presented haptically, the visual display depicted an arrow going in the same direction as the reference haptic force direction (interval 1 and 3 in the example depicted in Figure 5).

3. RESULTS

The mean threshold of each participant was estimated by first calculating six averages from the peaks and valleys corresponding to the α values (i.e., the displacement angle between the reference and target forces) of the last twelve reversal amplitudes, and then calculating the mean and standard error of these six averages (cf. Brisben et al. 1999). Table I shows the estimated mean thresholds for α as a function of the three conditions. A two-way mixed analysis of variance (ANOVA) was performed on the estimated mean threshold data to assess what effect, if any, the presence of congruent versus incongruent visual cues had on participants' haptic discrimination thresholds for different force directions. The within-participants factor was condition (H, HVcong, or HVincong) and the between-participants factor was reference force direction (up, right, left, diagonal right, or diagonal left).

The analysis revealed a significant main effect of condition, $F(2, 30) = 20.1$, $MSE = 45.5$, $p < .0001$. The participants could, on average, discriminate between target and reference forces at α of 25.6° when no visual information was presented (condition H). Subsequent paired comparison t-tests between condition H and conditions HVcong and HVincong showed that the presence of congruent visual information resulted in a significant improvement in the discrimination threshold to 18.4° (relative to

Table I. Estimated Mean Thresholds and Their Standard Errors (in Parentheses), in Degrees, as a Function of Experimental Condition and Reference Force Direction

	Force Direction					
Condition	Up	Right	Left	Diagonal Right	Diagonal Left	Mean
HVcong	12.7	11.9	19.5	21.9	26.0	18.4
	(0.8)	(3.1)	(9.2)	(5.2)	(3.3)	(2.4)
H	28.4	23.4	20.0	21.0	35.5	25.6
	(1.2)	(2.1)	(1.2)	(3.1)	(4.8)	(1.7)
HVincong	26.8	26.0	27.2	35.3	44.3	31.9
	(1.8)	(1.2)	(3.8)	(7.3)	(8.0)	(2.6)

condition H), $t(19) = 3.2$, $p = 0.005$, while the presence of incongruent visual information led to a significant impairment in the discrimination performance to 31.9° (relative to condition H), $t(19) = -3.3$, $p = 0.004$. A paired comparison t-test between conditions HVcong and HVincong also revealed a significant difference between the two conditions, $t(19) = -5.5$, $p < 0.0001$. There was a borderline significant main effect of reference force direction, $F(4,15) = 2.7$, $MSE = 157.5$, $p = 0.07$, though the interaction between condition and reference force direction was not significant, $F(8,30) = 1.5$, $p = 0.20$, suggesting that the direction in which the forces were presented to the participants' finger did not affect their discrimination performance per se.

4. DISCUSSION

The experiment reported in the present study was conducted in order to obtain an estimate of the force-direction discrimination threshold when only haptic information was available and when congruent or incongruent visual information was presented simultaneously. A relatively large haptic force-direction discrimination threshold of 25.6° was found. It was also found that congruent visual information significantly reduced the threshold to 18.4°, while incongruent visual information significantly increased the threshold to 31.9°. It can, therefore, be concluded that humans have a relatively poor sense of force direction and that the perception can be influenced by the presence of visual information (cf. Klein 1977).

