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Judging the Orientation of Sinusoidal and Square-Wave Virtual Gratings Presented via 2-DOF and 3-DOF Haptic Interfaces[1]

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ABSTRACT

The ability of observers to resolve the orientation of virtual gratings presented on two different haptic interfaces was investigated. Gratings were presented either with the 2-degree-of-freedom Immersion IE2000, or with the 3-degree-of-freedom SensAble Devices PHANToM. Results showed excellent resolution of both sinusoidal and square-wave gratings with both devices. Possible factors that may have influenced the results, such as force models, force vectors, and end effectors, are addressed.

INTRODUCTION

In human sensing and manipulation of everyday objects, the perception of surface texture is fundamental for both accurate identification and perceptual realism. The identification of everyday objects depends crucially upon texture information; for example, when sorting coins in one's pocket, one of the primary cues that distinguishes a dime from a penny is the ridged texture of the dime's outer circumference. It could also be argued that performance in a wide variety of tasks would be impaired if observers could discern object shape but not texture. For example, for a touch typist (such as the first author) who does not look at the keyboard while typing, a primary indicator that the thumb has contacted the track pad mouse on a laptop computer is the textural difference between the trackpad and the surrounding plastic. Without this cue, the typist might well need to look at the keyboard, losing time in the process. The importance of texture in everyday sensing has led to considerable interest in the mechanisms underlying texture perception in human observers.

Similarly, designers of haptic displays for virtual environment or telerobotic applications have attempted to provide textural information to users when conveying aspects of virtual objects, and have developed a variety of algorithms and hardware that can present a convincing simulation of surface textural features. Somewhat surprisingly, given earlier perceptual and physiological studies that argued for a spatial code in texture perception, three-dimensional haptic interfaces that provide point-source force feedback, such as the PHANToM (Sensable Devices, Inc.), are able to simulate surface texture with a surprising degree of fidelity. Even more surprisingly, devices that operate in only two dimensions, such as force-feedback joysticks, can also convey a convincing texture percept. The degree to which these devices actually do produce simulations that are convincingly "real" to the observer is a question of primary interest in our laboratory, and the goal of our longer-term research program. The present paper is an initial step in this program, and focuses on the resolution ability of human observers to discern differences in textural features of simulated surfaces. Although it does not address the question of perceptual realism directly, these data are needed for accurate simulation of surface texture. To the degree that simple point-source force feedback in a 3-DOF device, or forces exerted in the horizontal plane by a 2-DOF device, can be successful in simulating the perception of surface texture, some interesting questions arise regarding the physical stimulus that produces the percept of texture in human observers.

Equally important is the idea that, if such haptic interfaces do compel surface texture percepts that are indistinguishable from those generated by real surfaces, these interfaces can become a valuable research tool for researchers interested in human perceptual capabilities. In order to perform texture perception studies, researchers have been forced to rely on a selection of real surfaces to serve as stimuli. With a haptic interface, it may well be possible to present surfaces that vary in very small quantities, such as spatial frequency or amplitude, in a way that would be unwieldy with real surfaces. Further, haptic interfaces may permit researchers to investigate the perceptual aspects of surfaces that are not found in the physical world, and to vary multiple stimulus characteristics simultaneously in combinations that might not be possible with real surfaces. Finally, studying the perceptual response to simulated surface textures can provide information relevant to the modification and improvement of haptic interfaces. For all of these reasons, it is of considerable interest to investigate the perceptual aspects of stimuli generated by haptic interfaces.

Studies of texture perception with real and virtual surfaces

In designing hardware and software algorithms for haptic simulation of surface texture, knowledge of the stimulus cues that give rise to perceptually discriminable textures in real surfaces is crucial. This section briefly reviews the current state of knowledge of the psychophysics and physiology of texture perception, with an emphasis on concepts that are relevant for constructing convincing texture simulations.

The primary perceptual cue that permits observers to discriminate among textured surfaces is surface *roughness.* A combination of physiological recording from primary afferent fibers for mechanoreceptors in the hand and behavioral psychophysical measures has led Johnson and his colleagues (e.g., Blake et al., 1997a, b; Connor & Johnson, 1992; Johnson & Hsiao, 1994) to propose that the perception of surface roughness is mediated by slowly-adapting type I (SA-I) fibers conveying impulses from the Merkel disk receptor in the fingertips. The specific code is not average firing rate, however, but a measure of spatial variation in firing rate. Blake et al. (1997a) note that inputs from rapidly-adapting (RA) fibers might also play a role, but these might not do more than produce a mild inhibition of response. For very small surface spatial periods, such as those with interelement spacing less than 1 mm, Connor et al. (1990) suggested that some sort of nonspatial code might be required to mediate the perception of surface roughness. This notion is expanded by Hollins, Bensmaia, and Rismer (1998), who proposed a duplex theory of roughness perception. In their theory, very fine surfaces are coded via a vibratory-based mechanism, whereas surfaces with larger geometries are coded spatially.

These data are consistent with earlier psychophysical studies by Lederman and colleagues, who examined a number of surface parameters to find those that most strongly correlated with perceived surface roughness (e.g., Lederman, 1983). In their studies, observers judged the roughness of grating stimuli presented to the fingertip. Surprisingly, variables such as scanning velocity did not correlate with roughness percepts, suggesting that temporal variation across the fingertip surface was not an important cue for texture perception. Spatial variables, such as groove width and contact force, were more strongly correlated with perceived roughness. Another interesting point in Lederman's studies was the fact that perceived roughness was not affected by the manner in which the gratings were presented, i.e., whether the observer actively moved the fingertip across the grating or whether the grating was moved across a stationary fingertip.

