Interaction of Visual and Haptic Information in Simulated Environments : Texture Perception

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ABSTRACT
This paper describes experiments relating to the perception of the roughness of simulated surfaces via the haptic and visual senses. Subjects used a magnitude estimation technique to judge the roughness of "virtual gratings" presented via a PHANToM haptic interface device, and a standard visual display unit. It was shown that under haptic perception, subjects tended to perceive roughness as decreasing with increased grating period, though this relationship was not always statistically significant. Under visual exploration, the exact relationship between spatial period and perceived roughness was less well defined, though linear regressions provided a reliable approximation to individual subjects' estimates.

INTRODUCTION
It is generally the case that our perceptions of the world arise as a combination of correlated input across several of the senses. Our experiences are not based upon selective stimulation of certain receptors, as may arise in a laboratory situation. Consider the act of haptically exploring an object. Touching an object's surface often simultaneously yields information regarding the compliance, texture, shape and heat conductive qualities of the object. The touching process may also be perceived aurally, for example, a tap or scrape, and is usually supported by visual stimulus regarding the object's global structure and surface properties. Indeed, it is this correlative information that has led researchers to hypothesise that touch is more of a "reality sense" than the other four human senses (Taylor, Lederman & Gibson, 1973). In truth, it is likely not only the touch sensations themselves that give rise to this impression of "reality", for as our simple example has shown, several other senses are intrinsically involved. Our perception of something touched as being somehow more "real" may also be a result of the fact that, historically, sensory illusions have rarely appealed to the sense of touch. Visual illusions have existed in some form for centuries, from sleight of hand tricks to modern day computer generated cinema images. Audio signals are readily stored and reproduced with a high clarity. Yet, touch sensations have proved impossible to replicate until the advent of haptic interfaces. Even with the current state of available technology, we are limited to simulations of "remote" contact via a probe or intermediary link, rather than direct stimulation of the fingerpads.

Information regarding object properties has been shown to be differentially salient under conditions of pure haptic exploration, and haptic and visual exploration. When visual information is readily available, global shape and structural cues become the defining properties of an object. Conversely, under purely haptic exploration, material cues such as texture and compliance have a greater significance. It was hypothesised that this was a result of the ease of encoding these properties (Klatzky, Lederman & Reed, 1987). Thus, shape information is easily extracted by visual means, whereas to gather this information haptically requires execution of the "contour following" exploratory procedure (EP) (Lederman & Klatzky, 1987), which puts a large demand on the observer's memory for integration of temporally varying signals, and is also time consuming to perform. In contrast, the optimal EPs for extraction of compliance and texture - pressure and lateral motion, respectively, are simple and fast to execute.

However, despite the apparent importance of material qualities under haptic exploration, there is scant provision in current interfaces for texture representation (Wall & Harwin, 2000).Thus, low bandwidth haptic interfaces necessitate that the operator adopts a "visually-mediated" method of object identification. That is to say, that performance must rely on visual stimuli provided by a suitable display (e.g. monitor, headset), or that the user must haptically gather information regarding object properties that are more readily encoded by vision, such as size and shape. However, even this method is obviated, as typical interfaces operate on a principal of point interaction, which places considerable constraints on performance of contour following EPs and totally occludes enclosure. It has been shown that exploration via a probe is deleterious in tasks requiring the extraction of large scale geometric data, in terms of response times (Klatzky & Lederman, 1998).

What are the implications of these facts for haptic interface technology? Given the bewildering level of sensitivity in the human cutaneous system, it seems unfeasible at present to suggest a mechanical skin interface that can relay information regarding object material properties.

Currently, we can only strive to provide perceptual impressions that are merely discriminable (Fritz & Barner, 1996), or else provide simulation of object properties, such as roughness, rather than exact tactile replicas of real life materials. Most haptic interface applications, with the obvious exception of those designed for the visually impaired, seem to be augmented by visual feedback. To remove the visual interface would render the application useless, in most cases. It is evident, in their present state of development, haptic interfaces are dependent on existing HCI devices, such as the monitor, and to a much lesser extent, audio cues. However, given that interactions in the real world often incorporate information from several sensory modalities, this does not seem an unjust criticism. Despite this, until provision is made for greater accessibility to object properties, haptic interfaces will be largely dependant on existing HCI devices. Indeed, individual difficulties are often encountered in purely haptic simulations (Jannson et al, 1999, West & Cutkosky, 1997), and qualitative differences in perception between subjects is not uncommon.

