A Behavioral Adaptation Approach to Identifying Visual Dependence of Haptic Perception

James Sulzer*† Arsalan Salamat† Vikram Chib*† J. Edward Colgate*
(*) Laboratory for Intelligent Mechanical Systems, Northwestern University, USA
(†) Sensory Motor Performance Program, Rehabilitation Institute of Chicago, USA
E-mail: sulzer@northwestern.edu, arsalansalamat@berkeley.edu, v-chib@northwestern.edu, colgate@northwestern.edu

Abstract

Both haptic and visual senses play a role in how we explore our environment. Previous studies have shown that vision plays a very strong role in perception of object stiffness, yet quantification of the contributions of both haptic and visual feedback remains elusive. This study uses a behavioral adaptation approach in order to better understand how humans perceive stiffness. Namely, subjects make targeted reaches across a virtual surface of varying stiffness, adapting to the new environment. The hand's cursor position is visually distorted to seem more stiff for one group, less stiff for another, and no distortion for the control group. Area Reaching Deviation (ARD) and post-adaptation interface forces, used in previous studies, were the two outcome measures used to determine differences between groups. We compare the slopes of the post-adaptation force-stiffness relations to quantify the effect of visual distortion. Our results indicate that making a stiff surface look more compliant has a greater effect on humans than making a compliant surface look more stiff.

1. Introduction

When interacting with our environment we implicitly incorporate information about the shape and mechanical properties of objects into our actions. Consider the task of running your hand over the boundary of a surface. Depending on its compliance you may either displace the surface boundary (as in the case of a pillow) or maintain light contact with the surface without large displacements (as in the case of a rigid wall). To achieve these tasks we subconsciously incorporate haptic and visual information. In this study we focus on how visual information affects the perception of haptic properties of the environment.

During tasks that require the integration of visual and haptic information, vision has been found to dominate the judgement of size, shape, and position [1], [2], [3]. In particular, a study by Srinivasan et al. had subjects interact with linear springs with normal and altered visual stiffness (i.e. visual feedback was manipulated to make the spring look more or less stiff than its actual physical rendering) [4]. Using a forced-choice paradigm subjects' perceptions were found to be heavily biased by altered visual feedback. Given two springs of the same physically rendered stiffness, with altered visual stiffnesses, subjects would perceive the one with higher visually rendered stiffness as being stiffer.

In this study we utilized a paradigm similar to that of Srinivasan et al. We altered visual stiffness as subjects made reaching movements to targets on the boundary of curved surfaces of varying physical stiffness. However, a major difference between our experiment and those of Srinivasan et al. was that subjects were not explicitly instructed to judge surface stiffness. Instead, we used subjects' implicit learning and behavioral adaptation to classify the perception of surface stiffness. Implicit learning is a term used to describe subjects' ability to subconsciously incorporate information about their environment into their actions. In motor learning, it is common to use behavioral adaptation paradigms to study this form of learning. In these paradigms subjects are made to interact with a controlled environment with minimal instructions of their actions. This paradigm has been used in a number of haptic studies by our group [5], [6].

We hypothesize that visual feedback dominates during adaptations. For instance, making a surface look less stiff than it is will result in a trajectory further into a virtual surface and create higher interface force. The findings of this study agree with the hypothesis, and also indicate that humans are more susceptible to the illusion of a stiff surface looking more compliant than a compliant surface looking stiffer.

2. Experimental Methods

We performed the experiments using the two DOF planar Manipulandum shown in Fig. 1. Grasping the handle, the subjects reached from an initial position (shown as an 'X') to a final target (red dot) 10 cm apart. The virtual surface is shown as a dotted circle of radius 6.5 cm, invisible to the user. Graphics are plotted on an opaque workspace above the user's arm by an LCD projector located directly above the workspace, leaving only the initial position, target and cursor position (denoting hand position) visible. Position and velocity data were gathered from encoders on the two motors at a frequency of 100 Hz, while the controller's update rate was 200 Hz.

