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THE EFFECT OF AUDITORY CUES ON THE HAPTIC PERCEPTION OF STIFFNESS IN VIRTUAL ENVIRONMENTS

David E. DiFranco
G. Lee Beauregard
Mandayam A. Srinivasan

Laboratory for Human and Machine Haptics
Research Laboratory of Electronics and
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
http://touchlab.mit.edu

ABSTRACT

To explore the possibility that multisensory information may be useful in expanding the range of haptic experiences in virtual environments, psychophysical experiments examining the influence of sound on the haptic perception of stiffness were carried out. In these experiments, subjects utilized the PHANToM, a six-degree-of-freedom haptic interface device with force-reflection along three axes, to feel the stiffness of various virtual surfaces. As subjects tapped on the different virtual surfaces, they were simultaneously presented with various impact sounds. The subjects were asked to rank the surfaces based on their perceived stiffness. The results indicate that when the physical stiffnesses of the surfaces were the same, subjects consistently ranked the surfaces according to sound, i.e., surfaces paired with sound cues that are typically associated with tapping harder surfaces were generally perceived as stiffer. However, when sound cues were randomly paired with surfaces of different mechanical stiffnesses, the results were more equivocal: naive subjects who had not used the PHANToM previously tended to be more affected by sound cues than another group of subjects who had previously completed a set of stiffness discrimination experiments without sound cues. The possible implications of this result for the design of multimodal virtual environments and its comparison to prior work by some of the authors on the effects of vision on haptic perception are discussed.

1 INTRODUCTION

A major impediment to incorporating haptic devices into virtual environments (VEs) has been the inability of the current force and tactile display technologies to provide both the range and bandwidth of forces necessary to match the sensory and motor capabilities of the human haptic system. As a result, the tactual fidelity of many virtual objects has suffered. For example, it is very difficult to construct a virtual wall that is perceived as being sufficiently stiff or rigid.

There is, however, substantial psychophysical data that indicates that an individual's perceptual experience can be influenced by interactions among various sensory modalities. For example, visual information has been shown to alter the haptic perception of object size, orientation, and shape (Rock and Victor, 1963; Rock and Harris, 1967; Posner and Nissen, 1970; Easton, 1976; and reviews by Marks, 1978; Welch and Warren, 1986). Since in virtual environments, the presentation of multisensory information can be controlled by the VE designer, it is possible that there are techniques or methods that could compensate for limits in the performance of haptic interface hardware. This study is part of an on-going investigation to determine if such display techniques can be developed and effectively utilized with existing haptic interface devices to expand the range of tactual experiences in synthetic environments.

The first study in this series involved studying the impact of visually presented spatial cues on the perception of stiffness in virtual environments (Srinivasan, Beauregard, and Brock, 1996). The investigation consisted of a series of psychophysical experiments designed to measure human performance in discriminating the stiffness of two virtual springs. In these experiments, the relationship between visual information on spring deformation (presented to the subjects graphically) and actual spring deformation (experienced by the subject's hand when compressing the virtual spring displayed by a force-reflecting haptic device) were systematically varied. The results of this study showed that graphically manipulated visual information could give rise to compelling haptic illusions about mechanical properties such as stiffness of objects in VEs.

In this paper, we present results from a study to determine if a similar influence on haptic perception can be created through the use of auditory information. Specifically, we examine the effect that various impact sounds have on the perceived stiffness of virtual objects felt by tapping with a force reflecting device.

2 METHOD

2.1 Apparatus

The PHANToM (SensAble Technologies, Inc.) was used to create the virtual surfaces. The device, shown in Fig. 1, is a six-degree-of-freedom haptic interface. Subjects interact with the device by holding a stylus which is attached to a passive gimbal. The gimbal sits on the end of linkage structure, which enables the subject to move the stylus in a three-dimensional workspace. Optical encoders at the joints of the linkage structure enable the device to measure the position of the tip of the stylus. Force feedback is provided back to the subjects via three DC brushed motors. The motors are capable of providing a maximum of 8.5N of force to the tip of the stylus, with a maximum of 3.5N/mm of closed loop stiffness (Massie and Salisbury, 1994).

The control loop was run on a Pentium-90MHz IBM compatible personal computer, which communicated through an ISA interface card to the power amplifier of the PHANToM. The amplifier then sent the appropriate control signal to the haptic interface.