This paper describes experiments relating to the perception of simulated textures using both the visual and haptic senses. Experiments are described pertaining to the perception of the roughness of "virtual gratings" displayed using a PHANToM haptic interface, and a graphical representation. The study aims to assimilate any differences in the method by which roughness is perceived between the visual and haptic senses in a virtual environment. We first consider the relevant cues by which roughness is perceived in real and simulated environments.

PERCEPTION OF ROUGHNESS

The relevant literature regarding perception of roughness can be subdivided in to three categories. Bimodal perception is concerned with perception of real textures via visual and haptic channels simultaneously. Remote contact, as opposed to direct contact with the fingerpad, involves perception via a probe, finger sheath or other rigid link. It is possible to draw a direct analogy between sensations encountered in this mode, and when using a haptic interface. Finally, perception of roughness in a simulated environment is discussed.

Bimodal perception

During the development of haptic applications, there has been little study with regards to the interaction of the various senses and their effects on perception, though some research exists concerning the effects of audio and visual cues on stiffness perception(Srinivasan, Beauregard & Brock, 1996, DiFranco, Beauregard & Srinivasan 1997).

Several studies have addressed this issue in the real world. Early studies (Rock & Victor, 1964, Rock & Harris, 1967) implied that vision was somehow superior to touch. However, these results focussed on perception of object shape, which is necessarily image mediated due to the difficulties inherent in extracting this information haptically. Similar studies on intersensory conflict during perception of texture (Lederman & Abbott, 1981) showed that, when conflicts in the visual and cutaneous senses arose, the overall perception experienced by the subject was of a comprise between the two senses. It is not the case that one sense dominates the other, as an impression of roughness is easily obtainable by both the haptic and the visual sense, thus, one sense does not take a precedence over the other. The two above examples illustrate that there is no strict hierarchy to the senses, and one is not necessarily more "significant" than the others. The relative importance of sensory information is dictated by the properties we are searching for in an object, and the prevailing exploratory conditions.

Heller (1982) describes a series of experiments investigating the interaction of visual and haptic senses in perception of surfaces. Vision and touch produced similar levels of accuracy in the perception of roughness, however, bimodal perception proved to be superior for texture judgements. It was proposed that vision aids the perception of roughness by allowing an active explorer to guide their hand movements in a more efficient manner.

Remote contact

It has been proposed (Lederman & Klatzky, 1998) that probe exploration in the real world represents a very simple form of teleoperator system acting on a remote environment, therefore the psychophysical data obtained regarding intermediary links has especial relevance to the design of haptic interfaces and teleoperation systems.

During direct haptic exploration with the fingerpad, spatially distributed cues provide the main percept for subjects' judgements of surface properties (Lederman & Taylor, 1972). However, when exploring a remote environment, spatially distributed cues on the fingerpad do not correspond to the surface geometry at the distal point of the interface, rather, they correspond to the geometry of the probe itself. The user is therefore forced to adopt vibrational cues transmitted via the probe or link in order to make judgements regarding the properties of the surface (Kontarinis & Howe, 1993). Katz concluded that it is possible to judge the roughness of a surface with the same accuracy while using a probe as when using direct contact with the fingertip (Krueger, 1970). Performance was greatly deteriorated when the probe was "damped" using a cloth. Lederman, Klatzky and colleagues performed a series of investigations regarding the psychophysical effects inherent in remote contact. Subjects estimated the "perceived roughness" of surfaces by indicating a quantitative numerical estimate of the magnitude. It was observed that subject's estimates of perceived roughness decreased with increased inter-element spacing. An increase in contact diameter of the probe used caused a corresponding decrease in perceived roughness. When the speed of exploration was varied, an increase in speed correlated with a decrease in perceived roughness. For small inter-element spacing, roughness estimates were also larger with probes than with the bare finger, though it was also confirmed that roughness discrimination is improved using direct compared to remote contact. This was attributed to the differences in neural responses to surface characteristics during the two modes of contact. Direct contact facilitates provision of spatially intensive coding of surfaces contacting the fingerpad. However, for remote contact, spatial variation of signals on the fingerpad does not correspond to surface geometry at the distal point of the probe, hence, the primary method of encoding surface properties is via vibratory signals transmitted through the probe i.e. a temporally varying signal. Observations showed that performance using a rigid finger sheath was considerably below that achieved with more probe-like intermediary links, which are closer to the finger in terms of supporting discrimination accuracy. This was possibly a result of the larger contact area afforded by the rigid sheath. To concur with this, magnitude estimations of roughness with the rigid sheath were highly linear and had no downturn. However, the perceived roughness would be expected to drop if sufficiently wide inter-element spacing were introduced to the test stimuli.

