A Perceptual Study on Haptic Rendering of Surface Topography when Both Surface Height and Stiffness Vary

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Abstract

This study is concerned with the distorted perception of surface topography when both surface height and surface stiffness vary. Three psychophysical experiments were conducted using virtual surfaces rendered with a force-feedback device. In Exp. I, we found that the threshold for detecting a height difference between two adjacent planes was quite small (0.17–0.63 mm) and decreased as surface stiffness increased (0.4-1.0 N/mm). In Exp. II, we tested our force constancy *hypothesis which stated that users maintained constant penetration forces while exploring haptic virtual surfaces. Data collected during lateral stroking of surfaces of varying stiffness supported this hypothesis. In Exp. III, subjects stroked two surfaces with a surface height difference of 2 mm (well above the thresholds obtained in Exp. I) and with varying stiffness values. Our results showed that the relative stiffness of the two surfaces dramatically affected subjects' ability to discriminate the height of these surfaces. Our findings underscore the importance of understanding the interplay of haptic rendering parameters. Future work will focus on the development of compensation rules for ensuring perceptual accuracy of haptic virtual environments.*

1 Introduction

How do people perceive the surface topography[1] of a virtual surface rendered with a force-feedback device? Unlike the case of touching a real surface, the probe of the haptic device has to penetrate a virtual surface before a user receives force feedback. This resistance to penetration is then attributed to the existence of a surface. By stroking the probe across the surface, a user senses the movement of the probe and forms a mental image of the

Figure 1: An illustration of a surface (solid line) and the trajectory followed by the probe tip (dashed line) when the surface is explored with a haptic device.

surface's topography. In the simplest case, the probe penetrates the surface at a constant depth, and the tip of the probe follows a trajectory parallel to that of the virtual surface (Fig. 1). Although one might argue that the surface is perceived to be at a slightly lower location, the perception of the topography is nevertheless accurate.

What happens when both the surface height and the surface stiffness are varied? Consider, for example, a surgical training system. Among other things, the shape of an organ as well as its stiffness needs to be simulated in order to accurately simulate the haptic interaction between a surgical tool and the organ. Another example is the haptic rendering of co-located measurement data (height, stiffness, adhesion, etc.) collected by an atomic force microscope (AFM). Shown in Fig. 2 is a pseudo-color AFM image of a surface height map, $h(x,y)$, of crystallized proteins on mica substrate. The higher surfaces (protein) are encoded with lighter colors. Also available to us was a surface stiffness map $k(x,y)$ (not shown).[2] We rendered these two maps by computing the feedback force during probe tip penetration as

$$f_z(x,y) = k(x,y)\times[h(x,y)-p_z] \quad (1)$$

where f_z is the restoring force in the z direction, $k(x,y)$ is the stiffness value at location (x,y), $h(x,y)$ is the surface height at (x,y), and p_z is the z position of the probe tip. For simplicity of discussion, we will assume that the

[1] In this article, we are concerned with the macro-geometry (shape), as supposed to the micro-geometry (texture) of a surface (see [1]).

[2] The surface height map and stiffness data were provided by Scott Crittenden and Prof. Ron Reifenberger at the Purdue Nanophysics Laboratory.

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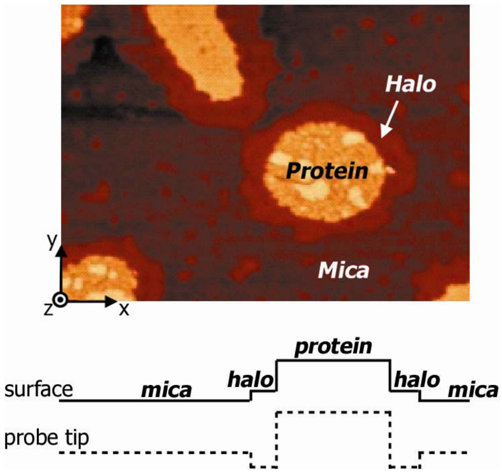