Johnson and Lamb (1981) found that observers were able to judge roughness even when there was no movement between fingertip and surface. When stationary gratings were impressed into the fingertip, observers showed a threshold for grating resolution of about 1.6 mm spatial period. Johnson and Lamb also argued that the primary cues for texture perception were spatial in nature, rather than temporal, given that vibrating the gratings against the fingertip at either 40 Hz or 200 Hz did not appreciably change the roughness percept.

Van Doren et al. (1987, 1989) reached a similar conclusion about the importance of spatial cues after studies with a somewhat different stimulus. In their work, "traveling" spatiotemporal sinusoidal gratings were presented to the fingertip, such that different locations on the fingertip were contacted sequentially, at a rate of either 8 Hz (designed to activate primarily slowly-adapting mechanoreceptor populations) or 128 Hz (designed to activate primarily rapidly-adapting mechanoreceptor populations). Van Doren found that good spatial resolution was obtained for the slowly-moving gratings, again suggesting that the SA population was primarily responsible for grating acuity.

Thus, it appears that studies from a variety of sources and employing a variety of stimuli and tasks support the idea that surface texture perception is mediated by the SA I mechanoreceptors under most typical circumstances. However, this conclusion does not provide an explanation for another, less typical, mode of texture sensing. Beginning with the work of Katz (1925/1989), researchers have been interested in the ability of observers to gain information about surface texture by moving some sort of pointed probe or stylus across the surface. Katz noted that it was possible to gain considerable information about surface texture, and even to discriminate among surfaces, by moving a pencil-point stylus across different grades of sandpaper. He suggested that the proximal stimulus that permitted textural distinctions was the pattern of vibrations transmitted to the fingers holding the stylus, which constitutes a purely temporal cue.

While these two views of texture perception are not consistent, it is reasonable to think that there might be more than one way to transmit surface texture information, depending on the task. Even though most studies of the physiological mechanisms underlying texture perception have focused on the more typical case, in which the fingers contact a surface directly and thus a spatial code is possible, the aforementioned development of haptic interfaces that provide point-source force feedback has generated a renewed interest in texture perception under circumstances where a spatially-distributed input does not occur.

A recent study by Lederman and Klatzky (1998) is one of only a few studies in which texture perception via direct fingertip contact with a surface was compared to texture perception via a rigid probe. Lederman and Klatzky obtained magnitude estimates of roughness for a set of raised-dot patterns with interelement spacings between .5-3.5 mm, sensed either by the fingertip or by one of two rigid probes with contact diameters of 2 or 4 mm. They found that perceived roughness grows most rapidly as a function of interelement spacing when the bare finger is used, followed in order by the large and small probes. For all sensing conditions, estimates were best fit with a quadratic function, consistent with other observations in the literature that perceived roughness is a U-shaped function of surface element density. The point at which the function reaches maximum roughness is related to the diameter of the contactor (fingertip or probe). In judgments of the differential roughness of pairs of surfaces, Lederman and Klatzky found that performance was best for the fingertip, followed by the large and small probes. This led them to suggest that although texture perception is clearly possible with a vibratory code, for small element separations a spatial-variation code of the sort suggested by Blake et al. (1997) is apparently superior. For element spacings greater than .25 mm, no difference in performance across sensing conditions was observed. Nonetheless, when Lederman and Klatzky asked subjects to identify common household objects with the probes, performance was much poorer than that for the bare finger. This may be because object identification requires more than texture perception alone.

Although Lederman and Klatzky's data suggest that for some sensing tasks a single point-source force cue may be insufficient, the perception of surface textural cues is nonetheless possible with this cue alone. The present study is a further investigation of the perception of surface texture of virtual surfaces, rather than real surfaces, presented on two rather different haptic interfaces.

With the development of high-fidelity haptic interfaces, researchers have begun to study the characteristics of perception with these devices. The ability of 2-DOF interfaces to convey surface texture information was evaluated by Minsky (1995), who used lateral force gradients to create virtual textured surfaces that could be scanned with a joystick. Her results led her to suggest that contact force was the primary variable governing perception, consistent with some earlier reports of real surface perception (e.g., Lederman, 1983; Green et al., 1979). Surprisingly, she also found that the spatial geometry of the stimulus was not a major contributor to perceived surface roughness.

West and Cutkosky (1997) reported results for a direct comparison of textures of real and virtual surfaces sensed via the same stylus connected to a haptic interface. In their study, subjects were asked to count the number of cycles in the stimulus as sensed either with the stylus or (for the real surfaces) with a bare fingertip. West and Cutkosky found that low spatial frequencies were counted more accurately by the fingertip, but that high spatial frequencies were counted more accurately by the stylus, probably because the diameter of the stylus tip was small enough to fit into the grooves of the higher spatial frequency gratings. Because this was a counting task, it is difficult to determine the implications of these results for texture sensing. It is possible that the proximal stimulus requirements for a counting task are different from those for judging surface roughness.

Systems that deliver force feedback come in a variety of configurations, depending on their intended use, and provide one or more degrees of freedom of operation. For highly accurate representation of three-dimensional objects, it is likely that three degrees of freedom are required. But Minsky's (1995) data suggest that even planar devices offering two degrees of freedom can create highly compelling simulations of textured surfaces. What is not known is whether psychophysical resolution of surface texture is similar for 2-DOF and 3-DOF devices, particularly in view of all the differences involved in rendering surfaces on the two types of devices. And while this very fact makes it difficult to do a direct comparison of 2- and 3-DOF devices using identical stimuli, it is nonetheless important to determine threshold boundary conditions for both types of devices. Such information is relevant for improving haptic interface designs. In addition, this information could increase our understanding of the mechanisms that govern the perception of texture in real surfaces.

Accordingly, the present study investigated texture perception by asking observers to judge the orientation of horizontal and vertical virtual gratings presented either via the 2-DOF Immersion IE2000 force feedback stick or the 3-DOF PHANToM haptic interface (Sensable Devices, Inc.). For both devices, threshold was measured as a function of the spatial period of the grating. In addition, for the 3-DOF device, the amplitude of the grating served as a parameter, and for the 2-DOF device, the damping constant of the force component was varied. In undertaking this evaluation, several additional factors were considered that might influence the perception of the stimulus, as discussed below.

