THE IMPACT OF VISUAL INFORMATION ON THE HAPTIC PERCEPTION OF STIFFNESS IN VIRTUAL ENVIRONMENTS

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ABSTRACT

To study the impact of visually presented spatial cues on the human perception of mechanical stiffness in virtual environments, a three degree of freedom, force-reflecting haptic interface, the Planar Grasper, was utilized. In a series of psychophysical experiments on the discrimination of stiffness of two virtual springs, subjects pressed the springs and felt the corresponding displacements and forces through their hands, in addition to seeing the deformation of the springs displayed graphically on a computer monitor. Unknown to the subjects, the relationship between the visually presented deformation of each spring and actual deformation was systematically varied between experimental trials. This relationship ranged from fully registered (visual deformation was equal to the actual deformation of each spring) to completely interchanged (visual deformation of the softer spring was equal to the deformation of the harder spring for that force and vice versa).

The results demonstrated a clear visual dominance over the kinesthetic sense of hand position. The subjects essentially ignored all kinesthetic hand position information regarding spring deformation, and based their judgment on the relationship between the visual position information and the indentation force sensed tactually. This caused an increasing misperception of stiffness with increasing mismatch between the visual and haptic position information, culminating in totally erroneous judgments when the two were interchanged. These results indicate such haptic illusions can be exploited to overcome some of the limitations of haptic interfaces and to enhance the range of haptic experience.

1 INTRODUCTION

Force reflecting haptic devices for use in virtual environments (VEs) are in their infancy. A major reason for the slow development has been the inability of current technology to provide the range, resolution, and frequency bandwidth of forces that sufficiently match the human perceptual capabilities (Srinivasan, 1995). It is known, however, that the perceptual experience in an environment depends on the interrelationships among the different sensory and motor modalities. In VEs, these interrelationships are programmable under the control of the VE designer. This research is motivated to find multimodal display methods and techniques that can be used with existing hardware to expand the range of haptic experience in synthetic environments.

In the past, psychophysical research into multisensory perception has shown ample evidence that visual information can alter haptic perception. Specifically, visual information has been shown to have a direct impact on the haptic perception of spatial properties such as hand position (Pick, et al., 1969), object size (Rock and Harris, 1967; Kinney and Luria, 1970) and shape (Rock and Victor, 1963; Easton, 1976; Easton and Moran, 1978). Many of these results have been reviewed by Marks (1978) and Welch and Warren (1986). Interestingly, the perceived size of an object appears to also affect weight perception. Koseleff (1957) reported that the perceived weight of an object changed when subjects were required to view the object through reducing or enlarging lenses. The effect was consistent with the general size-weight illusion: as the object size was perceived to be increased, its weight was judged to be less.

The aim of this study is to determine if manipulated visual information can also be used to influence haptic perception in the presence of force signals that are relevant to task

performance, such as in the discrimination of the mechanical impedance of deformable objects.

2 METHOD

2.1 Apparatus

The Planar Grasper, a three degree of freedom haptic interface, was used to present virtual springs to the subjects (Fig. 1). The device has the capability of controlling forces in two linear dimensions and a torque through a grasped knob. In these experiments, however, only the two translational degrees of freedom were used. The device is essentially a four bar linkage with an additional rotary degree of freedom at the end-effector (i.e. the knob which the user grasped). The system uses steel belts driven directly, without reduction, from three Maviolor NT300 motors. The motors provide approximately 200Ncm of sustained torque at 122V, 2.4amps. Lightweight kinematics, clean transmission, and high performance motors, allow the Planar Grasper to exert high loads at high speeds, without backlash or large inertias. Power to the Mavilor motors is regulated by three Infranor GmbH MsM0606 power amplifiers. Motor performance is controlled by servo control algorithms running on a 486DX-66MHz IBM clone personal computer that is connected to the motors through a three channel 10-bit D/A and a three channel encoder reader. Rotary encoders are used to measure the end effector position. The graphical images of the virtual workspace are presented to the subjects with a ViewSonic 15" 0.28mm color monitor also controlled by the computer.
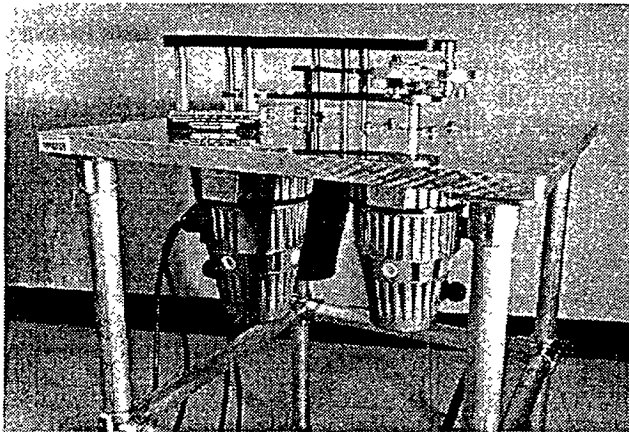