2.1 Force Fields and Visual Distortion

The force fields and visual distortion were piecewise-defined, shown in (1). They were nonzero only when the hand comes within the boundary of the virtual surface. The force F is a function of the penetration of the hand into the virtual surface r_p, and the haptic stiffness k_h:

$$F = \left\{ \begin{array}{ll} k_h r_p + b\dot{r}_p & r_p \geq 0 \\ 0 & r_p < 0 \end{array} \right\}, \tag{1}$$

where b is a damping constant, implemented to alleviate instabilities caused by sampling, but does not create forces high enough to be detected by the user. The magnitude of the force increases with penetration distance, and the direction is radial to the center of the virtual surface. This paradigm is illustrated in Fig. 2. The visual distortion of the hand position p_v, was computed similarly, except using a visual stiffness constant, k_v:

$$p_v = \left\{ \begin{array}{ll} R - k_v r_p & r_p \geq 0 \\ p_h & r_p < 0 \end{array} \right\}, \tag{2}$$

where p_h is the true hand position and R is the radius of the virtual surface. Like the forces, the direction of the visual distortion is radial to the haptic surface. Thus, a low visual stiffness constant (i.e. less than 1) produces the visual illusion of less hand penetration and thus a stiffer surface and conversely, a high visual stiffness constant produces a seemingly more compliant surface.

2.2 Subjects and Protocol

Fifteen naive, healthy, IRB-approved volunteers (ages 18-30) participated in this study. All subjects were right-handed and had normal vision or vision that was corrected to normal. Each subject's experience was composed of four blocks differing only in haptic stiffness (k_h = 200, 800, 1400, and 2000 N/m). Each block was further subdivided into four phases. The first phase was *familiarization* (10 movements) where no forces or visual distortions were applied. The second phase was *training* (48 movements), where the force field was introduced and the three subject groups forked into the *low visual stiffness group* (5 subjects, k_v = 1.7), the *high visual stiffness group* (5 subjects, k_v = 0.3), and the control group (5 subjects, k_v = 1.0). The visual stiffness constant for each group was chosen heuristically as the largest distortion undetected by subjects. After training was the *catch phase* (48 movements), using the same forces and distortions as the training phase, except during pseudorandomly placed catch trials (1 per 8 trials) where no forces or distortions are applied. Afterwards was the confluence of the three groups, the *washout phase* (30 movements), where no forces or distortions were applied and the subject de-adapts to the force field, exhibited by straight line movements.

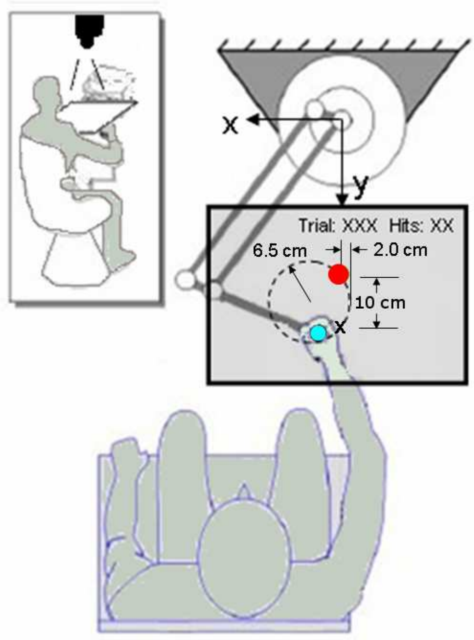

Fig. 1: Experimental setup is shown using two DOF planar manipulandum. An opaque rectangular surface above the hand is shown transparent here. Only hand cursor position (cyan), which is occasionally visually distorted, target position (red) and text on top right of workspace denoting "score" are visible to the subject.

Subjects made target reaching movements from a single starting location to a target, located vertically 0.5 and 0.4 m from the axis of the motors, respectively. The users were instructed to move to the target as fast as possible to ensure ballistic movement. Both sound effects and the target color changed when the subject reached the goal in the ideal period of time (0.45 s). The users viewed their "score", which was the number of movements completed in the desired time, and the trial number at the top of the workspace (Fig. 1).