Figure 2. A pseudo-color surface height map for "protein on mica" data taken from an AFM. The solid line shows a cross-section view of one protein patch, the lipid halo around it, and the mica substrate. The dashed line represents the trajectory traveled by the probe tip.

crystallized protein and mica regions are of similar stiffness, while the halo regions are considerably softer. In addition, the protein patches are roughly 5 nm above the mica substrate, and the halo regions are about 1 nm above mica (see the solid line in Fig. 2). When a user explored the data by stroking across a protein patch, the probe tip "dipped" when it entered the halo region, thereby creating the sensation that the halo region was lower than the mica substrate (illustrated by the dashed line in Fig. 2). This perceptual phenomenon is likely to occur in a variety of haptic rendering systems where multiple variables are rendered simultaneously.

Our interpretation of this phenomenon is based on the idea of ***force constancy***. We hypothesize that people try to maintain a constant penetration force (F_p) during haptic exploration of surfaces. When the probe tip moves from mica to halo (as shown in Fig. 2), the user continues to penetrate the surface deeper until the reaction force exerted on the probe increases to F_p. This explains why the relative height of two adjacent surfaces may not be preserved if the lower surface (in this case mica) happens to be stiffer than the higher surface (halo). Since the user can only infer the shape of the actual surface (solid line in Fig. 2) by feeling the probe tip positions (dashed line), the perception of the surface topography is distorted when the solid and dashed lines are not parallel.

Many researchers have investigated sensory illusions involving touch. In their classical study, Rock and Harris used lens and prisms to distort the visual appearance of objects and had subjects judge object properties such as size and orientation [2]. They reported *visual dominance*; i.e., when subjects were confronted with inconsistent haptic and visual cues, their perception was determined by vision. More recently, Srinivasan *et al*. asked subjects to judge the stiffness of virtual springs presented visually (displacement only) and haptically with a force-feedback device [3]. The relation between the visual representation of spring compression displacement and the actual displacement caused by subject's movement was systematically varied. The results demonstrated that subjects judged stiffness by integrating visual perception of displacement and haptic perception of force. In this case, kinesthetic hand position information was largely ignored by the subjects. Robles-De-La-Torre and Hayward decoupled force and motion cues when a user moved a probe-like robotic device over a bump or a hole [4]. Their results showed that force cues could override kinesthetic cues in geometric shape perception.

Our investigation is not about visual dominance or haptic illusion. We assume that a user is able to accurately perceive the trajectory of the tip of a probe held in the hand. We do not artificially create inconsistent visual/haptic or force/position cues. Instead, we hypothesize that a user maintains a roughly constant force during lateral exploration of surface geometry, and therefore the only useful cue available to the user is the kinesthetic perception of probe position.

The objective of this study is to gain a better understanding of how a user perceives the topography of a virtual surface when the surface height and stiffness both vary. We hope to apply our findings towards a perceptually more accurate haptic rendering system that displays multiple object properties. Specifically, we ask:

(i) What is the threshold for discriminating two uneven surfaces (Exp. I)? We show that the thresholds are small and they decrease as surface stiffness increases.

(ii) To what extent does the force constancy hypothesis capture haptic interaction patterns (Exp. II)? We conclude that as surface stiffness varies, penetration depth changes in a way that keeps penetration force constant. Furthermore, different subjects tend to maintain very different penetration force levels. A ***compensation rule***, based on the force constancy hypothesis, is proposed.

(iii) How effective is our proposed compensation rule (Exp. III)? We demonstrate that subject's ability to discriminate surface heights can be manipulated by changing the difference in probe-tip position inside two adjacent surfaces. This was accomplished by manipulating the relative height and stiffness between two surfaces.

2 General Methods

In this section, we describe experimental methods that are common to the three experiments. Experiment-specific details are presented later when the corresponding experiment is discussed.

2.1 Apparatus

A PHANToM force-feedback device (Desktop model, SensAble Technologies, Inc., Woburn, MA) was used for rendering virtual surfaces. The GHOST software development kit and the OpenGL library were used for generating the haptic stimuli and visual scenes.