Force models

A potentially important issue is how to generate and render the force cues used in a texture simulation. For a 3-DOF device such as the PHANToM, there are a number of possible algorithms that might be used to generate surfaces. Basdogan et al. (1997) suggest that a Fourier series algorithm might be used to create highly regular surface textures, such as dot patterns, but that a stochastic approach might be more appropriate for irregular surfaces. Additional approaches are described by Siira and Pai (1996), among others.

A further consideration is the model employed for delivering forces to the end effector of the interface. For many conditions, it might not matter from the point of view of the user of a haptic device exactly what model is used for generating forces; however, in certain boundary conditions the force model employed might change the nature of the percept. For the purposes of the present study, we decided to begin by using force models developed by the designers of the two haptic interfaces we tested. In Experiment 3, we compare more directly two different force models on the same interface.

For the 3-DOF PHANToM, Massie (1996) created textured surfaces defined by the equation $z = a \sin(bx) * \sin(cy)$, where a, b, and c were constants. In his implementation, the program did collision checking with a planar surface that moved up and down in a sinusoid, according to the user's X and Y position. Because the user was always touching a planar surface, the force vector was always vertical. The lack of tangentially-directed forces resulted in a "frictionless" percept, but nonetheless Massie reported that a convincing simulation of surface texture was achieved.

For the 2-DOF IE2000, a texture simulation is found in the demo software provided by Immersion Corporation with the device. In this approach, force is modeled as a pure linear damper, $F = b*v$, where b is the damping constant and v is movement velocity. This implementation is described in more detail in the Methods section for Experiment 1. Briefly, as the user moved the end-effector of the interface in the x or y direction, areas were encountered in which a force opposing the user's movement was generated, using the product of a particular damping constant and the user's movement velocity. Outside these areas, no opposing force was encountered. The geometry of these areas was designed to simulate the experience of moving across a grating. To create a situation somewhat analogous to our variation of surface amplitudes on the PHANToM, we varied the damping constant across blocks of trials for the IE2000. This variation did produce the perception of different grating amplitudes, as reported by the subjects tested under these conditions.

The use of different force models for the two devices does limit direct comparisons. Although such direct comparisons of devices were not a primary goal of the present study, the question of whether different force models generate different textural percepts is an important one for designers of haptic interfaces. Accordingly, the damping and stiffness models are compared more directly in Experiment 3.

Potential limiting factors

In measuring human thresholds for texture discrimination in a grating orientation task in which the spatial period of the grating might approach very small values, there are several possible limiting factors that might influence performance. First, the issue of interest in the present study is the resolution ability of the human tactile system, which is determined both by characteristics of the peripheral mechanoreceptors (most importantly the SA I receptors but also including contributions from RA and Pacinian channels) and by more central neural mediation, including effects observed in somatosensory cortex under haptic movement conditions (Chapman et al., 1996). A second consideration, as mentioned, is the potential for differences in surface perception that arise from the force model used to generate the surface. Over most of the range of possible surface conditions, it is likely that surfaces generated with, say, a linear damper force model, would not be perceived differently from surfaces generated with another model; however, there could be circumstances under which different models of force generation might produce different effects, e.g., in surface penetration. In addition, the “frictionless” forces that are generated with a z-vector point-source force model are a very artificial percept unlikely to be encountered in the real world, whereas the texture percepts generated by directing forces in opposition to motion on a planar surface, as is done with the 2-DOF IE2000, do induce a sense of friction but may create an artificial percept due to their planar nature. These possibilities must be kept in mind when evaluating the data from psychophysical tasks performed with these devices.

A final consideration is the resolution limits of a particular device. If two devices had very different fidelity, then it is possible that differences in texture discrimination threshold might be found that are attributable to the device rather than to the user’s perceptual system. The two haptic interfaces employed here actually report rather similar spatial resolution values, approximately .03 mm. Thus, in the present case, one would not expect differential effects of device resolution on obtained performance. However, other potential device differences, such as device inertia or mechanical friction, could nonetheless affect performance. Again, it is important to note that direct comparisons across devices were not a primary goal of the present study.

Experiment 1

Method

Subjects. A total of 4 observers (3 female, 1 male) between the ages of 22 and 33 participated in the study. All reported normal hearing and normal tactile sensitivity.

Apparatus. Two haptic interfaces were used in the study. The first was the PHANToM^{TM} haptic interface, a 3-DOF device that has been extensively described in the literature. Briefly, this device is a commercially-available force-reflecting display that can be fitted with either a stylus or thimble end-effector. In the present work, the thimble was chosen as the end-effector. After inserting a fingertip into the thimble, the user can move about in 3-dimensional space, and any forces reflected are controlled by three motors controlling x,y,z space, such that the user's fingertip is represented as a single point in the space. The PHANToM was interfaced to a Pentium-based PC for stimulus generation, experiment control, and data storage.

For this experiment, stimuli were generated as sinusoidal gratings on the "floor" of the PHANToM space. Forces were modeled as a point-contact in the z-direction employing the following equation:

$$z = A \sin(fx), \text{ or } z = A \sin(fy)$$

Gratings were presented in one of two orientations: "Y orientation" (grating bars oriented away from the observer's body); or "X orientation" (grating bars shifted by 90 degrees). Amplitude of the gratings ranged from .004 to .028 cm in .004 cm steps (a total of 7 values), and was used as the parameter in the experiment. A representation of this surface is shown in Figure 1 (note that axis values are arbitrary in this figure; the representation is intended to give the reader a sense of how the surfaces were rendered rather than conveying any particular surface).