One potential confounding factor in the way the experiment was set up concerns the constraint of the dominant index finger upon which forces were applied. Ideally, the finger should have been fixed in space by, for example, finger splints. However, finger splints could exert additional forces along the length of the index finger when the finger was being pushed or pulled by the forces applied by the force display, thereby contaminating the proximal haptic stimuli. A more serious concern was that the participants' fingers could sustain injuries because of force/torque being applied to them under normal or unexpected experimental conditions. During the actual experiment, the participants' dominant index fingers were free to move in any direction and could be pulled out of the thimble whenever the participants wished to. Finger movements were minimized by the use of a gel ball that provided an anchoring point for the palm of the hand and by instructing the participants to try their best not to move their fingers. One might argue that the perception of force direction using the aforementioned experimental set-up could have been aided by the perception of the extent of finger movements. This seems unlikely although because humans can reliably detect a 2.5° excursion of the metacarpophalangeal joint of the index finger (the joint where an index finger joins the palm of the hand; Clark et al. 1986), but the force-direction thresholds measured in this study were in the range 18.4°–31.9°, too large to be accounted for by proprioception of finger movements. Indeed, anecdotal reports from the participants indicate that it was difficult for them to control the extent of the finger motions during the experiment because the force directions changed from trial to trial. Therefore, the best strategy for the participants to adopt was to stabilize their dominant index finger to the best of their abilities, and to judge the directions of the applied forces despite any motion of their finger.

The findings that congruent visual cues reduced haptic force-direction discrimination thresholds and incongruent visual cues increased the thresholds are consistent with many previous studies. Although some studies have supported the idea of *visual dominance* (e.g., Rock and Victor 1964), others suggest that sensory experiences are multimodally determined (Lederman et al. 1986; Calvert et al. 2004) and that humans may well combine visual and haptic information in a way that takes into account the statistical variances associated with the two sources of information, at least when any discrepancy between the inputs available to the two modalities is not to great (Ernst and Banks 2002; Guest and Spence 2003; Hillis et al. 2002; Lederman et al. 1986). The latter view provides a more unifying framework for the many multimodal and crossmodal studies of human perception. In fact, Klatzky et al. (1987) argued that the haptic and visual systems may have distinct advantages over the different object properties under consideration, with haptics better suited for the encoding of substance (e.g., roughness) and vision for shape and spatial layout (see Lederman and Klatzky 2004, for a recent review; see also Van Beers et al. 2002). In this context, the study by Srinivasan et al. (1996) can be viewed as an example of people combining haptic force cues and visual displacement cues to judge stiffness. The participants in this study performed a stiffness discrimination task by pressing a virtual linear spring and watching a distorted visual representation of the spring deformation on a computer screen. It was shown that virtual springs were judged to be softer (or stiffer) when the visual displacement was greater (or less) than the actual displacement of the hand. The results showed that the participants essentially ignored the relatively inaccurate kinesthetic hand movement cues in favor of the more accurately perceived, but, in this case, experimentally distorted, visual displacement cues. In another study, when participants moved their fingers across a bump, but received force cues that were consistent with that of a hole through a manipulandum (Robles-De-La-Torre and Hayward 2001), they reported the sensation of a hole instead of a bump. This is yet another example of participants ignoring the relatively inaccurate finger movement cues in favor of the more salient force cues. This phenomenon should be viewed as reflecting the brain's ability to weigh multiple sources of information differently rather than as a case of force dominance, because the illusion subsided when the depth of the bump/hole was sufficiently large. Therefore, we interpret the results of our experiment as demonstrating that participants weighed the visual force-direction cues more heavily than haptic force-direction cues, presumably because the visual angle discrimination threshold is much smaller than the haptic threshold of 25.6° measured in the present study.

Since no published data exist for visual discrimination of vector angles, we conducted a follow-up experiment in which four participants (mean age of 28 years, age range from 24 to 32 years; three males and one female; all with normal or corrected-to-normal vision) participated in a vision-only vector-direction discrimination experiment (V condition). The experiment was conducted in a manner similar to the main experiment, with the following exceptions. The participant saw the arrows centered around a cube on the computer screen, but did not use the PHANToM haptic device. Each participant was tested with all five reference directions. The experimental session consisted of one practice block and one experimental block of trials. The practice block consisted of ten trials. The experimental block consisted of trials from five conditions corresponding to the five reference directions. Participants were presented with visual cues at all times during the experiment. The same three-interval one-up three-down adaptive procedure was used. Five separate threads of adaptive procedure were run for the five reference direction conditions. The same data analysis method used in the main experiment was applied to the V condition. The mean discrimination threshold for the V condition was only 3.25°, which was significantly smaller than the HVcong force-direction discrimination threshold of 18.4°. Therefore, we conclude that in our main experiment, participants combined haptic and visual information when both were present, despite the fact that the participants were explicitly instructed to base their responses on their haptic