2.3 Trajectory Analysis

Catch trials are applied after adaptation, and appear pseudorandomly applying no forces or visual distortion. Since the ideal movement between the two targets in a catch trial is a straight line, divergence from that path indicates the type of adaptation. The error metric in this paper is meant to help elucidate this behavior. This method, used previously in Chib et al. [6], is known as the Area Reaching Deviation (ARD), is where the divergence is summed across the trajectory for a given distance (cutoff distance is set to eliminate corrective movements). This can be calculated as the area between the trajectory and the ideal reaching movement:

$$ARD = \int_{y_1}^{y_2} x \; dy, \tag{3}$$

where y_1 and y_2 are chosen as the y-position 1 cm and 7 cm from the start position, respectively. These positions correspond to the first 150 ms of movement, before any corrective strategies begin to take place. Consistent with the coordinate system of the Manipulandum (see Fig. 1), a positive ARD indicates a net movement into the virtual haptic surface, while a negative ARD shows that the user ventured towards the boundary of the surface.

3. Results and Discussion

3.1 Catch Trials

Catch trials provide a window into the development of the subject's internal model during the experiment. For instance, if a subject is exploring a compliant surface, the movement will venture into the boundary. During a catch trial, when the force field is unexpectedly removed, the subject will travel even further into the boundary since no force resisted the planned trajectory into the surface.

On the other hand, as the surface becomes stiffer, there is less penetration. In fact, for a very stiff surface, the direction of the subject's trajectory will conform to the shape of the boundary. Therefore, because the planned trajectory is around the surface instead of into the surface as in the lower stiffness case, trajectory will continue to flow around the boundary even during catch trials. Examples of this behavior can be seen in the data of a single subject in this study from the control group shown in Fig. 3. The vertical dotted line serves as a reference.

This experiment delves further into this behavior, trying to devise the contribution of visual feedback to the subjects' chosen trajectories. If visual feedback plays a strong role as hypothesized, the catch trial trajectories should shift to imitate a stiffer surface, or a more compliant surface, depending on how the visual distortion is applied. In the case of low visual stiffness, the effect of the visual distortion should shift the catch trial trajectories inside the boundary, as seen in the raw data of a single subject in Fig. 4. Conversely, when the surface appears more stiff than it is, the catch trial trajectories should shift more to the outside of the surface boundary, as seen in the single subject of Fig. 5.

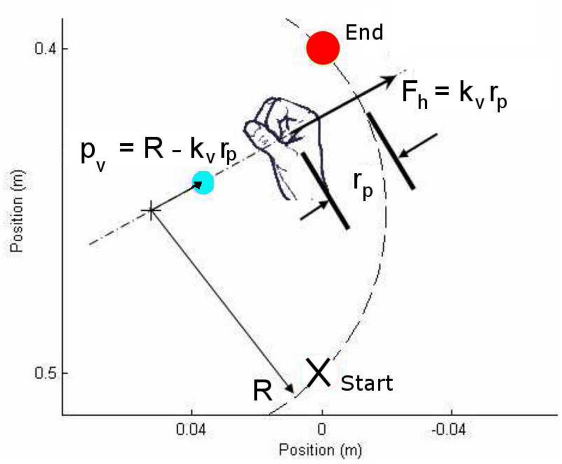

Fig. 2: Both force and visual distortion are radially applied using linear proportions. The user received visual feedback of hand position, p_v (cyan circle), which is occasionally distorted, and the target position (red circle). In the case shown here, the cursor is distorted so the surface looks more compliant.

The raw data show a qualitative dependence on visual feedback. The rest of the study quantitatively determines how much people depend on vision during haptic exploration. The quantitative metric ARD, described previously, becomes more negative as the trajectories move to the right of a straight line trajectory. In other words, a more negative ARD corresponds to a movement closer to the surface boundary.

Fig. 6 illustrates how mean ARD conforms to the surface boundary as stiffness increases. The ARD of the high visual stiffness, low visual stiffness and control groups (green, purple, and dashed blue, respectively) are shown here. The transparent boundaries around these data represent one standard error.