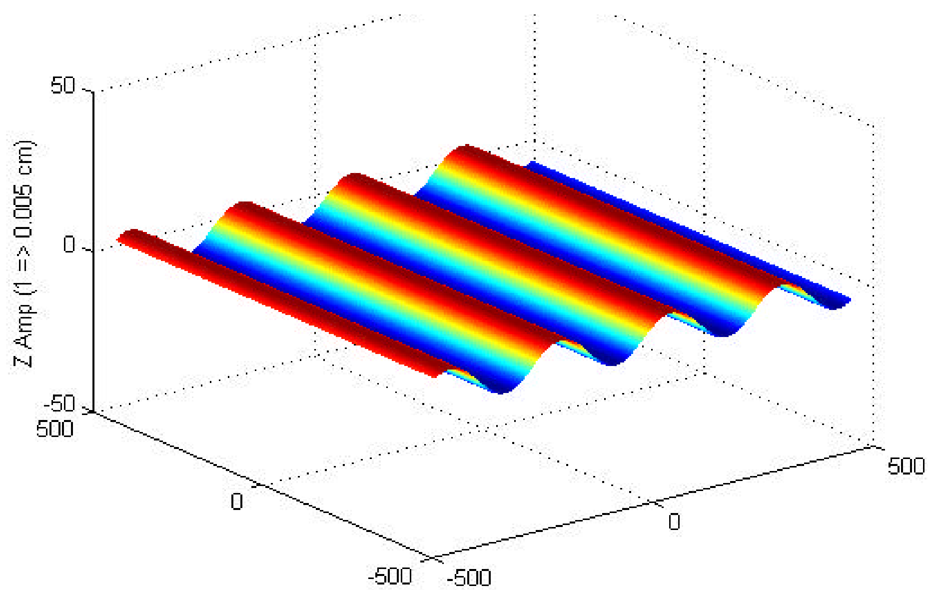

Figure 1. Schematic representation of surface presented on 3-DOF device.

The stiffness coefficient for Experiment 1 was set to .1. In addition, the average servo rate was monitored for each block of trials, to ensure that aliasing or other irregularities did not affect performance. The average servo rate across blocks was always greater than 5 kHz.

The second device used in the present work is the Immersion IE2000 force reflecting joystick (Immersion Corp.). For this work, the end effector was a cylindrical plastic stylus approximately 12.5 cm in length. The IE2000 is a 2-DOF device that permits observers to move the joystick to points in x,y space. This device was also controlled by a Pentium-based PC. For the present study, forces were reflected by changing damping on the end effector. The device generates force using a model of a pure linear damper. The magnitude of the resultant force can be represented as $F = b*v$, where b is the damping constant, and v represents scanning velocity. A total of 7 values of damping constant, ranging from 2-14 N/(m/s), were employed in the experiment. The surfaces generated for use in this experiment were analogous to square-wave gratings, constructed using the equation employed by Immersion Corporation in demonstration square-wave gratings, as follows:

$$\text{waveform} = (A*\text{xcoord}) \text{ MOD } P < D.$$

In this equation, the mod function was used to define an area P (period) of the workspace, such that a force was generated for all portions of P less than value D (duty cycle). In this experiment, P and D were fixed with P = 2D (50% duty cycle), such that one-half of area P contained a force, and the remaining half did not. Velocity of movement was not controlled, but rather was controlled by the observer. The actual reflected forces were not measured and recorded on a continuous basis. However, an estimate of the forces encountered by subjects was obtained by measuring output forces for “slow” and “fast” movements for the largest and smallest damping constants employed here. For the smallest constant (2), the obtained forces ranged from .02 to.09 N, and for the largest constant (30), the obtained forces ranged from .03 to .44 N. In a manner analogous to the PHANToM stimuli, the “grating” orientation was either in the “Y” direction (away from the observer, represented by vertical bars) or in the “X” direction (rotated 90 degrees, represented by horizontal bars). A representation of these surfaces is shown in Figure 2.

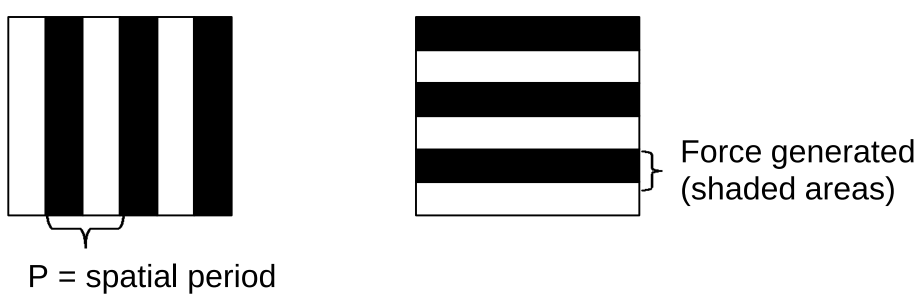

Figure 2. Representation of grating profiles for 2-DOF gratings.

Procedure

Observers were asked to perform an adaptive procedure, with one surface presented on each trial. Observers were asked to scan the surface with the appropriate end-effector and to determine whether the grating presented on that trial was oriented in the "X" direction or the "Y" direction. Based on the correctness of the response, the stimulus on the next trial was altered in spatial frequency. A two-step adaptive procedure was employed, so that two successive correct responses resulted in a smaller spatial period (higher spatial frequency) for the next stimulus, and a single incorrect response resulted in a larger spatial period (lower spatial frequency) for the next stimulus. Each reversal of direction of change (from larger to smaller spatial period or smaller to larger spatial period) is recorded, until a total of 8 reversals have occurred. In this manner the procedure tracks across the value at which observers can just discern the grating orientation, and converges to a value of approximately 71 percent correct. Thus a block of trials had no fixed number of trials, but rather the number necessary to achieve 8 reversals. Each block of trials was initiated with the grating spatial period set to a fixed value. The size of the step by which the spatial period of the surface was incremented or decremented was initially set to .01 cm, and was changed to .003 cm after the first reversal. Trial by trial feedback was provided.

