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Visual, Haptic, and Bimodal Perception of Size and Stiffness in Virtual Environments

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Abstract

Human psychophysical experiments were designed and conducted to investigate the effect of 3D perspective visual images on the visual and haptic perception of size and stiffness in multimodal virtual environments (VEs). Virtual slots of varying length and buttons of varying stiffness were displayed to the subjects, who then were asked to discriminate their size and stiffness respectively using visual and/or haptic cues. The results of the size experiments show that under vision alone, farther objects are perceived to be smaller due to perspective cues and the addition of haptic feedback reduces this visual bias. Similarly, the results of the stiffness experiments show that compliant objects that are farther are perceived to be softer when there is only haptic feedback and the addition of visual feedback reduces this haptic bias. Hence, we conclude that our visual and haptic systems compensate for each other such that the sensory information that comes from visual and haptic channels is fused in an optimal manner.

1. Introduction

Over the past few years, the topic of multisensory perception in virtual environments has aroused the interest of many researchers owing to a wide variety of applications of VEs. With recent advances in haptic interfaces and rendering techniques (Srinivasan and Basdogan, 1997), we can now integrate vision and touch into VEs to study human perception and performance. Compared to experiments in the real world, the VE technology enables better control over the stimuli needed to gain insight into human multimodal perception. Understanding the sensory interactions between vision and touch can have a profound effect on the design of effective virtual environments.

Ample evidence based on real world experiments has shown that visual information can alter the haptic perception of spatial properties like size, range, location, and shape (reviewed by Heller and Schiff, 1991). For example, it is known that for spatial information, we rely more on the visual cues than kinesthetic ones when the visual information conflicts with the haptic information. Previous research studies have also shown that visual and haptic modalities not only work in competition, but sometimes the combined information from the two can improve the human perception of object properties (Heller, 1982; Manyam, 1986). For example, subjects were asked to judge the smoothness of various surfaces in Heller's experiment (1982). His results suggest that bimodal perception (both vision and touch) gives the best performance.

In our earlier studies concerning multimodal perception in VEs, we have shown that vision and sound can affect the haptic perception of stiffness. In the study investigating the relationship between visual and haptic perception, strong dominance of visual position information over kinesthetic hand position information resulted in a compelling multimodal illusion (Srinivasan et al., 1996). Spring stiffnesses that were easily discriminable under purely haptic conditions were increasingly misperceived with increasing mismatch between visual and haptic position information, culminating in totally erroneous judgements when the two were fully in conflict. In the study on perceptual interactions between sound and haptics, it was shown that sharper impact sounds caused many subjects to overestimate the stiffness of the object they were tapping, but this illusion was not uniformly strong for all the subjects (DiFranco et al., 1997).

In this study, the influence of perspective visual cues on the human perception of object properties has been investigated. The role of 3D perspective graphics in multimodal VEs is important since it is a natural representation of a wide field visual scene, but involves nonlinear transformation of object geometries and therefore could result in a variety of perceptual illusions. We designed and conducted two separate sets of experiments to investigate the effect of 3D visual perspective on the visual and haptic perception of object size and stiffness. The motivation behind each experiment is explained in the following sections along with the details of the experimental design.

2. Experimental Methods

2.1. The perception of object size:

Purpose: Experiments were designed to test the effect of visual perspective on the visual and haptic perception of object size. Due to the visual perspective, objects that are farther from us appear smaller in 3D space. We investigated how well subjects allow for this during purely visual discrimination, the corresponding perceptual performance during purely haptic exploration of the objects, and the perceptual interactions when both visual and haptic displays are used.

Procedure: In this experiment, the subjects were asked to sit comfortably on a chair located at a fixed distance from the computer and the haptic device. Two rectangular slots, located on a rectangular block, were displayed to the user (Figs. 1-3). When haptic and visual cues were both provided, the subjects held the stylus of the PHANToM haptic interface and explored the slots while they saw what they were touching on the monitor. A visual cursor was displayed to help the subject navigate in the 3D virtual world and explore the slots easily. In each trial, the size of the "variable" slot was modified relative to the "standard" one and the subjects were asked to respond to the question "Which one is longer?" by pressing the appropriate keys on the keyboard. A curtain was placed between the subject and the PHANToM to prevent the subject from viewing the movement of his/her hand while he/she was manipulating the haptic device.