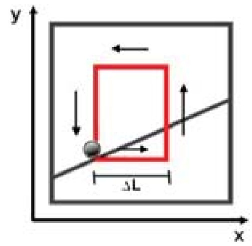

Fig. 6. Interaction with a tilted surface using an asymmetric device can produce unnaturally "active" force feedback. The user follows the red line and moves horizontally for a displacement of ΔL inside a tilted surface, forming an angle of α with the x-axis.

sensations. The fact that the threshold in the HVcong condition was much closer to the threshold in the H condition than the threshold in the V condition, indicates that the participants did try their best to ignore the visual information in the HVcong condition. According to the theory put forward by Ernst and Banks (2002), had the participants attempted to combine visual and haptic information in an optimal fashion, the discrimination threshold in the HVcong condition should have been much closer to 3.25°.

The knowledge of haptic thresholds for object properties can be exploited to overcome hardware and software limitations and to enhance the experience of interacting with a haptic virtual environment. This is particularly true in the case of haptic devices featuring asymmetric sensor/actuator configurations (the "asymmetric" haptic devices discussed in the Introduction). While it is generally desirable to use the least number of actuators in order to reduce costs and for easier design of back-drivable haptic devices (see Hayward and Astley 1996, for a definition of backdrivability), lack of symmetry between sensors and actuators can often lead to noticeable shortcomings in the display of certain classes of virtual objects. More specifically, two perceptual problems are likely to arise. The first problem, as discussed in the introduction (see Figure 1), is that users may notice that the directions of interaction forces fed back by the device do not match the ones expected when touching a visually displayed virtual surface. This typically happens when interaction forces cannot be faithfully rendered by the device because of the lack of actuators along all axes where positions/rotations are monitored. The second problem is that users may perceive the virtual surfaces to be unnaturally "active," or energetically nonconservative. As discussed in Barbagli and Salisbury (2003), the level of unnatural sensations grows monotonically with the level of asymmetry along a certain direction for a given haptic interface. Consider again the 2D virtual environment shown in Figure 1 where the haptic device is capable of sensing positions along both x and y-axes but can only exert forces along the y-axis. The amount of energy erroneously returned to the user over a closed loop (the red line in Figure 6) is given by $K \cdot \Delta L^2 \cdot \sin^2(\alpha)/2$, where ΔL is the amount of horizontal displacement inside the virtual surface, α the angle formed by the surface with the x-axis, and K the virtual surface stiffness coefficient. Ideally, no energy should be sent back to the user when the virtual environment is strictly conservative. Whereas the user can usually tolerate a small amount of feedback energy, moving to the right along the x-axis in Figure 6 starts to feel like traveling on an escalator when α is above roughly 40° (i.e., the tilted plane pulls the user upward).

The knowledge of force-direction discrimination thresholds obtained in the present study can therefore aid in the process of designing rendering algorithms for asymmetric haptic devices. When a one DOF force display with two DOF position sensing is used to render, for example, the 2D virtual environment shown in Figure 1, it is important that the polygonal surfaces comprising the object be within 25.6° of tilt from the x-axis in order to avoid any perceptual artifacts. This requirement, in turn, determines the maximum curvature of the virtual surfaces that can be rendered and perceived accurately. The knowledge that visual cues influence our ability to discriminate force directions can be used to our advantage to create the illusion of interacting with a wider range of virtual objects while ensuring that neither type of undesired perceptual effects (perceived deviation in force direction and unrealistic energy feedback) occurs. For example, it should be possible to create visually rendered surfaces that are more tilted than the corresponding haptic representations, thereby creating the impression of interacting with a more tilted surface while limiting unrealistic haptic effects because of the asymmetric nature of the device being used. Finally, these techniques can be applied to haptic rendering with symmetric haptic devices, so that more curved surfaces can be displayed visually without discernable "unnatural" sensations from the feedback forces.