The software algorithm consisted of several steps. First, the position of the tip of the stylus was calculated by sampling and converting encoder output signals. Second, this position was tested as to whether it was within a simulated surface. If so, the force vector to be returned was calculated to simulate the behavior of a linear elastic spring, **f = kx**, where f is the force, k is the spring stiffness, and x is the depth of indentation. The force was then translated into an appropriate *motor torque* by the *motor* control electronics. The entire control loop ran at approximately 1 kHz.

The sounds that were presented in the experiments were first recorded by tapping various instruments (e.g. pen, screwdriver) against various surfaces (e.g. styrofoam, metal plate). This was done to create auditory stimuli that would realistically capture the type of impact sounds that can be heard when tapping soft and hard surfaces. The sounds were recorded with a Sony DTC 59ES digital audio tape recorder in a sound-insulated room. The sound files used in the experiments were each 0.18 seconds long. The nine sounds chosen for the first experiment are described in Table 1.

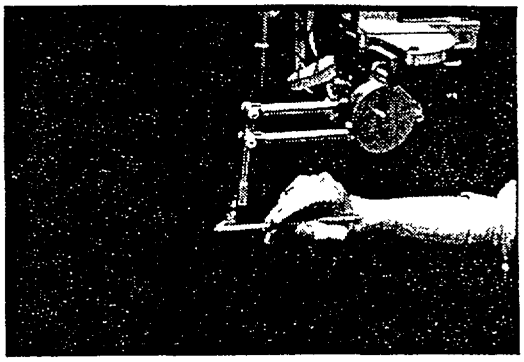

Figure 1: The PHANToM Haptic Interface

Sounds used in Experiments 1 and 3

Sound Stimuli in Experiment 1	*Sound Stimuli in Experiment 3*	*Description*
1	1	Low intensity sound of plastic pen striking cloth
2	2	Low intensity sound of pen striking wood
3	--	Pen striking styrofoam
4	--	Pen striking cloth
5	3	Pen striking an open notebook on table
6	--	Pen striking a small cardboard box
7	--	Pen striking a piece of wood
8	4	Pen striking a metal tray
9	5	Metal screwdriver tip striking a metal plate

Table 1: Sound Stimuli for Experiments 1 and 3

Sounds were presented to the subjects during the experiment by a SoundPlus ES688 16-bit stereo sound card through JVC HA-D810 stereo headphones. The sound cues were played the instant the stylus came into contact with the virtual surface. In the experiments, subjects were given no visual information regarding the stiffness of the surfaces.

2.2 Procedure

All the experiments involved ranking a collection of virtual surfaces on the basis of perceived stiffness. In each trial, subjects were presented with a set of virtual surfaces, which they could tap as often as they wanted to in order to rank them. The ranking was accomplished by rearranging a set of icons, one associated with each surface on the computer monitor by clicking and dragging the mouse. A total of 15 subjects, ages 18-23, participated. All were right handed with no known hand or hearing problems, and used only their right hands for the experiments. No feedback about their performance was given to the subjects in any of the experiments.

In the first set of experiments, subjects were instructed to rank nine surfaces on the basis of perceived stiffness. Unknown to the subjects, all of the virtual surfaces had the same stiffness (k = 0.82 N/mm). Each surface was paired with one of the nine different impact sounds listed in Table 1. This experiment was conducted to evaluate if, in the absence of haptic cues, subjects used auditory information to make decisions about the relative stiffness of different surfaces. It was also used to calibrate the order of perceived stiffness associated with the recorded sounds, to be used in Experiment 3 (see below) Five subjects, three males and two females aged 18-23, completed the experiment.

The second set of experiments measured subjects' ability to rank surfaces with only haptic information about stiffness. These data served as a baseline from which to compare the subjects' performance in the third set of experiments when both haptic and auditory information were available (described below). In each trial, subjects were presented with a set of five different surfaces, in random order, to rank with respect to perceived stiffness. In each trial the surfaces had stiffnesses of 0.82, 1.00, 1.17, 1.35, and 1.52N/m. Thus, the surfaces deviated from the median (1.17N/m) by 15% and 30% in either direction. Five subjects were used in the experiment, three males and two females, aged 18-20. Each completed a total of 50 trials.