Slot Configurations: Two different slot configurations were considered in the experiment. The dimensions of slots and the condition of perspective display are shown in Figures 1 and 2.

a) Side by Side (S-S): Two slots, close to each other, were placed side by side along the x-axis on a rectangular block and displayed to the subject. The dimension of each slot along the z-axis (i.e. the axis normal to the monitor screen) was significantly larger than the other two dimensions. The length of the standard slot (the right one) was kept constant for each trial whereas the length of the variable slot (the left one) was altered. The subjects pressed "←" (left) or "→" (right) key on the keyboard to select the slot they perceived to be longer. The S-S configuration was considered as the reference for comparison with the results for the "Rear and Front" configuration in which the visual perspective was expected to have an effect on the size judgement.

b) Rear and Front (R-F): Two slots were placed back to back on a rectangular block along the z-axis. As in the S-S configuration, the dimension of each block along the z-axis was significantly larger than the other two dimensions. In this configuration, the slot that was farther from the subject appeared smaller due to perspective effects. The length of the standard slot that was closer to the subject was kept constant whereas the length of the rear slot (i.e. variable slot) was altered for each trial. The subjects pressed "↑" (rear) or "↓" (front) key on the keyboard to select the slot they perceived to be longer.

Experimental Conditions: Three different experimental conditions were considered.

a) Visual display Only (VO): Only visual images were provided and the subjects did not use the haptic device at all. They made their choices based on what they saw on the screen (Figure 3) by pressing the appropriate keys on the keyboard.

b) Haptic display Only (HO): Only haptic cues were provided. The subjects made their choices based on their manual exploration of the slots using the haptic device. In order to keep the subjects informed of which slot they were touching, a descriptive text reading "LEFT" or "RIGHT" for S-S configuration and "REAR" or "FRONT" for R-F configuration was displayed on the screen without any images.

c) Visual and Haptic displays (VH): Visual images (as shown in Figure 3) as well as haptic cues were provided to the subject.

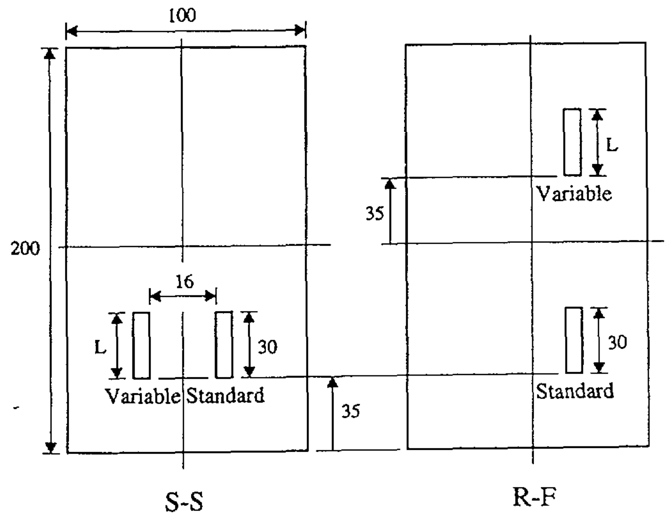


Figure 1. Schematic description of the configuration of the slot sets. The distances shown are in mm.

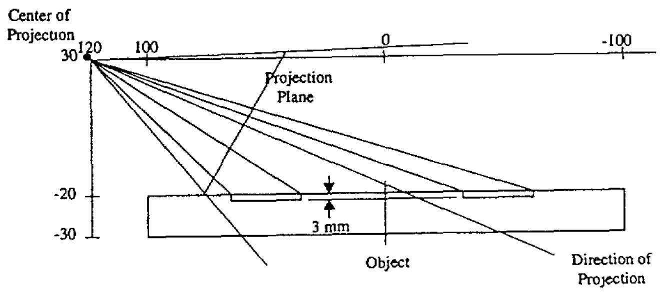


Figure 2. Schematic description of the center, direction and plane of perception relative to the rectangular block. The distances shown are in mm.