2.2 Subjects

Three subjects (two males and one female) participated in all three experiments. All subjects are right-handed and did not report any known sensory or motor abnormalities with their hands or arms. The subjects are experienced users of the PHANToM device. We found it necessary to employ experienced users because some of the experimental conditions required the subjects to maintain a consistent interaction pattern.

2.3 Stimuli

The haptic stimuli consisted of two planes, one on the left (P_1) and the other on the right (P_2). The relative height offset of the two planes, defined by $\Delta h = h_2 - h_1$, and the associated surface stiffness, denoted by k_1 and k_2, were manipulated as the independent variables. Furthermore, the planes were rendered as vertical walls (like a relief sculpture). A larger h value meant that the plane was closer to the user (see Fig. 3). By rendering vertical surfaces, we took advantage of the relatively larger workspace in the xy (vertical) plane than in the zx (horizontal) plane and eliminated the effect of gravity.

One important detail of the haptic stimuli concerned the vertical line separating the two disjoint planes. The step change in the surface height resulted in a step change in the feedback force when the PHANToM probe crossed the boundary. This "glitch" was easily perceived by the user, and served to indicate a difference in surface height (i.e., $\Delta h \neq 0$) regardless of whether the user could perceive the difference in h_1 and h_2. To circumvent this problem, we used a Hanning window (a half-cycle sinusoidal function) to smoothly connect the two planes at heights h_1 and h_2 (see the region between the two dashed lines in Fig.3). When the probe tip was inside the region between the dashed lines, the height and stiffness values were interpolated using Eqns. (2) and (3):

$$h = 0.5\times(h_2-h_1)\times\sin(\pi\cdot\Delta x/W) + 0.5\times(h_1+h_2) \quad (2)$$

$$k = 0.5\times(k_2-k_1)\times\sin(\pi\cdot\Delta x/W) + 0.5\times(k_1+k_2) \quad (3)$$

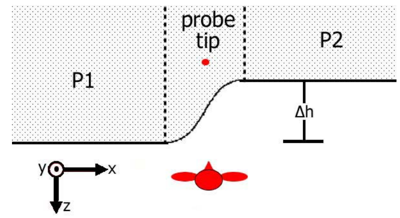

Figure 3. Top view of haptic stimulus consisting of two vertical planes. The x-distance between the two dashed lines is 4 mm.

where Δx was referenced to the center of the interpolation region, and W was the width of the region (4 mm).

The visual scene used in all experiments served to provide a spatial reference to the probe position without revealing the independent variables Δh, k_1 and k_2. Two blocks represented the beginning and end points for each stroke of the haptic stimuli (Fig. 4). The subjects were instructed to move the probe towards the left block until the block turned from red to green, indicating the beginning of a trial. Once the probe tip entered a ± 5 mm band along the y-axis (centered around the line connecting the centers of the two blocks shown in Fig. 4), the (gstPhantom *) → setEffect(constraintEffect) function was used to constrain the probe's motion to the zx plane. The subject then stroked the virtual surface from left to right until the probe tip hit the right block. The color of the right block then turned red to indicate the end of the current trial.

3 Exp. I: Surface Height Discrimination

The purpose of the first experiment was to estimate the threshold for surface height discrimination. This threshold determines the smallest height difference between two adjacent planes that can be reliably perceived by a user. The threshold value estimated from Exp. I was subsequently used in the design of Exp. III. In order to investigate whether the threshold depended on surface stiffness, two stiffness values were used in Exp. I.

3.1 Procedure

A three-interval forced choice (3IFC) one-up three-down adaptive method was used to estimate surface height discrimination threshold [5]. On each trial, the subject made three left-to-right stroking motions (three intervals) to judge whether the two vertical planes were of the same height. During one randomly-selected interval, two uneven surfaces ($h_1 \neq h_2$) were presented. During the other two intervals, two equal-height surfaces ($h_1 = h_2$) were presented. The subject's task was to indicate which interval contained two uneven surfaces by entering the number "1", "2" or "3" on a keyboard (forced choice). The initial value of Δh was set to $h_2 - h_1 = 3$ mm. This