For the 3-DOF PHANToM conditions, each block of trials was run at a fixed grating amplitude. Across blocks, amplitude was varied from .004 to .028 cm, in a random order, to avoid possible order effects. Subjects completed 6 blocks of trials for each amplitude. For the 2-DOF IE2000, damping constant was fixed within a block, but varied randomly across blocks, with values between 2 and 14 N/(m/s). Again, observers completed 6 blocks at each damping constant.

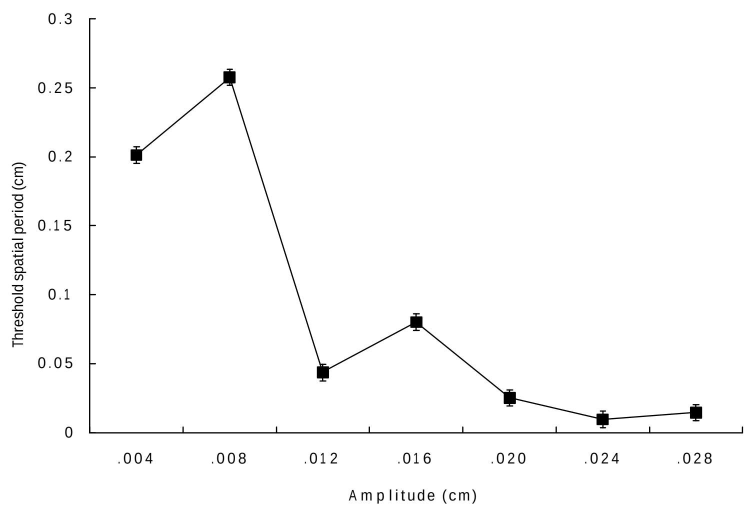

Figure 3. Threshold spatial period in cm as a function of grating amplitude for the 3-DOF device.

Results and Discussion

Results for Experiment 1 are averaged across subjects, and are plotted as the threshold spatial period of the grating at which subjects could identify grating orientation with approximately 71% accuracy. Results for the 3-DOF PHANToM are shown in Figure 3.

In this figure, threshold is shown as a function of grating amplitude. These results indicate that threshold improves as the amplitude of the grating is increased. The "leveling off" of threshold for the highest grating amplitudes may not indicate the lower limits of human sensitivity, however. For one thing, we did not investigate still higher grating amplitudes, as pilot testing at these amplitudes showed a tendency toward instability in the PHANToM, and the exerted forces were not deemed reliable.

One important aspect of this testing merits further discussion. All subjects reported that they based discrimination on percepts from scanning movements across the surface. These percepts were most salient when the direction of scanning was orthogonal to the grating orientation, compared to a case where the scanning direction was in the same direction as grating orientation. However, it was very difficult for subjects to scan completely across a surface maintaining an exactly orthogonal or exactly codirectional vector. As a result, when scanning in the same direction as the grating orientation, subjects did not stay in the grooves of the grating, so that some "bumpiness" was encountered. This perception became particularly important when the grating's spatial period became very small. For larger spatial periods, subjects chose grating orientation based on the scanning direction that yielded the "rougher" percept in a fairly straightforward fashion. However, as spatial periods became very small, this orthogonal scanning behavior produced a less and less rough percept, such that in some testing blocks, the surface scanned orthogonally actually felt smoother than the surface scanned codirectionally. When this occurred, observers seemed to "switch" their response criterion (i.e., to use the smoother percept as a guide in selecting grating orientation), and were able to drive the spatial period down to values well below the resolution limit of the device and thus physically impossible to realize. In these cases, the experiment program eventually terminated without yielding a threshold. It is not clear why this phenomenon occurred; however, all subjects reported that for at least some testing blocks they felt the need to switch their response criterion. This phenomenon may be of some interest in other applications with the PHANToM in which fine-textured anisotropic surfaces are rendered. A more frequent occurrence was that observers began to make errors at the point where they could no longer feel the correct orientation as rough, and the tracked threshold tended to converge at that point.

Figure 4 shows results for the 2-DOF device, the IE2000. In this figure, threshold spatial period is plotted as a function of damping constant. These data show an abrupt drop in threshold from the lowest value of damping constant to all the remaining values, which have nearly identical thresholds. In addition, subjects experienced the same difficulty with criterion shifting at very small spatial periods as was observed for the PHANToM. When spatial periods became very small, the surface was perceived as "viscous" rather than rough during orthogonal scanning, and the nature of the task changed.

The data in the literature for the perception of real gratings (e.g., Johnson & Phillips, 1981; Lederman, 1983) do not employ stimuli extending down to these values (not to mention that spatially-extended scanning via the fingertip is not really an analogous situation). For the task of sensing the orientation of real gratings with the fingertip, Johnson and Phillips (1981) found threshold values for grating discrimination

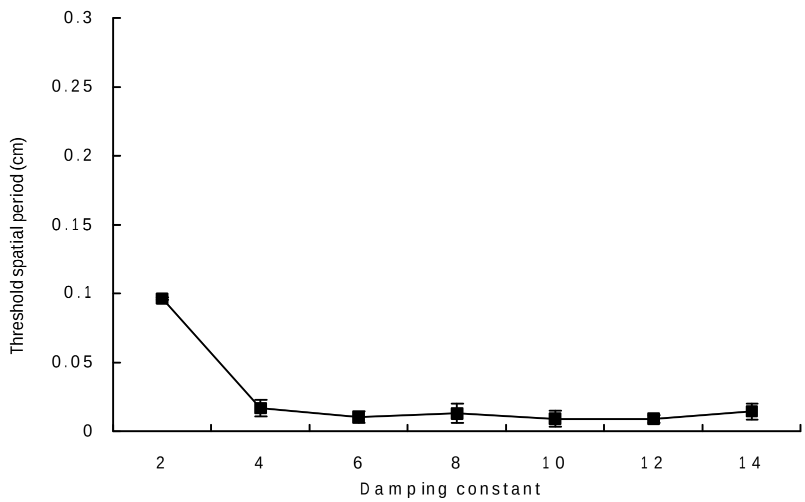

Figure 4. Threshold spatial resolution as a function of damping constant for the 2-DOF device.