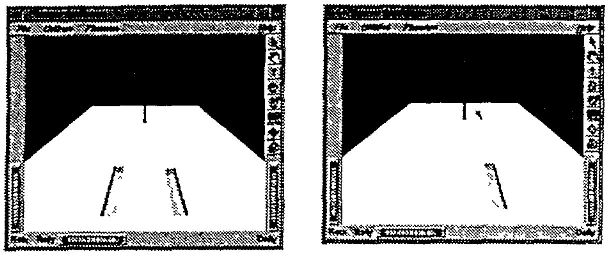


Figure 3. The visual cues shown in VH and VO conditions.

Number and Order of Stimuli: We altered the length increment of the variable slot (left in the S-S and rear in the R-F configurations) to be -20%, -10%, -5%, +5%, +10%, +20%, +30%, and +40% of the standard one (see the variations in slot lengths in Table 1). Slots were displayed as a pair to the user at the same time and the length of the variable slot was altered from trial to trial in random order. However, the sequence of stimuli that were displayed to each subject was the same. A total of 320 trials were displayed to each subject for each experimental condition.

Subjects:
A total of 10 naive subjects participated in this experiment. They were recruited from the MIT community. The ages of the subjects ranged from 18 to 30.

Table 1. The lengths of the slots displayed to the user in the "size perception" experiment (mm).

Percentage Change	Side by Side		Rear and Front	
	Left(L)	Right	Rear(L)	Front
-20%	24.00	30.00	24.00	30.00
-10%	27.00	30.00	27.00	30.00
-5%	28.50	30.00	28.50	30.00
5%	31.50	30.00	31.50	30.00
10%	33.00	30.00	33.00	30.00
20%	36.00	30.00	36.00	30.00
30%	39.00	30.00	39.00	30.00
40%	42.00	30.00	42.00	30.00

2.2. The perception of object stiffness:

Purpose: Experiments were designed to investigate the effect of visual perspective on the visual and haptic perception of object stiffness. Due to 3D perspective graphics, a compliant object that is farther from us deforms less on the projection plane, and thus the monitor screen, than when it is nearer to us, under the same force. We investigated if they would be perceived as softer/stiffer when their stiffness characteristics are explored via a haptic device with or without accompanying visual displays.

Procedure: In this experiment, two virtual compliant buttons placed on a rectangular block were displayed to the subjects (see Figure 4). For each trial, the stiffness of the "variable" button was modified relative to the "standard" one and the subjects were asked to respond to the question "Which one is softer?" by pressing the "1" or "2" keys on the keyboard corresponding to the numbered buttons on the screen.

Button Configurations: As in the slot experiments, S-S and R-F configurations were displayed. The arrangement and dimensions of the buttons are shown in Figure 4. The conditions for perspective display are given in Figure 5.

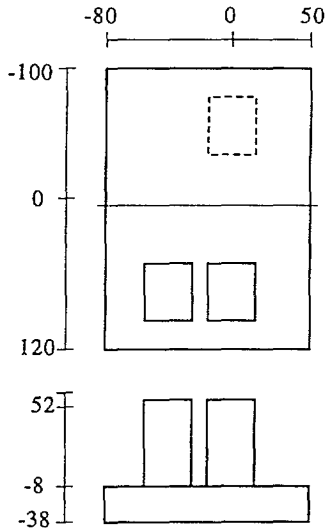


Figure 4. The dimensions of the virtual buttons used in "stiffness perception" experiment (mm). S-S configuration along with the position of the rear button (shown dashed) for the R-F configuration are shown.

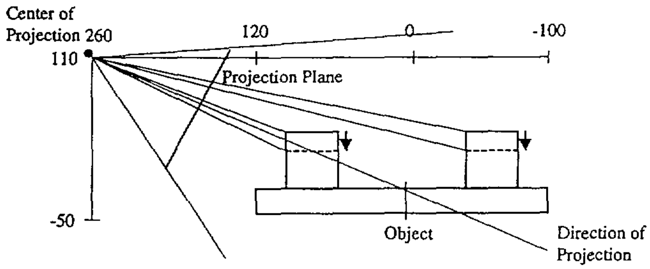


Figure 5. Schematic description of the center, direction, and plane of projection. All distances shown are in mm.