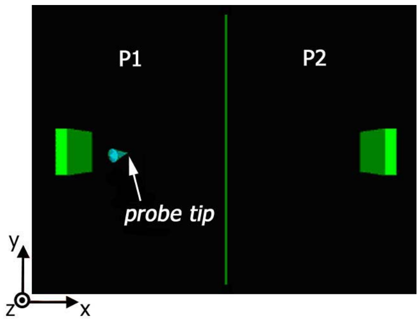

Figure 4. The visual scene used in our experiments. The probe tip position is indicated by the (blue) cone. The (green) vertical line indicates the location of the common border between the two planes.

value was found to be clearly perceivable by all three subjects. The Δh value was increased every time the subject made an incorrect response (one up), and was decreased only after three consecutive correct responses (three down). Thresholds obtained this way correspond to the 79.4% percentile point on the psychometric function [6]. The value of Δh was initially changed by 4 dB, and then by 1 dB after the first three reversals (reversal = when the Δh value changed from increasing to decreasing, or vice versa). An experimental run was terminated after twelve reversals at the 1 dB level. The stiffness values of the two planes were kept the same (i.e., $k_1 = k_2$) at all times. Two stiffness values were used to determine the extent to which height discrimination threshold depended on stiffness. The chosen stiffness values were 0.4 N/mm (for a relatively soft surface) and 1.0 N/mm (for a relatively hard surface without inducing instability [7]).

3.2 Data Analysis

To obtain a threshold value, the average of the Δh values at the last 12 reversals was taken. To estimate the standard error of the estimate of the threshold, 6 estimates of the threshold were calculated from the 6 pairs of the 12 reversals, and the corresponding standard error was obtained (see [8], p. 1550, 2nd column, for details).

3.3 Results and Discussion

The surface height discrimination thresholds for three subjects are shown in Table 1 along with the standard errors. These thresholds were in the range 0.17–0.63 mm for the two stiffness values tested. The average thresholds obtained with stiffness 0.4 and 1.0 N/mm were 0.56 and 0.30 mm, respectively, indicating a higher sensitivity to surface height difference when the surface stiffness increased. This dependence on stiffness was consistent with the subjective impression that stiffer surfaces were perceived to be crisper and better defined in space.

Table 1. Surface height discrimination thresholds.

Subject	threshold ± standard error (mm)	
	$k_1 = k_2 = 0.4$ N/mm	$k_1 = k_2 = 1.0$ N/mm
S1	0.47 ± 0.04	0.17 ± 0.04
S2	0.63 ± 0.03	0.37 ± 0.01
S3	0.59 ± 0.03	0.37 ± 0.04
Average	**0.56 mm**	**0.30 mm**

These thresholds are much smaller than the length discrimination thresholds reported by Durlach *et al.* (roughly 1 mm for reference lengths of 10 to 20 mm) [9]. In their study, subjects placed the thumb and the index finger at the two ends of an apparatus modified from a vernier caliper. While those subjects judged length by the perceived spacing between the tips of the thumb and index finger, our subjects based their judgments on the perceived position of the PHANToM probe tip through a moving arm anchored at the elbow. One might expect the subjects in the Durlach *et al.* study to show a lower threshold because finger movements were anchored at the web between the thumb and the index finger rather than at the elbow. However, those subjects had to remove their hands from the vernier-caliper device while it was being adjusted between trials. This loss of a reference might have contributed to the higher threshold.

4 Exp. II: Force Constancy

The purpose of the second experiment was to examine the extent to which an experienced user of the PHANToM haptic interface maintains a constant penetration force while exploring surfaces of different height and stiffness values. While the idea of force constancy appeared to be an intuitive one (see our earlier discussion of this idea in the Introduction), it nevertheless needed to be tested empirically.