Consistent with the findings of Chib et al., the ARD changes with stiffness level. As expected, the ARD of the control group decreases signficantly using a repeated measures ANOVA and Tukey post-hoc comparisons (F =18.23, df = 3, p = 0.0001, α = 0.05). According to our hypothesis, if humans have a high dependence on visual feedback, the ARD of the high and low visual stiffness groups should remain small and large respectively, inde-

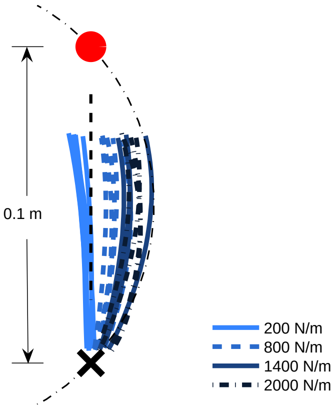

Fig. 3: The catch trial trajectories of a single subject in the control group are consistent with previous work. More specifically, as the surface becomes stiffer, the trajectories conform to the boundary. The vertical dotted line is a reference for comparison to an ideal trajectory (ARD = 0).

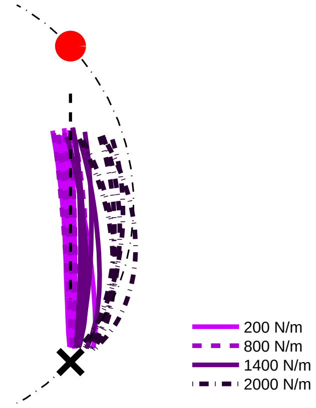

Fig. 4: Catch trial trajectories of one subject from low visual stiffness group are shifted into the surface boundary. The visual distortion makes the surface look more compliant, and here the subject behaves accordingly.

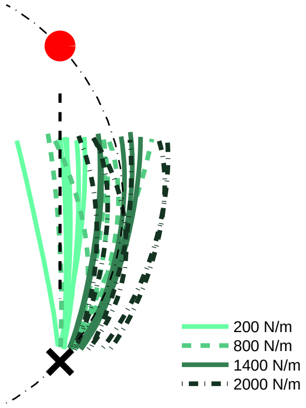

Fig. 5: Catch trial trajectories of a single subject from the high visual stiffness group make the subject act like the surface is stiffer. Compared to the trajectories of the previous two figures, the trajectories of the high visual stiffness group are shifted towards the virtual surface boundary.

pendent of stiffness, while the ARD of the control group changes. Using the same statistical methods above, the high visual stiffness group does change significantly (F = 15.07, df = 3, p = 0.002), but the low visual stiffness group does not (F = 4.52, df = 3, p = 0.025).

The differences between groups (or lack thereof in some cases) is interesting. Our hypothesis would suggest the ARD of the high visual stiffness group would be lower than the control group at low stiffness levels, but using a one-tailed t-test, there is no significant difference between these groups at any point (see Table 1). Perhaps a larger difference could have been obtained if lower stiffness levels were tested. It is consistent with the hypothesis that less of a difference would be noticed between the control group and the high visual stiffness group at high stiffness levels since the penetration into the surface is less noticeable.

Table 1. Significance levels for ARD across stiffness levels

	Hypothesis	
Stiff.(N/m)	p(Low>Cont.) (t =)	p(Cont.>High) (t=)
200	0.882 (-1.28)	0.3388 (0.43)
800	**0.0287 (2.22)**	0.2459 (0.72)
1400	0.1163 (1.29)	0.5567 (-0.15)
2000	**0.0235 (2.35)**	0.7995 (-0.89)

At low visual stiffness, even a small penetration into a stiff surface is noticeable, and this effect shows up in Fig. 6 as a significant difference at higher stiffness levels (800 and 2000 N/m), indicated on the plot with asterisks. At lower stiffness levels, the ARD of the low visual stiffness group is actually lower than the control group, indicating that distorting a compliant surface to look more compliant has lit-