Experimental Conditions: Two different experimental conditions were considered:

a) Haptic display Only (HO): Only haptic cue was provided. The top view of the buttons was displayed to the subjects to help them locate the buttons more easily, but the visual display did not provide any cues concerning the deformation of the buttons (Figure 6). A rectangular groove on top of each button helped in preventing any slip when the subjects pressed each of the buttons.

b) Visual and Haptic displays (VH): Visual and haptic cues were both provided to the subject (Figure 7).

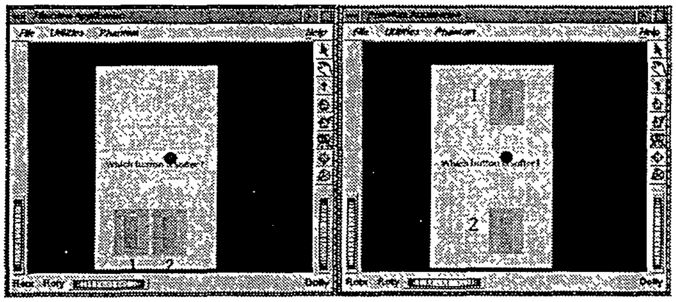


Figure 6. The visual cues displayed to the subjects in HO condition. Only the top view was shown to eliminate button deformation cues.

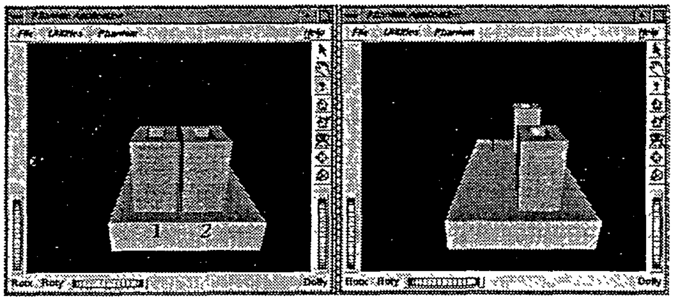


Figure 7. The visual cues displayed to the subjects in VH condition

Number and Order of Stimuli: We altered the stiffness increment of the variable button (right in the S-S and front button in the R-F configurations) to be -30%, -20%, -10%, 0%, +10%, +20%, and +30% of the stiffness of the standard one (left and rear buttons in the S-S and R-F configurations respectively, as listed in Table 2). The pair of buttons was displayed at the same time and the stiffness of the variable button was altered from trial to trial in random order, but the sequence of stimuli that were displayed to each subject was the same. A total of 168 trials were displayed for each experimental condition.

Subjects:
A total of 10 subjects participated in this experiment. They were recruited from the MIT community. The ages of the subjects ranged from 18 to 30.

Table 2. The stiffness coefficients of the buttons in the "stiffness perception" experiment (N/mm).

Percentage Change	Side by Side		Rear and Front	
	Left	Right	Rear	Front
-30%	0.20	0.14	0.20	0.14
-20%	0.20	0.16	0.20	0.16
-10%	0.20	0.18	0.20	0.18
0%	0.20	0.20	0.20	0.20
10%	0.20	0.22	0.20	0.22
20%	0.20	0.24	0.20	0.24
30%	0.20	0.26	0.20	0.26