4.1 Procedure

Subjects were instructed to stroke the vertical planes in a consistent manner. Penetration depths were recorded for ten stiffness values ranging from 0.1 to 1.0 N/mm in 0.1 N/mm increment. As in Exp. I, the stiffness of the two planes was kept the same at all times (i.e., $k_1 = k_2$). The surface height was also kept constant ($h_1 = h_2$). The order of the ten stiffness values was randomized for each subject. For a given stiffness value, the subject repeatedly stroked the surface until 15 seconds of data had been collected. The penetration depths were recorded at 1 kHz whenever the probe tip was inside the surface.

4.2 Data Analysis

For each 15-second record of penetration depth data, the average and standard deviation were calculated. According to the force constancy hypothesis, penetration depth (D) would vary with surface stiffness (K) so that the penetration force (F_p) remained constant; i.e., $D = F_p/K$ (ref Eqn. 1). To the extent that the D vs. K data points followed a reciprocal relationship, we would conclude that the subjects indeed tried to maintain a constant penetration force in their haptic exploration patterns. Therefore, for each subject, we took the ten average penetration-depth data points (with the associated stiffness values) and estimated F_p by finding a constant that produced the least square error, using the standard deviations of the data points as weights. Alternatively, we also estimated penetration force at each stiffness value as K∗D, and then fitted the resulting force vs. stiffness curve with the aforementioned weighted least squares method.

4.3 Results and Discussion

The results are shown as penetration depth vs. stiffness curves (Fig. 5) and as penetration force vs. stiffness lines (Fig. 6), with the associated best-fitting curves/lines. From Fig. 5, it is clear that for each subject, penetration depth decreased as surface stiffness increased. The standard deviations followed the same decreasing trend as stiffness increased, indicating that it was easier to maintain a consistent penetration depth when the surface was stiffer. Also shown in Fig. 5 are the individual best-fitting curves using $D = F_p/K$. The r.m.s. error averaged over the three subjects was 0.67 mm, confirming a good fit between the data points and the curves. From Fig. 6, it appears that the average forces were more variable for softer surfaces but stabilized for harder surfaces. These results support our *force constancy* hypothesis, especially for surfaces with higher stiffness values.

It is clear from the data shown in Figs. 5 and 6 that the three subjects maintained different levels of penetration forces. From Fig. 5, the average force values were 1.15, 2.25 and 1.58 N for subjects S1, S2 and S3 respectively. Results from Fig. 6 were similar. We also note that the forces applied by the three subjects were considerably smaller than the maximum controllable forces for male or female users (see Table 3 in [10]).

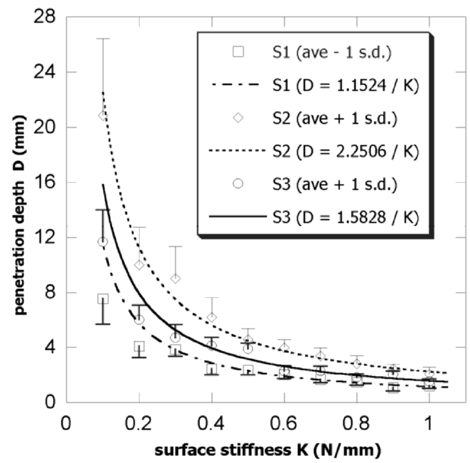

Figure 5. Penetration depth D vs. stiffness K for three subjects. Each symbol (square, diamond, or circle) represents the average penetration depth over 15 seconds for a given surface stiffness value. The error bars indicate the –1 standard deviations (for S1) or +1 standard deviations (for S2 and S3). Each line shows the best fitting curve based on the force constancy hypothesis. See text for further details.

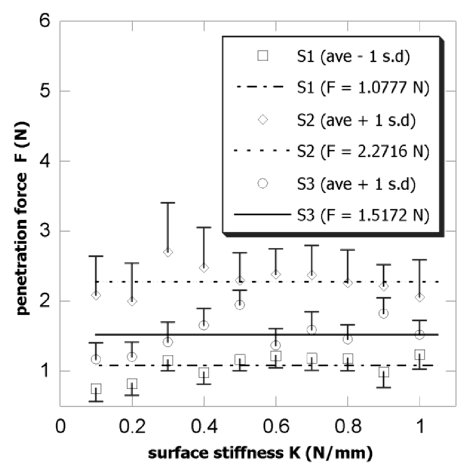

Figure 6. Penetration force F vs. stiffness K for three subjects, based on the same data as shown in Fig. 5. See text for further details.