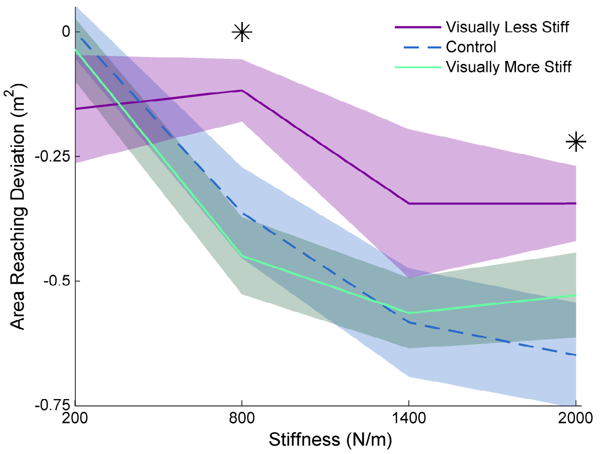

Fig. 6: ARD decreases with stiffness for all groups. When the surface appears stiffer than it is in reality, the catch trial trajectories move to the surface boundary (indicated by more negative ARD). Asterisks indicate a significant difference between two groups in a given stiffness level. Shaded regions indicate one standard error.

tle effect. Table 1 provides a summary of the significance levels across stiffness levels.

3.2 Interface Force

Aside from catch trial behavior, the post-adaptation interface force provides valuable information into how the nervous system has adapted to the new environment. Post-adaptation in this experiment is defined as the last ten trials of the training phase.

If visual feedback dominates perception of stiffness, then the interface force will vary between groups. More specifically, the low visual stiffness should have a higher interface force than the control group, and the high visual stiffness group should have a lower interface force. Qualitatively, this seems to be the case as shown in Fig. 7.

As supported by Table 2, the high visual stiffness group is either significantly lower or on the borderline of statistical significance at each stiffness level when compared to the control group, using a one-tailed t-test. As opposed to the previous section, the interface force of the high visual stiffness group shows a much more convincing difference to the control group than ARD.

Consistent with the results from the previous section, the lower visual stiffness group varied from the control group more as the stiffness level increased, reaching its maximum difference at 2000 N/m. Interestingly, there is a much greater amount of variability between subjects in this group, which may signify a greater dependence on visual feedback in some subjects more than others.

Chib et al. found that the interface force is relatively constant at each stiffness level. Therefore, the interface force of the control group should be constant. This seems to be the case, where using a repeated measures ANOVA with Tukey post-hoc comparisons, the control group does not change significantly ($F = 1.73$, $df = 3$, $p = 0.213$).

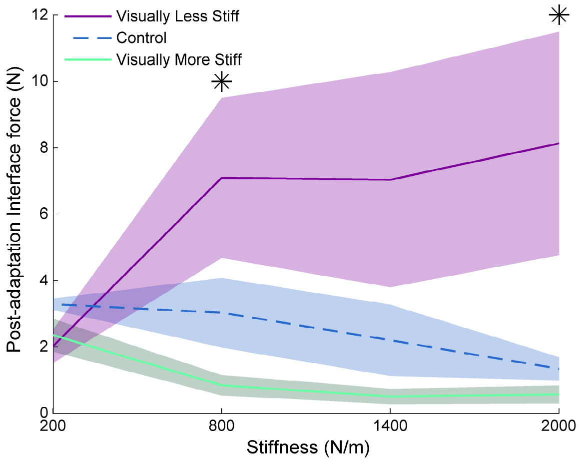

Fig. 7: Post-adaptation interface force is affected by visual distortion. While few comparisons are statistically significant (shown by asterisks), the qualitative comparison exhibits some of the predicted behavior.

If humans depend on visual feedback in haptic perception, then making a surface look more stiff than it actually is would result in a lower interface force than the control group at low stiffness levels, and as stiffness increases, will converge to the control group. The behavior of the high visual stiffness group is seen in Fig. 7, where a repeated measures ANOVA and Tukey post-hoc comparison shows a significant decrease ($F = 6.67$, $df = 3$, $p = 0.007$).

Likewise, in the low visual stiffness group, making a surface look more compliant should cause the interface force to rise as stiffness increases. However, this increase is not significant ($F = 3.07$, $df = 3$, $p = 0.069$). This may be due to the same adaptation that caused the interface force of the control group to decrease with increasing stiffness.