Figure 1: The Planar Grasper

The software algorithm for creating the virtual springs and surfaces was straightforward. First, the encoders were read to determine the position of the joints. Forward kinematics were then calculated to determine the location of the end-effector. Second, the position of the end-effector was tested to determine whether it had penetrated a software defined virtual surface. If it had, the distance from the virtual surface to the current end-effector location in the direction normal to the surface was determined. Third, given the normal and distance from the surface, a force vector was constructed. Finally, using the inverse kinematics, this force vector was translated into joint, and thus, motor torques, which were then issued as torque commands to the motor controllers. The complete cycle time from joint angles recording to motor commands was approximately 1ms to 10ms, depending on the complexity of the environment and the level of graphic presented on the computer screen.

2.2 Procedure

Three subjects, two males and one female, aged 18-2(years old, participated in the experiments. The subjects were undergraduate students and paid on an hourly basis. All subjects were right handed with no known hand disorders and used their right hand for all experiments

The experiments used a two interval-two alternative forced choice (2I-2AFC) paradigm. During each trial, the Planar Grasper was programmed to provide subjects with the force profiles of two virtual springs. A visual display showing the two springs located side by side was presented graphically to the subjects on the computer monitor. While the subjects felt each spring's stiffness (by pushing the contact knob of the planar grasper) they were instructed to watch the image on the computer monitor showing the corresponding compression of that spring. The subjects were allowed to compress the springs as many times as they wanted. When finished, subjects were required to select which one of the two springs *felt* stiffer by typing 'l' for the left spring or 'r' for the right spring. At no point during the experiments were the subjects given feedback on their performance.

In each trial, the stiffness of one of the two springs was always equal to a reference stiffness ($K_o = 0.33$N/mm). The stiffness of the remaining spring was equal to the reference plus an increment ($K_o + \Delta K$). The value of the increment was constant within an experimental run of fifty trials and was equal to either 50, 75, or 100% of the reference stiffness. For each trial, both the left and right spring had an equal a priori probability of having the reference stiffness. All subjects completed a total of 1,500 trials.

During the experiment, the Planar Grasper was physically configured so that the subjects could not readily observe the location of their hands. Once they initially grasped the contact knob, a cursor, displayed on the computer screen, allowed subjects to orient their hand position relative to the springs The relationship between contact knob position when the springs were being compressed and displayed position via the image on the computer screen was systematically varied across trials. The degree of discrepancy between actual deformation of the spring and visually displayed spring deformation ranged from zero (complete registration) to completely interchanged (visual deformation of the softer spring was equal to the deformation of the harder spring for that force and vice versa) This relationship between the actual and visually displayed spring deformation was determined mathematically using the following set of equations:

$$x_{rh} = \frac{F}{K_r}, \qquad x_{rv} = \frac{F}{(1-\lambda)K_r + \lambda K_l}$$

$$x_{lh} = \frac{F}{K_l}, \qquad x_{lv} = \frac{F}{(1-\lambda)K_l + \lambda K_r}$$

where F is the force applied by the subject; K_r and K_l are the spring constants (or stiffnesses) of the right and left spring, respectively; x_{rh} and x_{lh} are the actual displacements of the right and left springs, respectively, as measured by the Planar Grasper; x_{rv} and x_{lv} are the visually displayed deformations of right and left spring, respectively; and λ is the visual scaling parameter.