to be approximately 1.6 mm spatial period. However, sensing gratings with the bare finger is very different from sensing a point-source force; it might be expected that smaller resolution values would be found with the present apparatus. A closer analogy is found in Lederman and Klatzky's (1998) probe sensing study, but this study did not examine the perception of surfaces with spatial periods less than 0.5 mm. However, Lederman and Klatzky did examine smaller differences between gratings in their discrimination experiment, as low as .125 mm, and found fair performance on this task both for the bare finger and for the probe stylus.

Interestingly, the threshold values measured for the 2-DOF devices are slightly better than those for the 3-DOF device. As stated previously, variations in grating amplitude on the 3-DOF device do not exactly correspond to variations in damping constant on the 2-DOF device; thus, it is not valid to compare results for the two devices directly, and we make no attempt to do so. Nonetheless, it is somewhat surprising that the perception of gratings can be so convincingly simulated by a planar device with a linear damper force model that such low thresholds are obtained.

There are several possible factors that may have produced such good performance for the 2-DOF device. First, the two devices utilize different models for generating forces, and it is possible that different perceptual effects are created by linear damper vs. stiffness models of force, particularly at boundary conditions, as mentioned above. A second factor of potential importance is the directional vector of the exerted force. Both the 2-DOF and 3-DOF force implementations created surface sensing situations that would not occur in the real world; on the 3-DOF device, all forces were vectored in the z-direction, and no tangential forces were applied, whereas on the 2-DOF device, all forces were horizontal, with a vector normal to the observer's movement. In real surface sensing, neither of these situations would be encountered. The contributions of the force vector to psychophysical resolution of grating orientation, as well as the perceptual realism of rendered surfaces, constitute a topic for further investigation.

A third factor may well be a determinant of the obtained results. A goal of this experiment was to take a first look at grating orientation resolution with the PHANToM and the IE2000, and we chose to use algorithms for generating surfaces that were suggested by the device developers. However, for the PHANToM this algorithm resulted in a sine-wave grating with no "sharp" edges, whereas the algorithm used with the IE2000 generated an abrupt onset/offset of force more closely analogous to a square-wave grating. It is certainly the case that in spatially-distributed sensing of real gratings by the fingertip, there is an advantage for squared edges, in that the response of the SA mechanoreceptors shows a pattern resembling edge enhancement (Phillips & Johnson, 1981; see also LaMotte et al., 1998 for a more detailed model of SA activation in response to surfaces moved across the fingerpad) that may arise from fingerpad deformation along the surface edges. Although this situation is not directly comparable to the present experiment, it is likely that abrupt changes from "no force" to "force" might be more salient than the more gradual transitions of the sinusoidal gratings.

The speculation that such stimulus differences may have influenced the perception of grating orientation motivated the second experiment of the present study, in which psychophysical resolution of both sinusoidal and square wave gratings was directly compared for both the 2-DOF and 3-DOF devices.

Experiment 2

Method

Subjects. Four female adults between the ages of 23 and 33 served as subjects. One had served in the first experiment; the others received several sessions of pretraining prior to the onset of data collection, to ensure stability of thresholds. This training was done with the grating stimuli of Experiment 1, so that similarity of performance between these subjects and those from Experiment 1 could be established.

Apparatus. The same two devices (PHANToM and IE2000) as in Experiment 1 were employed in Experiment 2. To generate square wave gratings on the PHANToM, the original equation, $z = A \sin(fy)$, was modified such that, for $z < 0$, $z = -A$, and for all other cases, $z = A$. For the IE2000, the equation used to generate sinusoidal gratings was

$$\text{Force} = v * (\text{damp}/2)*\sin[\text{abs}(\text{xcoord})] + (\text{damp}/2).$$

This equation generated a sinusoidally-varying force that did not contain negative values (due to the addition of damp/2 to the quantity), but instead reached a minimum at 0, to avoid the generation of forces codirectional with the direction of the user's movement.

As in Experiment 1, grating amplitude was varied across blocks of trials as a parameter in the 3-DOF conditions, and damping constant was varied across blocks of trials in the 2-DOF conditions. Pilot testing indicated that the range of grating amplitudes used in the first experiment was not practical for the square wave gratings rendered on the 3-DOF device, as high amplitudes created a degree of audible motor noise that we could not successfully mask. Similarly, for the 2-DOF device subjects were not able to converge to threshold for the highest damping constant values, because they did not make errors in determining orientation over more than 100 trials. Thus, high values of damping constant were also excluded from testing.

Procedure. The same procedure was used as in Experiment 1. A total of 25 blocks of trials (5 at each damping constant) were obtained for each device from each subject.

Results and Discussion

Figure 5 shows the threshold spatial period (means and standard errors) for grating orientation as a function of grating amplitude for the 3-DOF device. Results are again averaged across subjects. The results for sinusoidal gratings from Experiment 1 are plotted with filled circles, and the results for square-wave gratings from Experiment 2 are plotted with filled squares. Somewhat surprisingly, the data for sinusoidal gratings show lower thresholds than those for square wave gratings for all grating amplitudes except .02 cm. This result was not expected, given the assumption that the squared edges of the square-wave gratings would lead to an enhanced roughness percept.