3. Results and Discussion

3.1 The perception of object size

The results are given in Figure 8 with the average values shown by the solid curves and short vertical bars (plotted on only one side of the curves for clarity) representing the range of data for 95% confidence level. In addition to the curves representing the results of the S-S and R-F configurations, a trace that represents the expected results for an ideal subject with perfect resolution and no perceptual bias is also plotted in each figure for comparison. Note that this trace overlaps with the results for the S-S configuration in panels (a) and (c). We can see from Figure 8a that under the VO condition, the subjects' performance was very close to the ideal curve for the S-S configuration. However, the results deviate from the ideal curve for the R-F configuration and indicate the presence of a bias as well as a decrease in resolution. For example, the 50% response (i.e. PSE: Point of Subjective Equality) in Figure 8a corresponds the variable slot being about 14% longer than the standard slot. It means that when only visual cues were provided and the actual length of the rear slot was about 1.14 times the length of the front one, the two slots were perceived to be of the same size, i.e. a visual bias of 14%. This result clearly shows that farther objects are perceived to be shorter when only visual feedback is available ($p<0.05$ for –10%, 5%, 10%, and 20%). Moreover, the length increment of the variable slot that is discriminable from the standard one is >22% for longer variable slots (corresponding to 75% response) and < 6% for shorter variable slots (corresponding to 25% response). By subtracting the visual bias of 14% at PSE, we can infer a visual resolution of ±8%.

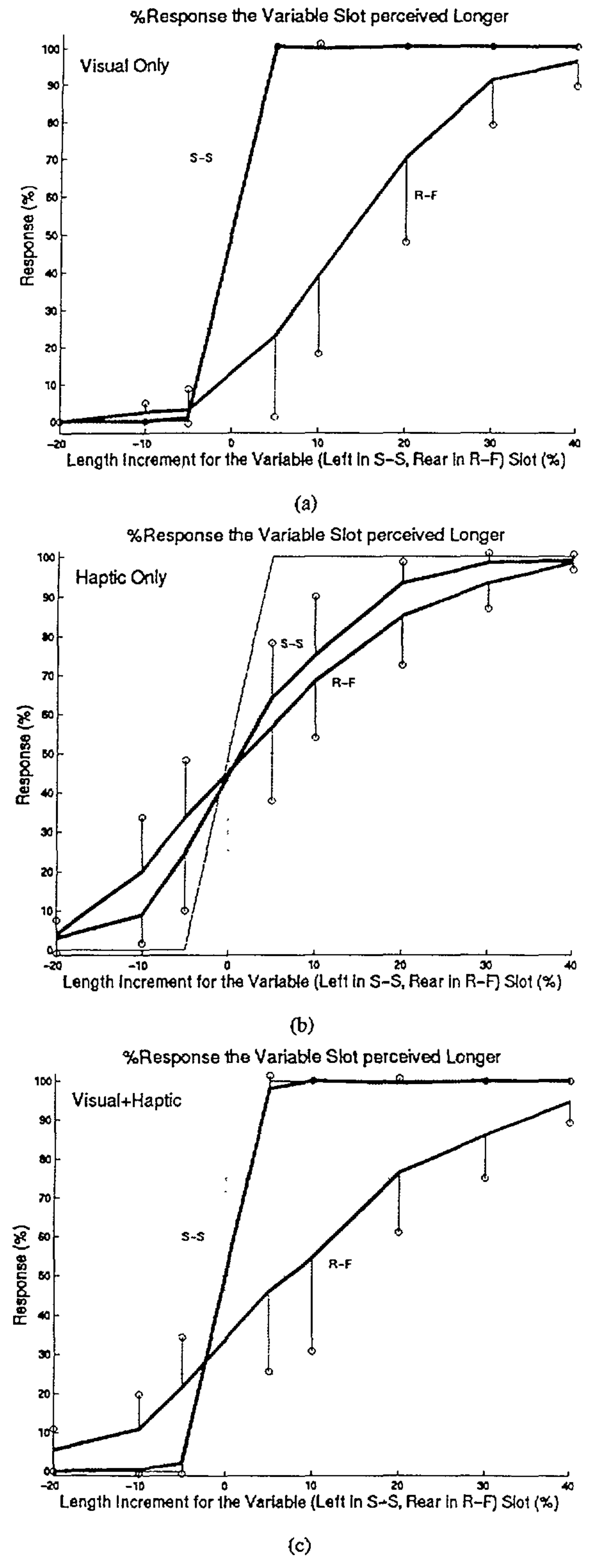


Figure 8. The results for the "size perception" experiment for (a) VO (b) HO (c) VH conditions.