REFERENCES

Armstrong, L. and Marks, L. E. 1999. Haptic perception of linear extent. *Perception Psychophys. 61*, 1211–1226.

Barbagli, F. and Salisbury, K. 2003. The effect of sensor/actuator asymmetries in haptic interfaces. In *Proceedings of the 11th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. 140–147.

Brisben, A. J., Hsiao, S. S., and Johnson, K. O. 1999. Detection of vibration transmitted through an object grasped in the hand. *J. Neurophysiol. 81*, 1548–1558.

Calvert, G., Spence, C., and Stein, B. E. (Eds.) 2004. *The Handbook of Multisensory Processes*. MIT Press, Cambridge, MA.

Clark, F. J. 1992. How accurately can we perceive the position of our limbs? *Behavioral Brain Sci. 15*, 725–726.

Clark, F. J., Burgess, R. C., and Chapin, J. W. 1986. Proprioception with the proximal interphalangeal joint of the index finger: Evidence for a movement sense without a static-position sense. *Brain 109*, 1195–1208.

DiFranco, D. E., Beauregard, G. L., and Srinivasan, M. A. 1997. The effect of auditory cues on the haptic perception of stiffness in virtual environments. In *Proceedings of the ASME Dynamic Systems and Control Division, DSC-Vol. 61*, 17–22.

Durfee, W. K., Hendrix, C. M., Cheng, P., and Varughese, G. 1997. Influence of haptic and visual displays on the estimation of virtual environment stiffness. In *Proceedings of the ASME Dynamic Systems and Control Division, DSC-Vol. 61*, 139–144.

Durlach, N. I., Delhorne, L. A., Wong, A., Ko, W. Y., Rabinowitz, W. M., and Hollerbach, J. 1989. Manual discrimination and identification of length by the finger-span method. *Perception Psychophys. 46*, 29–38.

Ernst, M. O. and Banks, M. S. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature (London) 415*, 429–433.

Guest, S. and Spence, C. 2003. What role does multisensory integration play in the visuotactile perception of textute? *Int. J. Psychophysiol. 50*, 63–80.

Hayward, V. and Astley, O. R. 1996. Performance measures for haptic interfaces. In *Robotics Research: The 7th International Symposium*. G. Giralt and G. Hirzinger, Eds. Springer Verlag, New York, 195–207.

Heller, M. A., Calcaterra, J. A., Green, S. L., and Brown, L. 1999. Intersensory conflict between vision and touch: The response modality dominates when precise, attention-riveting judgments are required. *Perception Psychophys. 61*, 1384–1398.

Hendrix, C. M., Cheng, P.-M., and Durfee, W. K. 1999. Relative influence of sensory cues in a multi-modal virtual environment, In *Proceedings the ASME Dynamic Systems and Control Division*, Vol. DSC-Vol. 67. ASME, 59–64.

Hillis, J. M., Ernst, M. O., Banks, M. S., and Landy, M. S. 2002. Combining sensory information: Mandatory fusion within, but not between, senses, *Science 298*, 1627–1630.

Jones, L. A. 1989. Matching forces: Constant errors and differential thresholds. *Perception 18*, 681–687.

Jones, L. A. and Hunter, I. W. 1990. A perceptual analysis of stiffness. *Experimental Brain Res. 79*, 150–156.

Jones, L. A. and Hunter, I. W. 1992. Differential thresholds for limb movement measured using adaptive techniques. *Perception Psychophys. 52*, 529–535.

Jones, L. A. and Hunter, I. W. 1993. A perceptual analysis of viscosity. *Experimental Brain Res. 94*, 343–351.