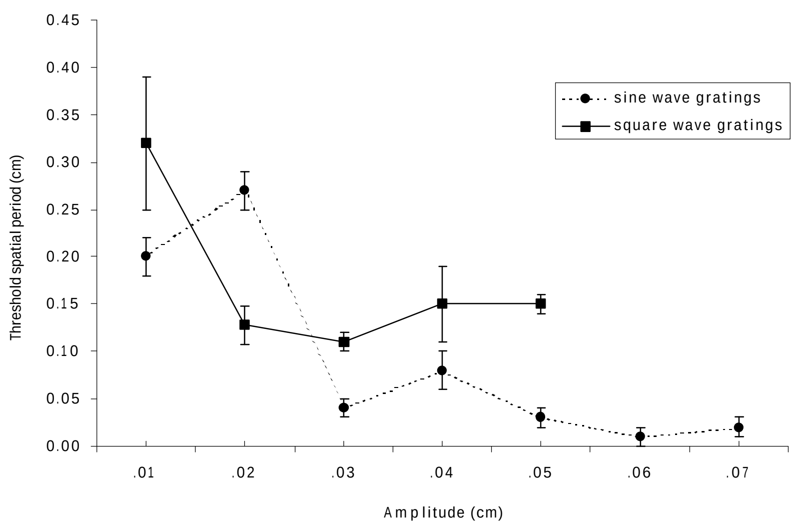

Figure 5. Sine and square wave grating resolution for the 3-DOF device.

A comparison of sinusoidal and square-wave grating resolution for the 2-DOF device is shown in Figure 6. Threshold spatial period is again plotted as a function of damping constant. As above, results from Experiment 1, this time for square-wave gratings, are plotted in filled squares, and Experiment 2 results for sinusoidal gratings are plotted as filled circles. The variability in these data is sufficient that essentially no differences in performance are found for the two grating types.

Again, it is not possible to compare results for the two devices directly, given that the true similarity of damping constant to stimulus amplitude is not clear. However, given the relatively higher thresholds obtained for the square-wave gratings with the 3-DOF device, the results for both stimulus types on the 2-DOF device are even more striking.

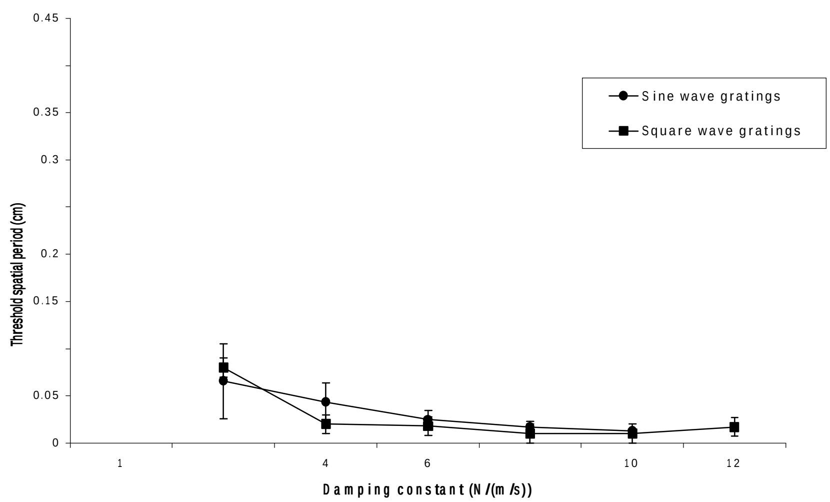

Figure 6. Sine and square wave grating resolution for the 2-DOF device.

Statistical analysis was performed on these data sets using analysis of variance. Because the two types of stimuli were not tested at exactly the same values of amplitude or damping constant, we did not look for main effects of these factors. Rather, main effects of grating type were analyzed for each device. For the 3-DOF device, the main effect of grating type did not reach significance at the .05 level, but was significant at the .1 level ($F(1,3)=4.74$, $p=.1$). The borderline significance level here might be attributable to the small number of subjects. For the 2-DOF device, no significant main effect of grating type was found, as would be expected from Figure 6 ($F(1,3)=.002$, ns).

As was true for the data from Experiment 1, a number of differences in the types of surfaces generated on the 2-DOF and 3-DOF devices prevented direct comparison of the results for the two instruments. Although on some level the differences in surfaces are sufficiently great that no direct comparison should be attempted, one issue that arises for both experiments is the difference in type of force model (stiffness model vs damping model) employed in generated the surfaces for the two devices. Although there is no *a priori* reason to suspect that the implementation of different force models should produce different results, nonetheless this remains an empirical question.

To address the question of whether the differences obtained between devices could be attributed to differences in the force models used to generate virtual surfaces, an additional experiment was conducted. In this experiment, both the stiffness ($f = kx$)

model used with the PHANToM in Experiments 1 and 2 and the damping (f = bv) model used with the IE2000 were implemented on a single device, and were compared directly by generating an equal range of forces. In order to determine actual presented forces, for both models a running average of force was recorded during experimental testing, and values averaged over test blocks were used in analysis.

A number of decisions were made to enable this comparison. Because this experiment represents only an initial look at the effects of force model on surface perception, it will be useful in future work to examine the influence of changing other stimulus and experimental parameters. First, only the PHANToM was used in this comparison, and it may be that different results would be obtained with the IE2000. Second, only square-wave gratings were employed, for ease of implementation of the force models. Third, it was decided to present these stimuli as planar surfaces in x,y space, rather than implementing the damping model in three dimensions. Thus, both models were implemented in a 2-DOF representation. Finally, in order to achieve these planar surfaces and not permit the subject to "push through" the surfaces with the PHANToM thimble, it was necessary to provide a z-direction "floor" for both model implementations.

Experiment 3

Method

Subjects. Three female adults between the ages of 23 and 33 were subjects. Two had served in the second experiment; the third was given several sessions of pretraining prior to the onset of data collection. The pretraining for this subject consisted of the experimental conditions from Experiment 2.