For the HO condition, the results do not show any haptic bias since the length increment for the variable slot is almost zero at the PSE for both S-S and R-F configurations (see Figure 8b). However, the haptic resolution is, on the average, poorer than the visual resolution for each of the two slot configurations: about 5 to 10% for S-S and 9 to 14% for R-F.

The results of the VH condition suggest that there is some form of sensory fusion: the performance in S-S configuration is about the same as that for VO which is better than for HO; the performance in R-F has a reduced bias of 8% compared to VO and a poorer resolution of around 12%. These results are better shown in Figure 9 where the results for the VH condition are between the HO and VO curves. In other words, visual and haptic modalities of our sensory system seem to work together along the direction of gaze (the direction in which the perspective effects are dominant) in perceiving object size.

3.2. The perception of object stiffness

In the stiffness discrimination experiments, when only haptic cues were available (HO condition), for the S-S configuration the bias is approximately zero and the resolution is about 6 to 8%. In the R-F configuration, the subjects felt the rear button to be haptically softer than the front one. This effect can be seen in the curve for the R-F configuration in Figure 10a: when the stiffness coefficient of the variable button (the front one) is the same as the standard one (the rear one), the rear button is perceived to be softer in about 80% of the trials ($p<0.05$ for -20%, -10%, and 0%). As determined by the PSE, the haptic bias for the R-F configuration is approximately -10% and the resolution is about 10% under the HO condition. This bias disappears and the resolution improves to about 5% for both S-S and R-F configurations when visual cues are added to the scene (see Figure 10b for the PSE). From Figure 11b, we can also see that the effect of the visual feedback on the R-F configuration is to shift the R-F curve to the right (i.e. reduce bias) and make it steeper (i.e. better resolution). This results in the standard button (the rear one) being perceived as stiffer. It should be noted that there is no significant difference between the curves corresponding to S-S and R-F configurations when visual and haptic cues are both available to subjects.

4. Conclusions

The results of the experiments described above show that the 3D perspective visual displays in VEs indeed generate visual and haptic illusions due to biases in perception such that the farther objects are perceived to be (1) shorter in length when there are only visual cues and (2) softer when there are only haptic cues. However, when both sensory cues are provided, sensory data is fused such that vision and touch compensate for bias due to each other.

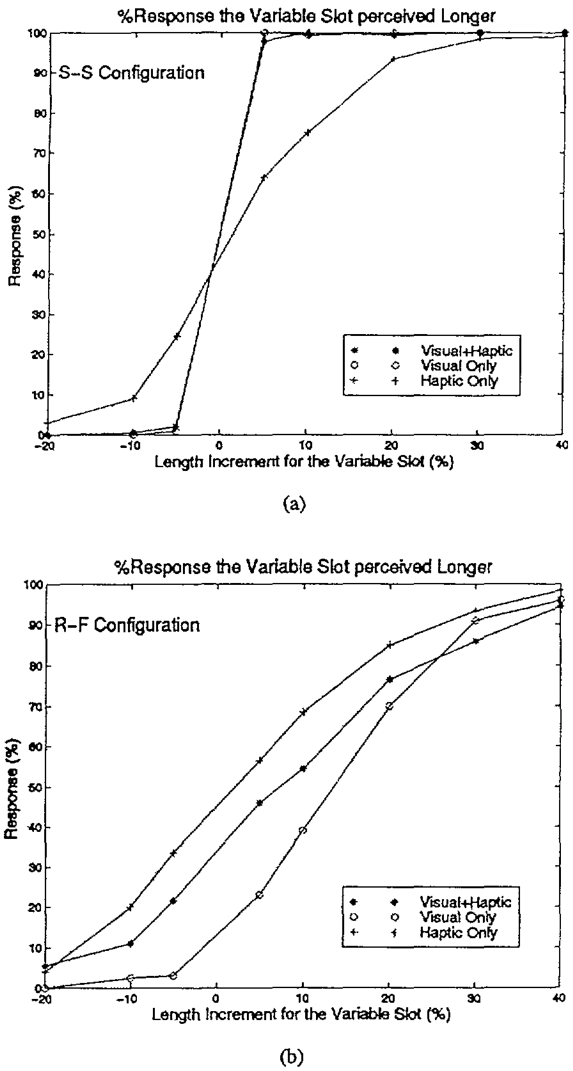


Figure 9. The results of the "size perception" experiment for (a) S-S (b) R-F slot configurations. Note that in (a) the results for VH and VO overlap.