In the final set of experiments, these five surfaces were paired with a corresponding number of auditory stimuli. The five auditory cues were chosen from among the nine sounds from the first experimental set. The stimuli, listed in Table 1, were chosen based on the results of Experiment 1 as best representing sounds when tapping both hard and soft surfaces. During the experiment, sounds and surfaces were paired and presented randomly, but were chosen so that over the course of the experiment all possible sound-surface pairs were presented an equal number of times. Ten subjects were used - five of whom had also completed Experiment 2 The subjects consisted of seven males and three females, aged 18-20. Each subject completed 200 trials.

2.3 Data Analysis

Results were evaluated with a point system. First, subjects ranked sound-surface pairs in order of stiffness. This was converted by a computer algorithm into a point scale, from 1-9 in Experiment 1 and 1-5 in Experiments 2 and 3. Each time a sound-surface pair was ranked least stiff, it received 1 point. Correspondingly, each time it was ranked stiffest, it received 9 points (in Experiment 1) or 5 points (in Experiments 2 and 3). Likewise, it received a proportionate number of points if it was ranked somewhere in between. This point scale was developed so that subjects' rankings of the surfaces could be effectively recorded.

In Experiment 3, on average, a subject who ranked surfaces purely on the basis of haptic stiffness would gain an equal number of points for each sound, and an increasing number of points for increasingly stiff surfaces. A subject who ranked purely by sound cues would gain an equal number of points for each stiffness, and an increasing number of points for each increasingly stiff-sounding auditory cue.

In addition, in Experiments 2 and 3, the percent of correct responses was also calculated. Each time a subject ranked a sound-surface pair correctly according to its stiffness, this was counted as a correct response. Thus, for each trial, there were five opportunities for correct responses. Each trial was scored by percent correct, and an average percent correct for all trials was calculated for each subject. A subject who ranked surfaces purely on the basis of stiffness would receive a percent correct of 100% A subject who ranked strictly by sound would rank a sound-surface pair correctly by stiffness exactly one in five times, or 20% of the time, since each sound-surface pair was presented an equal number of times.

3 RESULTS

The results for Experiment 1 are presented in Fig. 2 as boxplots, where the central horizontal line of each box represents the median, the top and bottom of the box represent the upper and lower quartiles, and the dashed vertical lines enclose the range of data. The results indicate that when the surface was paired with sounds associated with tapping on harder surfaces it was generally perceived to be stiffer than when it was paired with impact sounds associated with tapping on softer surfaces. For example, when the surface was paired with sound stimulus 1, the softened sound of a pen striking cloth, it received only an average of 2.3 points (out of 9 possible points). However, when the same surface was paired with sound stimulus 9, the sound of a metal screwdriver striking a metal plate, it received an average of 8.6 points.

In Experiment 2, in which subjects ranked five different surfaces in the absence of sound cues, the subjects were able to distinguish fairly well between the surfaces, with an average percent correct of 83%.

In the final experiment, results differed noticeably between subjects who had participated in Experiment 2 (non-naïve subjects), and those who had not (naïve subjects). The naïve subjects correctly ranked the surfaces in order of stiffness only 44% of the time, as compared with 73% for the non-naïve subjects. In addition, as indicated in Fig. 3, they tended to rank by sound cues, similar to the subjects in Experiment 1.