From the equations on the left, it is seen that the application of a force to either spring results in an actual displacement of the spring equal to the force divided by the stiffness of that spring. But in the equations on the right, the spring displacement that is visually displayed to the subject is equal to the force divided by a weighted average of both spring constants. The relative influence of each spring constant in this weighted average is determined by a scaling factor, λ, which was varied from zero to one in the experiments.

By choosing different values of λ, the degree of registration between the physical and visually displayed compression of both springs is altered. For example, when $\lambda = 0$, the actual and visual displacements of each spring are the same. However, increasing λ skews visual information so that the stiffer spring is graphically compressed farther than the other spring for the same actual displacement. As a result, when $\lambda = 0.5$, both the left and right springs display the same visual displacement for the same amount of applied force, regardless of each springs' physical displacement for that force. Thus in this case, the discrepancy is such that the stiffness of the two springs should feel identical if visual cues dominate kinesthetic cues about hand position. Finally, when $\lambda = 1$, the visual displacement of each spring is determined only by the spring constant of the *other* spring. Again if visual cues dominate kinesthetic cues about hand position, the discrepancy is such that the perceived stiffnesses of the two springs should feel switched compared to their actual stiffnesses. In each block of 50 trials, the λ values were randomized among 0, 0.25, 0.5, 0.75 and 1.

3 RESULTS

Results indicate that the perception of stiffness is greatly influenced by visual information. The results of each experiment are presented in Figures 2 - 4 as plots of percent correct versus the parameter λ, which represents the magnitude of the visual/haptic discrepancy. The thick line in the graphs represents the average across subjects. The results are also numerically presented in Tables 1 - 3 for the stiffness differences of 50, 75 and 100%, respectively.

When λ is zero and there was no discrepancy between visual and haptic spatial information, subjects performed extremely well, getting nearly 100% of the their responses correct. However as λ is increased, performance declined for all subjects. At $\lambda = 0.5$, when the discrepancy was such that the stiffness of the springs should feel identical if the visual cues dominate haptic cues about hand position, the average percent correct performance over all experiments dropped to 67%. Finally, when λ was equal to one and the discrepancy was such that the perceived stiffnesses of the two springs should feel switched compared to their actual stiffnesses, subjects responded correctly in only 17% of the trials.

λ	Subject 1	Subject 2	Subject 3	Average
0	99.5%	100.0%	97.4%	99.0%
0.25	90.6%	97.4%	71.4%	86.5%
0.5	66.2%	76.0%	44.3%	62.2%
0.75	39.6%	13.5%	9.4%	20.8%
1.0	20.8%	1.6%	1.0%	7.8%

Table 1: Percent Correct versus λ when $\Delta K/K_o = 50\%$

λ	Subject 1	Subject 2	Subject 3	Average
0	100.0%	100.0%	99.0%	99.7%
0.25	98.0%	100.0%	96.0%	98.0%
0.5	77.0%	90.2%	44.0%	70.4%
0.75	67.0%	25.0%	1.0%	31.0%
1.0	43.0%	11.8%	1.0%	18.6%

Table 2: Percent Correct versus λ when $\Delta K/K_o = 75\%$

λ	Subject 1	Subject 2	Subject 3	Average
0	100.0%	100.0%	100.0%	100.0%
0.25	100.0%	100.0%	98.0%	99.3%
0.5	95.0%	84.0%	30.0%	69.7%
0.75	70.0%	11.0%	0.0%	27.0%
1.0	52.0%	1.0%	0.0%	17.7%