Klein, R. M. 1977. Attention and visual dominance: A chronometric analysis. *J. Exp. Psychol. Hum. Perception Performance 3*, 365–378.

Klatzky, R. L., Lederman, S., and Reed, C. 1987. There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *J. Exp. Psychol. General, 116*, 356–369.

Lawrence, D. A., Pao, L. Y., Dougherty, A. M., Salada, M. A., and Pavlou, Y. 2000. Rate-hardness: A new performance metric for haptic interface. *IEEE Transactions on Robotics and Automation 16*, 357–371.

Lederman, S. J. and Klatzky, R. L. 2004. Multisensory texture perception. In *The Handbook of Multisensory Processes*, G. A. Calvert, C. Spence, and B. E. Stein, Eds. MIT Press, Cambridge, MA, 107–122.

Lederman, S. J., Thorne, G., and Jones, B. 1986. Perception of texture by vision and touch: Multidimensionality and intersensory integration. *J. Exp. Psychol. Hum. Perception Performance 12*, 169–180.

LEVITT, H. 1971. Transformed up-down methods in psychoacoustics. *J. Acoustical Soc. Am. 49*, 467–477.

O'MALLEY, M. AND GOLDFARB, M. 2002. The implications of surface stiffness for size identification and perceived surface hardness in haptic interfaces. In *Proceedings of the IEEE International Conference on Robotics and Automation*. 1255–1260.

OTADUY, M. A. AND LIN, M. C. 2003. Sensation preserving simplification for haptic rendering. *ACM Trans. Graphics* 22, 543–553.

PANG, X. D., TAN, H. Z., AND DURLACH, N. I. 1991. Manual discrimination of force using active finger motion. *Perception Psychophys. 49*, 531–540.

ROBLES-DE-LA-TORRE, G. AND HAYWARD, V. 2001. Force can overcome object geometry in the perception of shape through active touch. *Nature (London) 412*, 445–448.

ROCK, I. AND VICTOR, J. 1964. Vision and touch: An experimentally created conflict between the senses. *Science 143*, 594–596.

RODER, B., ROSLER, F., AND SPENCE, C. 2004. Early vision impairs tactile perception in the blind. *Curr. Biol. 14*, 121–124.

SOTO-FARACO, S., SPENCE, C., FAIRBANK, K., KINGSTONE, A., HILLSTROM, A. P., AND SHAPIRO, K. 2002. A crossmodal attentional blink between vision and touch. *Psychonomic Bull. Rev. 9*, 731–738.

SPENCE, C. AND DRIVER, J. EDS. 2004. *Crossmodal Space and Crossmodal Attention*. Oxford University Press, Oxford.

SPENCE, C. AND DRIVER, J. 1997. Cross-modal links in attention between audition, vision, and touch: Implications for interface design. *Int. J. Cognitive Ergonomics 1*, 351–373.

SPENCE, C., PAVANI, F., AND DRIVER, J. 2000. Crossmodal links between vision and touch in covert endogenous spatial attention. *J. Exp. Psychol. Hum. Perception Performance 26*, 1298–1319.

SRINIVASAN, M. A., BEAUREGARD, G. L., AND BROCK, D. L. 1996. The impact of visual information on the haptic perception of stiffness in virtual environments. In *Proceedings of the 5th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, K. Danai, Ed., Vol. 58. Atlanta, GA: ASME, 555–559.

TAN, H. Z., DURLACH, N. I., BEAUREGARD, G. L., AND SRINIVASAN, M. A. 1995. Manual discrimination of compliance using active pinch grasp: The roles of force and work cues. *Perception Psychophys. 57*, 495–510.

VAN BEERS, R. J., WOLPERT, D. M., AND HAGGARD, P. 2002. When feeling is more important than seeing in sensorimotor adaptation. *Curr. Biol. 12*, 834–837.

Received February 2005; revised June 2005 and August 2005; accepted August 2005