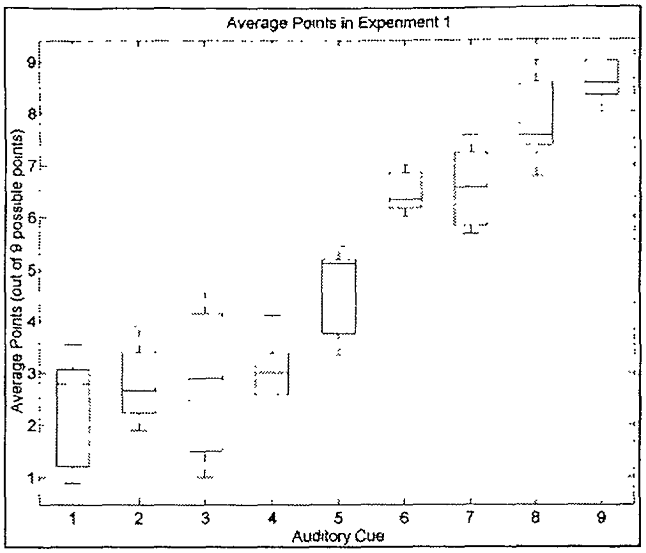

Figure 2

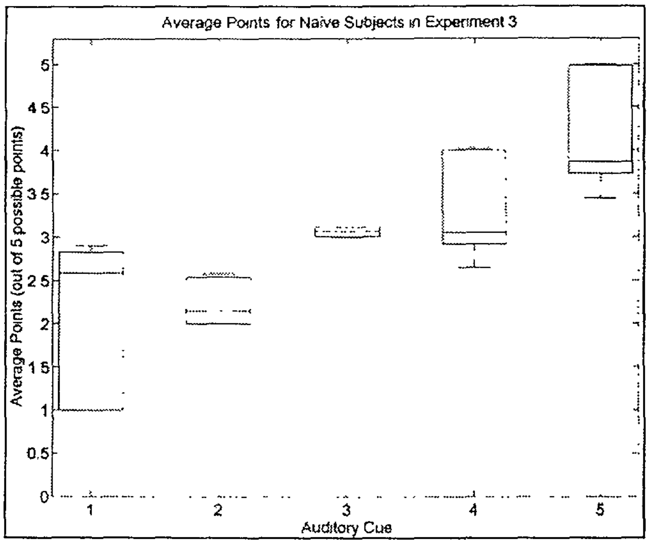

Figure 3

The naïve subjects in Experiment 3 could be divided into two groups by their performances. The difference in the type of response of these two groups accounts for the high variance in the data seen in Fig. 3. Two of the subjects, designated group A in Fig. 4, ranked the surfaces completely by sound, both obtaining a percent correct of exactly 20%. There is virtually no variance in the data, because both chose exclusively by sound cues.

The other three naïve subjects, designated group B in Fig. 5, displayed results which fell in between those of the non-naïve subjects and those of group A. These three subjects obtained an average percent correct of 61%, and all ranked the surfaces somewhat in order of sound cues. All three of these subjects ranked the surfaces associated with sounds 1, 3, and 5 (using the numbering system of Experiment 3) - the three sounds with distinctly different point values in Experiment 1 - in order of increasing apparent stiffness. However, sounds 1 and 2 were not ranked significantly different in Experiment 3. This may be attributed to the fact that the corresponding sounds were also ranked approximately the same in the results of Experiment 1. At the same time, however, sounds 3 and 4 were ranked about the same in Experiment 3, but the corresponding sounds were ranked different in Experiment 2.

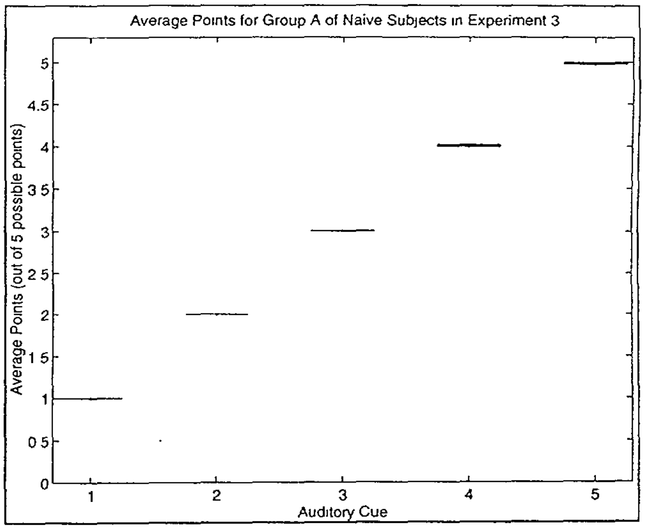

Figure 4

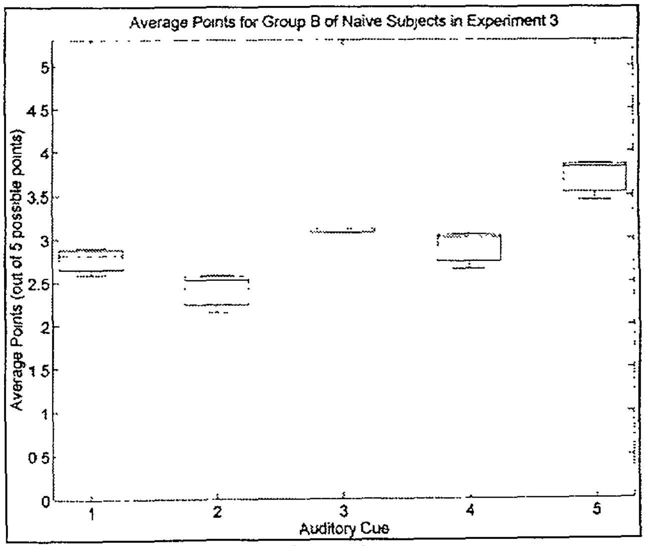

Figure 5

In contrast, subjects who had already discriminated surface stiffness without impact sounds in Experiment 2 did not appear to consistently associate the auditory stimuli with surface stiffness in Experiment 3 (Fig. 6). Still, the average percent correct for this group of subjects decreased to 73% in Experiment 3, from 83% in Experiment 2, indicating that sound cues did play a role in the perceived stiffness.