5 Exp. III: Towards a Compensation Rule

An immediate consequence of the force constancy hypothesis is that the probe tip follows the virtual surface topography only if stiffness remains constant over the whole surface (e.g., Fig. 1). Otherwise, the trajectory of the probe tip is not parallel to the surface topography, and therefore the perceived surface profile based on probe tip position is no longer accurate (e.g., Fig. 2). What, then, can we do to ensure that the solid and dashed lines in Fig. 2 are *always* parallel? We can change the surface height map $h(x,y)$ and/or the stiffness map $k(x,y)$. The problem with changing the stiffness map is that it will change the perceived surface stiffness (hardness), especially when a user taps the surface. Given that the user does not have direct access to the solid line in Fig. 2, we propose the alternative method of modifying $h(x,y)$ so that a surface rendered with the new height map $h'(x,y)$ and the original stiffness map $k(x,y)$ produces a probe-tip trajectory that is parallel to the original height map $h(x,y)$. To fix ideas, let's use the example shown in Fig. 2 and assume that

F_p user's preferred penetration force level

k_m stiffness of mica surface

h_m height of mica surface

p_m probe-tip position inside mica

k_h stiffness of halo surface ($k_h < k_m$)

h_h height of halo surface

p_h probe-tip position inside halo

h'_h height of halo surface, *modified*

It follows that

$$h_m - p_m = F_p/k_m \quad \text{(penetration depth inside mica)} \quad (4)$$

and

$$h_h - p_h = F_p/k_h \quad \text{(penetration depth inside halo).} \quad (5)$$

It is our goal that

$$p_h - p_m = h_h - h_m \quad \text{(parallel dashed and solid lines).}$$

This can be accomplished by modifying h_h such that

$$(h'_h - F_p/k_h) - (h_m - F_p/k_m) = h_h - h_m$$

Or equivalently,

$$h'_h = h_h + (F_p/k_h - F_p/k_m) \quad (6)$$

In other words, we increase the height of the halo surface by the difference in penetration depth due to the different mica and halo stiffness values, so that p_h is above p_m by exactly ($h_h - h_m$). This ***compensation rule*** for the halo surface height is illustrated in Fig. 7.

In Eqn.(6), the correction term for the halo surface height, $h'_h - h_h$, depends on the stiffness of the two adjacent surfaces (k_h and k_m) as well as the user's chosen penetration force (F_p). The fact that different users tended to maintain different force levels makes it necessary to design compensation rules that are tailored to each user's individual F_p values.

The purpose of the third experiment was to test the feasibility of the proposed compensation rule based on the force constancy hypothesis. We hoped to demonstrate that changing either the surface height map $h(x,y)$ and/or the stiffness map $k(x,y)$ affects subjects' ability to discriminate the relative heights of two surfaces.

5.1 Procedure

A one-interval two-alternative forced-choice (1I-2AFC) paradigm was used in Exp. III. There were two possible stimulus alternatives: P_1P_2 (P_1 was presented on the left and P_2 on the right) and P_2P_1 (P_2 was presented on the left and P_1 on the right). On a given trial, the subject was presented with either the P_1P_2 or the P_2P_1 configuration, but not both (one interval). The subject's task was to indicate whether the right-half of the vertical surface was higher or lower (forced-choice).

Three sets of surface parameters were used in this experiment (Table 2). Surface P_2 was always 2 mm

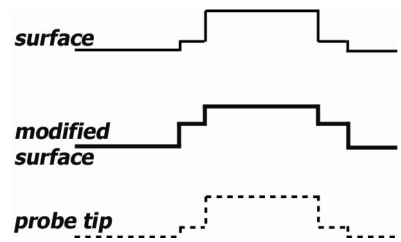

Figure 7. Illustration of the compensation rule. The original surface profile (top solid line), *h(x,y)*, was modified according to Eqn. 6 so that the surfaces corresponding to the halo region in Fig. 2 were raised (middle thick line). When subjects interacted with this modified surface profile, *h'(x,y)*, the probe tip followed a trajectory (bottom dashed line) that was parallel to the original surface profile *h(x,y)*.