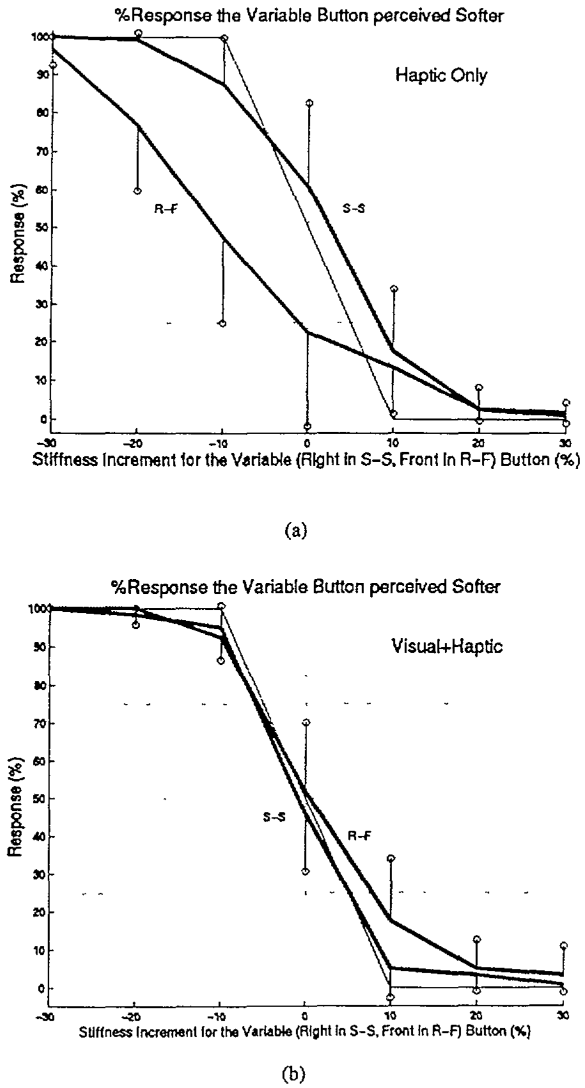
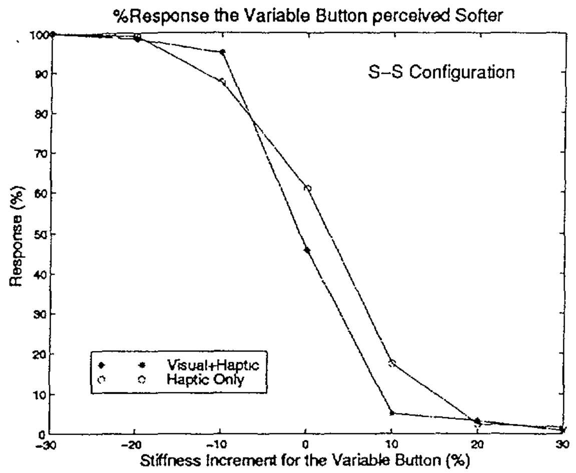


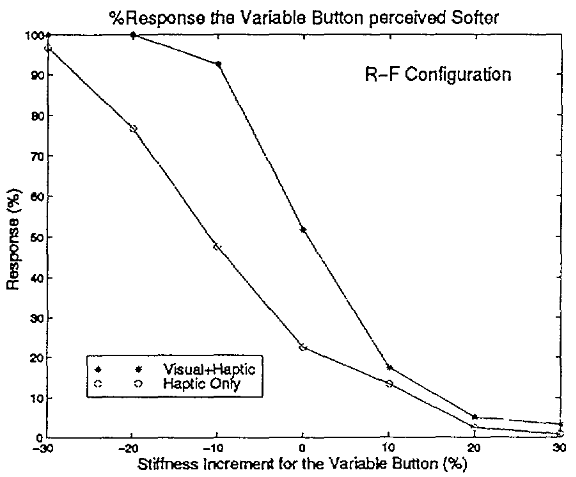
Figure 10. The results of the "stiffness perception" experiment for (a) HO (b) VH conditions.