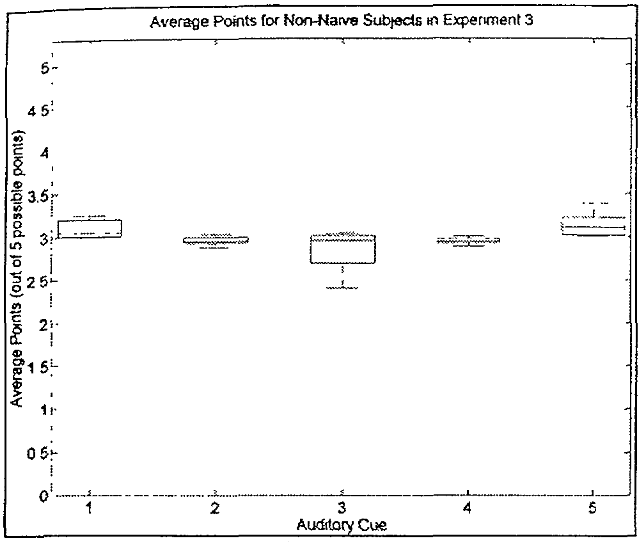

Figure 6

4 DISCUSSION

The results of these experiments show that in many cases, sound cues affect the ability of subjects to discriminate stiffness. The results of Experiment 1 show that in the absence of haptic cues, subjects ranked by auditory cues alone without any disbelief or perception of unnaturalness in the stimuli. Interestingly, several of the subjects of Experiment 1 remarked afterward that they felt a physical difference in the stiffnesses associated with different sounds, even though, unknown to them, the stiffnesses were always the same.

In Experiment 3, the naïve subjects who had not participated in Experiment 2 also ranked by auditory cues. The average percent correct of only 44% for these subjects reflects the fact that their perceived stiffness had little to do with haptic stiffness. The naïve subjects' responses varied widely: two subjects ranked purely by sound, whereas the remaining subjects based their responses on both stiffness and auditory cues. Even so, Figs. 4 and 5 show that among both groups of the naïve subjects, perceived stiffness was correlated with the sound cues presented.

The non-naïve subjects in Experiment 3 also appeared to be influenced by sound cues, but to a lesser extent. The average percent correct for this group fell from 83% to 73%, suggesting that sound did play a role in their perceived stiffness.

The effect of sound cues on all of these subjects' perception of stiffness is much weaker than the effect of visual spatial cues on perception of stiffness demonstrated in a previous set of experiments (Srinivasan, et. al., 1996). In these experiments, subjects were much more strongly influenced by the visual cues, with all subjects displaying responses which corresponded to visual rather than haptic information.

One possible reason that the result of the previou experiment was stronger is that the visual cues provided representation of spatial information, whereas the sound cue did not. When the subject moved the stylus of the hapti interface, its position was seen on the monitor. Visu information was skewed by changing the amount of sprin displacement on the screen. In the auditory experimen however, there was no such intuitive relationship between t auditory and haptic information. The auditory cues gave spatial information, but only suggested contact with surfac of varying stiffnesses.

Despite the fact that the result of this experimen not quite as strong as those of the visual-haptic experiment, is still a useful result. Subjects follow auditory cues in ranking surfaces when there is no difference in haptic stiffness between the surfaces. Also, subjects who are not preconditioned to pay close attention to ranking stiffnesses by participating in a stiffness-ranking task are influenced by sounds. This shows that in virtual environments, where subjects will not be concentrating on ranking surface stiffnesses carefully, auditory cues will be useful in augmenting the haptic display of stiffness. With the magnitude, resolution, and bandwidth of force reflection limited by current technology in haptic devices, adding sound cues is a simple way expand to our ability to create haptic illusions. For example, it is likely that in simulating mechanical switches in a control panel, adding appropriate sharp sounds will provide a more realistic feel of the switches, even if the haptic interface cannot accurately simulate the desired abrupt force transitions.

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