Table 2. Surface parameters used in the three conditions in Exp. III. Note that k_2 was the only variable that varied across conditions. The last row Δp predicts the *perceived* surface height difference based on probe-tip positions. See text for further details.

Parameter	Condition		
	C1	C2	C3
k_2 (N/mm)	0.290	0.333	0.392
k_1 (N/mm)	0.6		
F_p (N)	1.5 ± 0.3		
$\Delta h = h_2 - h_1$ (mm)	2 mm		
$\Delta p = p_2 - p_1$ (mm)	**– 0.67**	**0.00**	**0.67**

higher than P_1 in its height. This value of Δh was much higher than the thresholds obtained in Exp.I. Therefore, the subjects were expected to judge P_2 as higher on all trials. However, k_2 was always lower than k_1. According to the force constancy hypothesis, if P_2 was softer than P_1, then the probe tip would penetrate deeper into P_2. Depending on the relative values of k_1 and k_2, it was conceivable that the probe tip may move away from the subject as the probe stroked from P_1 to P_2. This would result in the (incorrect) perception that P_2 was lower than P_1. The parameters shown in Table 2 were carefully designed to test whether such a reversal in perception would occur. Specifically, the last row in Table 2 shows the calculated difference between probe-tip positions inside P_1 and P_2, with a positive value indicating that P_2 would be perceived as higher than P_1 (see Eqns. 4 and 5). We chose parameters that resulted in a Δp value that was larger than the thresholds measured in Exp. 1, but not too large to make the discrimination task trivial for the subjects. We predicted that subjects would judge P_1 to be higher in condition 1 (C1), and P_2 to be higher in condition 3 (C3). We also predicted that subjects would perform at a chance level in condition 2 (C2), since the probe-tip would remain at nearly the same position across the two planes.

While it was straightforward to implement the values of k_1, k_2 and Δh, the subjects had to cooperate in order to produce the target penetration force of 1.5 N. This was accomplished by providing visual feedback for three force ranges: below 1.2 N, between 1.2 and 1.8 N, and above 1.8 N. The ±0.3 N force tolerance range was based on our earlier work on human users' ability to control force output (see Table 4 in [10]).

Three 100-trial runs were conducted per condition and per subject. The order of the nine experimental runs (3 conditions × 3 100-trial runs) was randomized for each subject. Training with correct-answer feedback was provided for each subject. No feedback was available during data collection.

5.2 Data Analysis

Experimental data were summarized as a 2-by-2 stimulus-response matrix. The rows corresponded to the two stimuli (P_1P_2 and P_2P_1), and the columns corresponded to the two responses ("right plane felt higher", "right plane felt lower"). For each subject and each experimental condition, we pooled the 300 trials into one matrix and calculated the sensitivity index d' and response bias β (see [11] for details on data processing). With this setup, a positive d' indicated that the subjects judged P_2 to be higher than P_1, a small d' (≈0) indicated that they could not discriminate P_2 from P_1, and a negative d' indicated a reversal in perception. Since the response biases were relatively small, they are not reported here.

One reason for the relatively large number of trials collected per condition (300) was to obtain a good estimate of the standard deviation of the d' estimates. We used the following formula to estimate $\sigma_{d'}$:[3]

$$\sigma_{d'} = \sqrt{\sigma^2_{z(H)} + \sigma^2_{z(F)}}$$

where

$$\sigma_{z(F)} = \sqrt{\frac{2\pi F(1-F)}{N_1}} \cdot e^{0.5[z(F)]^2} \text{, and}$$

$$\sigma_{z(H)} = \sqrt{\frac{2\pi H(1-H)}{N_2}} \cdot e^{0.5[z(H)]^2}$$

5.3 Results and Discussion

The results are shown in Fig. 8 in a bar graph. The general trend of the data was exactly what we had