Table 3: Percent Correct versus λ when $\Delta K/K_o = 100\%$

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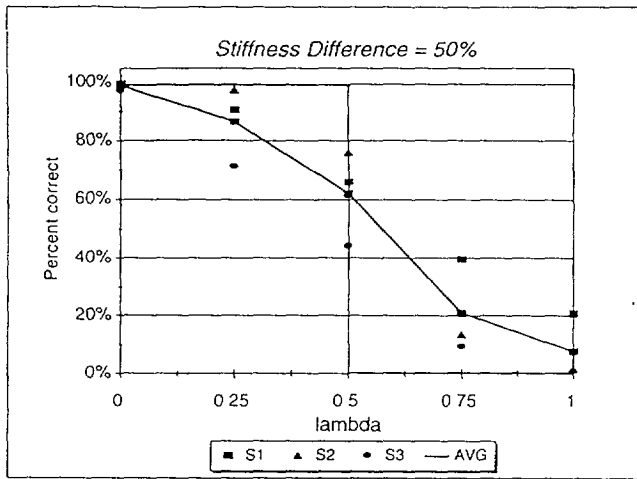
Figure 2: Percent correct versus λ when $\Delta K \backslash K_o = 50\%$
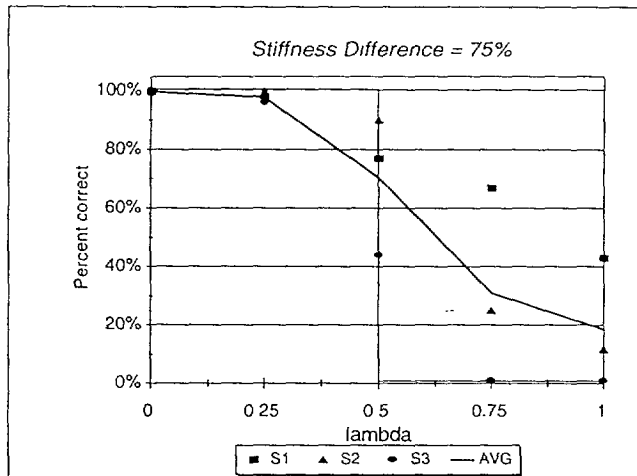
Figure 3: Percent correct versus λ when $\Delta K \backslash K_o = 75\%$
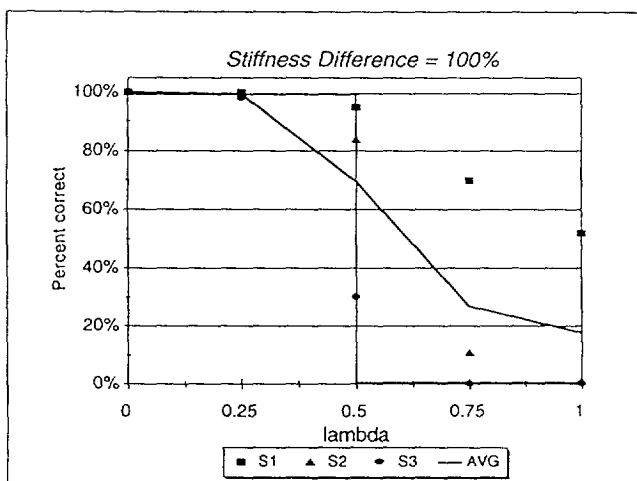
Figure 4: Percent correct versus λ when $\Delta K \backslash K_o = 100\%$

4 DISCUSSION

The experiments were performed with relative stiffness differences of 50%, 75% and 100%. These stiffness differences were significantly greater than measured JNDs for stiffness and compliance (Tan et al, 1995). Thus, if subjects discriminated solely on the basis of haptic force and kinesthetic displacement information, the subjects should get close to all responses correct, independent of lambda. In independent experiments where the subjects discriminated the two springs in the absence of visual information, percent correct responses were greater than 98%. Based on the spatial scaling method in these experiments, if subjects discriminated on the basis of haptic force and visual displacement information, the percent of correct responses would be close 100% for $\lambda = 0$, 0.25, approximately 50% for $\lambda = 0.5$ and near zero for $\lambda = 0.75$ and 1.0. This expected strategy is represented in Figures 2 - 4 as a solid line step function.

The data plots in Figures 2 - 4 clearly show that the number of correct responses does decrease dramatically with λ. Some subjects (S2 & S3) are almost completely misled by the discrepant visual information for λ values of 0.75 and 1.0. All subjects are influenced by the visual cues to a certain amount, though subject S1 appears to be less influenced as the difference in the stiffness stimuli increased from 50% to 100%. Overall it appears that the visual cues have had a compelling impact on the perceived stiffnesses of the springs. The existence of this haptic illusion implies that by suitably controlling the relationship between visual and haptic displays in multimodal VEs, it may be possible to overcome many of the limitations of haptic interfaces to enhance the range of haptic experience. Additional studies to map out the limits of this illusion are currently underway.

ACKNOWLEDGEMENTS

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