Perception of simulated surfaces

Jansson et al (1999) showed that the PHANToM can be used to display "virtual sandpapers" by modelling the normal and tangential forces recorded during exploration of a real sandpaper. Perceived roughness was unanimously greater for the virtual sandpaper for all grit values employed in the investigation. The difference, however, did not appear to be significant, though it was inferred that it may prove to be so should a greater number of test subjects be employed. The results showed that the real and virtual sandpapers were perceived in a similar fashion. In a related test using an Impulse Engine (www.immersion.com), both blind and sighted subjects estimated the roughness magnitude of virtual gratings with a sinusoidal profile. The spatial period of the gratings ranged from 0.375 to 1.5mm, with a fixed amplitude of 0.0625mm. There was a highly significant relationship between the perceived roughness magnitude of the virtual surface and its spatial period. The majority of the participants perceived wider groove widths to be rougher, although some perceived the narrower groove widths as rougher. All the blind participants showed a meaningful relationship between spatial period and roughness, but only 5 of the 13 sighted subjects showed a significant relationship. Thus, it was concluded that the virtual surfaces employed in the study were only suitable for visually impaired users.

Minsky and Lederman (1996) investigated the perception of surface textures using only lateral forces with a 2 degree of freedom (D.O.F.) joystick, using the "sandpaper" system, whereby the users hand is pulled towards low areas and away from high areas on a texture height map, using virtual spring forces (Minsky et al, 1990). The amplitude of surface features was varied between 0.7 and 10mm, and lateral forces from 18 to 382g. Perceived magnitude of roughness was predicted almost entirely by the amplitude of the lateral force exerted on the subject's hand. There was no significant variation of estimated roughness with grating feature size.

Siira and Pai (1996) describe a stochastic method in which textures are approximated by a Gaussian distribution, the parameters of which are dependant on measured surface properties. Given restrictions imposed on computation time, and the limits of human tactile perception, it was deemed that a realistic approximation of surface texture may produce the desired psychophysical impression. A virtual surface was implemented combining normal constraint forces with normal and tangential texture impulses. It was observed that a higher variance of Gaussian distribution gave a higher estimate of perceived roughness.

Fritz and Barner (1996) reproduced Gaussian texture effects in 3D using a PHANToM. It was found that simple textures could be rendered from a multivariate probability density function (PDF, e.g. Gaussian, uniform), and that by combining a number of PDFs, more complex surfaces could be portrayed. Perceived roughness of simulated surfaces increased with increasing variance of the Gaussian distribution.

West and Cutkosky (1997) described experiments investigating the point at which individual peak or valley features on a sinusoidal surface gave way to an overall sensation of "roughness" or "smoothness". At higher frequencies, performance was improved by using a stylus, as opposed to the fingerpad. It was surmised that this was due to the fact that the stylus could fall between features that are too small for the fingertip. It was noted that average error rates were higher for virtual walls than for physical walls, especially at low amplitudes. It was concluded that in order to improve performance at low amplitude and high spatial frequency it would be necessary to improve the bandwidth of the haptic device employed.

Summary

It is clear that perception differs in the three modes considered. Relationships between perception and the simulated properties of virtual surfaces are less well defined than their real life counterparts, however, investigations have focussed purely on haptic perception of these surfaces. The following section describes an experiment investigating both visual and haptic perception of a simple, simulated surface.

EXPERIMENTAL PROCEDURE

The subjects employed in the investigation were 12 students from the University of Reading, 11 male and 1 female, aged between 22 and 27. Subjects were presented virtual gratings of a sinusoidal profile under two stimulus conditions, "haptic" and "visual". In the haptic condition, the gratings were displayed using a PHANToM haptic interface. In the visual mode, a graphical representation of the virtual environment and the gratings were displayed on a standard monitor.

During each iteration of the test, the subject was presented with 2 virtual gratings on the "wall" of the workspace. The gratings were vertically aligned, and each constituted an area of height 30mm and length 100mm. There was a 30mm vertical gap between the two gratings, such that the user could readily distinguish between the two.