The results displayed in Figure 9b can be interpreted in terms of the relative roles played by vision and haptics as follows. For each length increment of the variable slot, the difference in the response (%) between the VH case and the VO case can be thought of as the effect of haptics on vision. Similarly, the difference in response (%) between HO and VH can be thought of as the effect of vision on haptics. Normalizing the sum of the values to 100%, we obtain the bar graph shown in Figure 12. We only plot the range from -10% to +20% because it seems that outside this region, due to obvious differences in the lengths of slots, the judgement is not a typical compromise between the two senses. In Figure 12, we can see that as the lengths of the two slots presented to the subjects get closer, the subjects rely more on haptic information which has no bias (Figure 8b).

In particular, the result that the farther objects are perceived to be softer when only haptic cues are present is interesting and perhaps suggests a new concept of *haptic perspective*. To ensure that this result was not an artifact of the robot arm (i.e. position and force errors due to the kinematics of the haptic device) or our experimental design, we performed three different tests, but the result did not change. The haptic device was rotated 90 degrees and the experiment was repeated for both S-S and R-F configurations. The calibration of the device was checked by hanging known weights and by measuring the displacement of the stylus. Force and displacement data showed



(a)



(b)

Figure 11. The results of the "stiffness perception" experiment for (a) S-S (b) R-F

perfect agreement. To further verify the results, the left and rear buttons were designated as the "variable" button and the experiments were repeated for S-S and R-F configurations, respectively. Based on the fact that these tests did not change the result, we speculate that this may be due to the human kinesthetic system. We observed that the subjects typically pressed each button one at a time and palpated it using vertical oscillatory up and down motion until they made a decision. During this process, only the wrist and elbow joints of the arm were active if the button was close to the subject. However, if the button was further away, the subjects extended their arm to reach the button and their elbow and shoulder joints were activated and thus contributed to the judgment of stiffness.

In these stiffness perception experiments, we did not observe any significant difference in the response of subjects for S-S and R-F configurations when visual and haptic cues were both provided to the subjects. We believe that there are two effects that contribute to the outcome. These effects cancel each other, leading to "no observable difference" between the curves: (1) Due to perspective effects, perceived deformation of a button that is farther from us is less than the closer one. Hence, the button that is farther from us is expected to be perceived as stiffer if only visual cues are available. (2) Due to the attributes of human kinesthetic system, we have also seen that (see discussion above) the objects that are farther from us are perceived to be softer when there is no perspective cue in the visual scene. Hence, it seems that these two effects cancel each other and our sensory system successfully integrates the information coming from haptic and visual modalities, resulting in a practically unbiased perception.

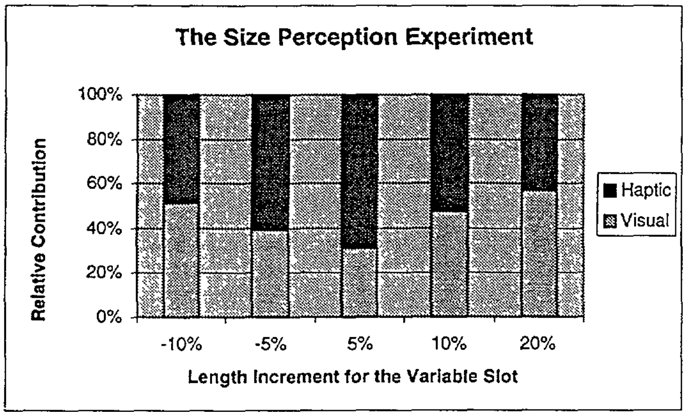


Figure 12. Fusion of sensory data in the "size perception" experiment.

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