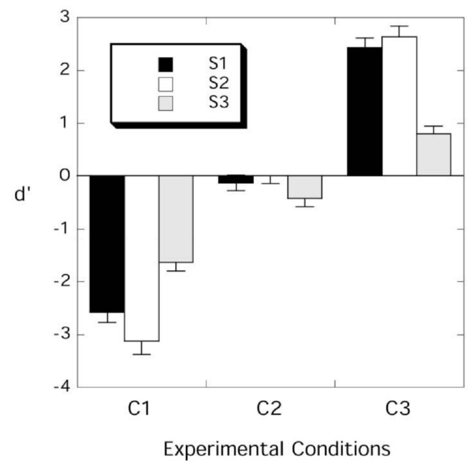

Figure 8. Sensitivity index for the three experimental conditions tested in Exp. III along with error bars.

predicted. In condition 1 where Δp was negative, all subjects showed a large negative d' indicating that the subjects were able to discriminate the two adjacent planes but the higher plane (P_2) was judged to be lower (like the halo region shown in Fig. 2). This was the result of the relatively small k_2 value used in C1 (i.e., the higher plane P_2 was too soft). In condition 2 where Δp was 0, d' was close to 0 indicating that the subjects could hardly discriminate the height of the two surfaces. In condition 3 where Δp was positive, all subjects produced a positive d' indicating that they were able to perceive P_2 as being higher in a consistent manner. These results clearly demonstrated that the perceived relative height of two adjacent planes was not entirely determined by their surface profile (Δh) alone. The perception depended on the relative stiffness of the planes as well. This conclusion is consistent with the force constancy hypothesis. Furthermore, the data support the feasibility of a compensation rule based on the manipulation of surface height and/or stiffness values in order to achieve a target percept of surface topography.

It can be readily observed from Fig. 8 that subject S3 produced a relatively small d' in condition 3. Post-experiment debriefing revealed that S3 tried to maintain a constant stroking velocity, in addition to maintaining a constant penetration force. In an attempt to understand S3's performance, we examined penetration forces based on recorded (x, y, z) positions from several strokes for subjects S1 and S3. It seemed that both subjects were able to maintain a penetration force within the 1.5±0.3 N range. It was therefore unclear why S3's discrimination performance was relatively poor in C3.

6 Conclusions and Future Work

The main conclusions to be drawn from this work are (1) our perception of surface topography can be distorted

[3] For definition, derivation and assumptions, see psychophysics course notes developed by Tan and Pizlo at http://shay.ecn.purdue.edu/~ee595tp/lectureNotes2002/pp092402.pdf

when both surface height and surface stiffness vary in a haptically rendered environment; (2) this phenomenon can be explained by the hypothesis that users interact with a virtual surface by maintaining a constant penetration force (as supposed to a constant penetration depth); and (3) the distortion in perception can be compensated for if we know the penetration force exerted by the user and the virtual surface parameters.

The significance of this work lies in the fact that increasingly complex virtual environments are being rendered haptically for scientific data perceptualization, medical simulation and teleoperation. It is important for the designer of the haptic virtual environment to be aware of the interplay of object parameters that can result in distorted perception of these properties. Our work is a first step towards more perceptually accurate haptic representation of object properties.

To the extent that our force constancy hypothesis is true, our future work will focus on incorporating appropriate compensation rules into haptic rendering of virtual objects. The challenge lies in the fact that different users tend to use different penetration forces when interacting with a virtual surface, and it is also conceivable that the same user might adopt different force levels from session to session. A successful compensation rule will therefore have to take into account the penetration force employed by a user for a given application at a given time. It is possible that a valid compensation rule may not be obtainable, unless certain environmental factors (e.g., penetration force and stroking velocity) are constrained.

Finally, our work underscores the importance of the role played by haptic manipulation during haptic sensing. Increasingly, designers of haptic virtual environments need to understand how humans optimize sensing through appropriate actuation. We will explore how to incorporate the findings reported by Lederman & Klatzky [12] into the haptic rendering of scientific data such as those on nanostructures measured with an AFM.

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