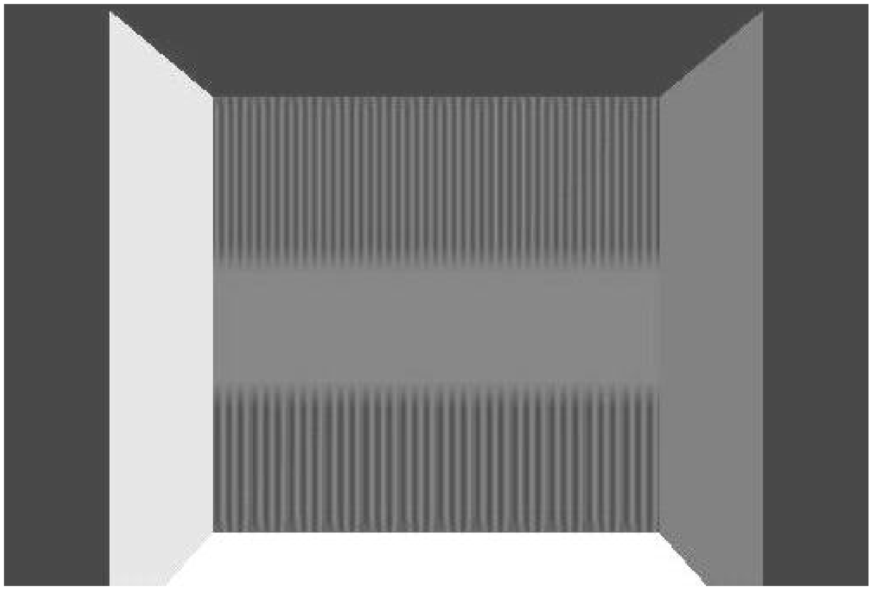

Figure 1. Sample visual environment. Top grating is standard, spatial period = 2mm. Lower grating is test, with spatial period = 2.5mm.

The uppermost grating was the "standard" surface, and remained at a constant spatial period of 2.0mm throughout the whole investigation. The lower grating was the "test" surface. The spatial period of the test surface varied between 0.5 and 3.5mm, in increments of 0.125mm, this giving a test set of 25 surfaces. Each test surface was presented once per subject in each stimulus condition. The surfaces were randomly ordered during each of the tests. The height of the sinusoidal profiles was 2.5mm peak to peak.

In the haptic condition, gratings were represented by checking for collisions with a sinusoidal surface of the appropriate height and spatial period. In the visual mode, the gratings were represented as textures defined in 2D, using an RGB scale. The R and G values were constant, whereas the B value was dependant on the height of the grating profile. A sample virtual environment is illustrated in Figure 1.

The magnitude estimation technique was used to assess the perceived roughness of the gratings. Subjects were instructed to assign the standard surface 100 roughness units, and were asked to provide a number for each test surface the represented the perceived roughness relative to the standard.

RESULTS

The spatial period and roughness magnitude estimate data for each subject was converted to logarithmic scales and a linear regression analysis was then performed. The results are summarised in Table 1, for the haptics mode and Table 2 for the visual mode. The tables show the x-coefficient fof the linear regression calculated for each subject, which corresponds to the slope of the graph, the standard error for this value, and the t-stat and P-value, corresponding to the statistical analysis of the significance of the results.

For the haptics condition, 3 of the 12 subjects did not display a significant relationship between spatial period and roughness magnitude. However, all the subjects showed a significant relationship when the visual stimulus was employed. Using haptic cues, 2 of the subjects had a positive co-efficient, thus, roughness increased with spatial period, however, for the remaining 10 subjects, the co-efficient was negative, indicating that roughness increased for narrower groove widths. In the visual modality, the split was more equal, with 7 out of the 12 subjects showing a positive co-efficient, which included the 2 subjects who displayed this trend in the haptics condition.

Discussion

It is evident from the differences in the results that the nature by which roughness is perceived under visual and haptic exploration differs, given the constraints imposed by the equipment and simulated environment that has been employed in the current investigation. Positive and negative co-efficients for haptic roughness magnitude estimates related to spatial period has been noted in a previous study (Jansson et al, 1999), so it is therefore poignant that this effect should also occur under visual exploration, aswell.