Table 2. Significance levels for interface force across stiffness levels

	Hypothesis	
Stiff.(N/m)	p(Low>Cont.) (*t*=)	p(Cont.>High) (*t*=)
200	0.9979 (-2.39)	0.0565 (1.78)
800	0.0806 (1.54)	**0.0405 (1.99)**
1400	0.0973 (1.41)	0.0815 (1.54)
2000	**0.0398 (2.01)**	0.0608 (1.73)

3.3 Quantifying Visual Dependence

One of the advantages of the behavioral adaptation paradigm is the ability to quantify behavior. The previous sections agree with previous work in showing that there

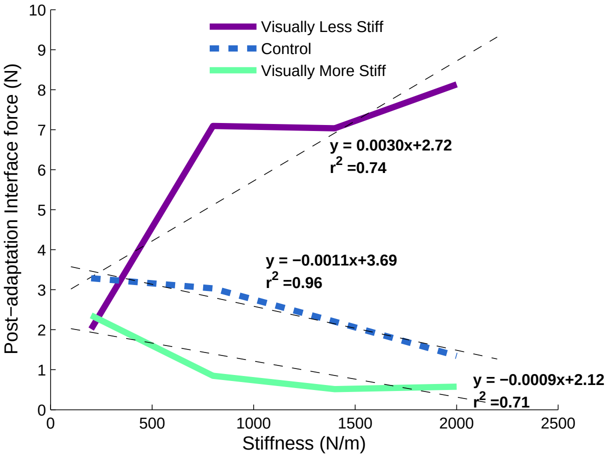

Fig. 8: Linear regression of post-adaptation interface forces used to obtain a visual dependence metric.

is at least some dependence on visual feedback, but how much do we depend on vision?

We began by identifying a consistent behavior in the control group, and then comparing to the two test groups. Since many studies have shown that interface force remains constant at different stiffness levels [6], [7], then deviation from this relationship during visual distortion would be another indicator of haptic dependence on vision. In other words, we compared the linear regression models from each case. This model assumes that subjects' interface force changes in a linear manner in both the high and low visual stiffness groups.

Fig. 8 illustrates this model, along with regression values. The slope of the control group was close to zero, as hypothesized (-0.0011 N/Nm), while the slope of the low visual stiffness group was relatively much higher (0.0030 N/Nm). Not showing much dependence on visual feedback, the slope of the high visual stiffness group appears to become flatter (-0.0009 N/Nm). This further illustrates the drastic the effect of compliant distortion.

A larger study is necessary to more accurately define these relationships and answer some important questions. Are humans more susceptible to compliant visual distortion? If so, how susceptible are we? How best can we characterize this effect?

4. Conclusions

Interactions and learning of our environment inherently requires implicit information. When we interact with our environment we do not explicitly make queries about our environment, instead we subconsiously incorporate information about the shape and mechanical properties of obstacles into our actions. While this implicit learning is a hallmark of our motor learning and perception, haptic pshychophysics to date has neglected this. Instead haptic studies bias perception by asking subjects explicit questions in forced-choice paradigms.

This study uses a behavioral adaptation paradigm to elucidate the effect of vision on haptic perception of stiffness. We used two different metrics, ARD and post-adaptation interface force, to determine how much humans depend on visual feedback during object perception.

Unexpectedly, both ARD and interface force of the high visual stiffness group were not significantly lower than the control group at low stiffness levels. However, as anticipated, the ARD and interface force of the low visual stiffness group were both significantly higher than the control group at higher stiffness levels. This would indicate that humans are more susceptible to this type of low visual stiffness distortion than high visual stiffness distortion.

In this study we have shown evidence that vision plays a strong role in haptic sensing, which is in agreement with previous work. But this study goes an extra step in quantifying how much vision can play a role. A key issue in haptic devices is rendering stiff surfaces. Therefore knowing how stiff a surface can feel with visual distortion will change the design criteria of haptic devices. Finally, on a more fundamental level, these results provide insight to how humans control movement.

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