It is hypothesised that the main reason for these discrepancies in perception is that the representation of the surfaces employed in the study, in both the visual and haptic mode, are both approximations to real life surfaces, rather than exact physical replicas. The most obvious example of this is that all perturbations due to the gratings in the haptic condition are normal to the surface, whereas a real surface would also provide some frictional components tangential to the surface. Also, auditory and thermal cues are omitted, which could also provide some cues as to the nature of the surface.

	X - Coefficient	*Standard Error*	*t Stat*	*P-value*
Subject 1	1.218	0.183	6.647	8.8E-07
Subject 2	-1.010	0.116	-8.702	9.8E-09
Subject 3	-0.819	0.099	-8.259	2.5E-08
Subject 4	0.266	0.244	1.091	0.28678
Subject 5	-0.162	0.219	-0.740	0.46701
Subject 6	-0.556	0.050	-11.201	8.6E-11
Subject 7	-0.775	0.105	-7.413	1.5E-07
Subject 8	-1.172	0.201	-5.839	6E-06
Subject 9	-0.678	0.054	-12.511	9.6E-12
Subject 10	0.344	0.277	1.243	0.22643
Subject 11	-0.553	0.052	-10.597	2.5E-10
Subject 12	-0.647	0.083	-7.787	6.8E-08

Table 1. Summary of relationship between perceived roughness and spatial period during haptic perception.

	X - Coefficient	*Standard Error*	*t Stat*	*P-value*
Subject 1	1.113	0.223	4.998	4.69E-05
Subject 2	-0.788	0.125	-6.325	1.87E-06
Subject 3	1.352	0.278	4.862	6.57E-05
Subject 4	1.782	0.396	4.499	0.000162
Subject 5	-1.323	0.202	-6.539	1.13E-06
Subject 6	-0.462	0.067	-6.898	4.94E-07
Subject 7	-0.571	0.100	-5.716	8.04E-06
Subject 8	1.939	0.393	4.929	5.56E-05
Subject 9	1.003	0.211	4.759	8.49E-05
Subject 10	1.633	0.393	4.157	0.000381
Subject 11	-0.460	0.095	-4.847	6.82E-05
Subject 12	1.219	0.239	5.109	3.56E-05

Table 2. Summary of relationship between perceived roughness and spatial period during visual perception.

Subjects responses tended to agree on a negative co-efficient under the haptic condition. Lederman and colleagues modelled the relationship between perceived roughness and spatial period when exploring via a probe as a quadratic function, which showed an increasing perceived roughness over the spatial periods of interest. Lederman and Klatzky argued that “one possible reason for the shift (in relationship between spatial period and perceived roughness) might be due to the fact that as probe size increases, so too does the minimum value of inter-element spacing at which the probe can penetrate between the raised elements and drop down to the underlying surface". The PHANToM based simulation utilises a point interaction model of contact, thus, the user can always penetrate between the raised elements of the grating, within the resolution limits of the device. Hence, perception in the current study is equivalent to the downturn phase of the quadratic function.

It was unclear whether a positive or negative co-efficient was the dominant case for visual stimulus, however, all subjects showed a meaningful relationship between spatial period and corresponding roughness estimates. The discrepancies in the results likely arise due to the fact that roughness is infrequently judged using visual stimulus alone, without tactile information. As Heller (1982) stated, "people may have learned that visual texture does not provide reliable information about surface irregularities and consequently depend upon touch". Examples of this are a photograph, a painting, or a visual display unit.

CONCLUSION

To conclude the results presented in this paper, haptic perception of texture is important in simulated environments, as roughness is naturally a "haptically-mediated" dimension, that is to say, it is more easily encoded using the tactile senses. However, progress still needs to be made in order to develop superior models for textured surfaces, as inaccuracies in the simulated haptic sensations could account for the lack of a significant relationship between roughness and spatial period displayed by some subjects. Frictional cues and simulation of finite diameter (as opposed to point based) interaction models are two possible methods by which a more realistic representation may be achieved. There was a greater amount of disagreement with regards to the relationship between spatial period and perceived roughness during the visual simulation. However, subjects easily related the simulation to a roughness scale, as all subjects displayed a significant relationship between the surfaces physical parameter and estimated roughness.

The immediate future work pertaining to these results is to combine visual and haptic display in order to investigate the effects of bimodal perception. It is hypothesised that this will combine the benefits of both a significant linear relationship between spatial period, while helping to standardise subjects' responses to a negative co-efficient trend.

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