Apparatus. For this experiment, only the PHANToM was employed. In order to enable a direct comparison of the two force models, surfaces were generated that varied only in the x,y plane. For both force models, a force in the z-direction was activated to create a planar "floor" through which the PHANToM thimble did not penetrate. This force was activated whenever the user reached a point in a horizontal plane defined near the bottom of the PHANToM work area. This was done to make the stimulus analogous to that provided on the 2-DOF IE2000 in the first two experiments. The values associated with this floor were identical for both force model implementations.

Damping constant forces were generated in a manner similar to that used for the IE2000, by dividing the available stimulus plane into areas in which a force was generated by providing a fixed amount of damping against the subject's movements, and other areas in which no damping was present. Damping constant was varied across blocks of trials, but was held fixed within a block. By maintaining a record of the running average velocity of subject movement of the PHANToM thimble, it was possible to determine the forces produced during testing.

The stiffness model forces were generated using a similar algorithm to divide the planar surface into areas in which a stiffness component was present. When the observer moved the thimble into one of these areas, a force was generated in the direction opposite to the direction of movement (in either the x or y dimension, depending on the specific grating being simulated), as the product of the stiffness coefficient and the displacement of the thimble. When the thimble was moved outside the prescribed area, no stiffness component was present. Across blocks, the value of stiffness was varied to produce different products of displacement and stiffness, and thus different forces.

Procedure. As in Experiments 1 and 2, the subject's task was to determine the orientation of the presented grating stimulus. Across trials, two successive correct responses resulted in a reduction of the spatial period of the stimulus, and one incorrect response resulted in an increase in spatial period. Eight reversals in response direction determined the threshold spatial period for a particular block.

Results and Discussion

Results for this comparison are shown in Figure 7. For each model, the threshold spatial period is plotted as a function of the generated forces, in N. For the damping model (f = bv), this force is the product of damping constant and the average velocity of movement for all subjects for blocks employing that damping constant. For the stiffness model (f = kx), this force is the product of stiffness and displacement, as defined above. The values plotted are the means and standard errors for the three subjects.

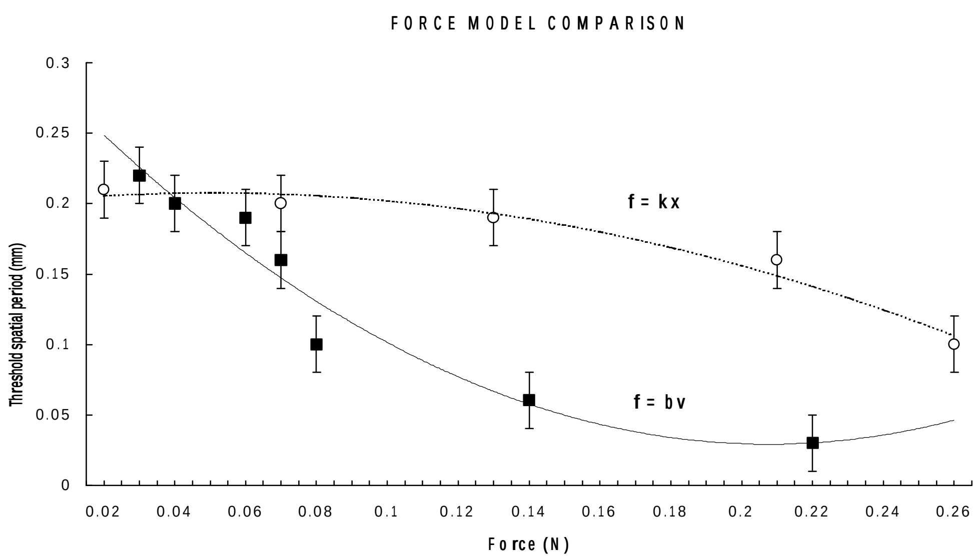

Figure 7. Threshold spatial period as a function of total force for stiffness (f=kx) and damping (f=bv) force models on the PHANToM.

Several points are worth noting. First, the trends in the data are represented with best-fitting functions, in this case second-order polynomial functions. No particular theory or hypothesis is suggested by this fitting; rather, as mentioned, it was done to reflect trends. Second, it appears that for most of the range of forces examined in this experiment, the surfaces created using the damping model f = bv produce somewhat better thresholds than those created using the stiffness model f = kx. Again, because arbitrary decisions were made to generate these experimental conditions, no conclusions regarding the appropriateness of either force model should be drawn from these data. However, it is interesting that a difference in performance is observed; for a particular force, it seems that a given spatial period is perceived slightly differently. This cannot be said for the smallest values of force, below about .06 N. Statistical analysis using repeated measures analysis of variance supports these conclusions, showing a significant main effect of force model ($F(1,2)=11.66$, $p=.049$).

Next, it is interesting to note that the data shown in Figure 7 indicate slightly better thresholds than those in Figure 5 for square-wave stimuli. However, because so many experimental parameters differ between Experiments 2 and 3, the two figures should not be compared in any systematic way. Nonetheless, it is interesting to speculate whether the use of the 2-DOF simulation for Experiment 3 produced surfaces that were more easily discriminated than true 3-DOF surfaces. Future work should investigate this issue in greater detail.

General Discussion

This paper presents three experiments that represent an initial look at how human observers perceive textured surfaces (in the form of gratings) implemented on 2-DOF and 3-DOF haptic interfaces. Overall, the results suggest surprisingly good acuity in determining the orientation of gratings for both devices. This is particularly interesting for the 2-DOF device, which is limited to rendering simulated gratings in two dimensions. In Experiment 2, a difference in acuity for sinusoidal and square wave gratings was observed for the 3-DOF device, but no corresponding difference was found for the 2-DOF device. Finally, in Experiment 3, a direct comparison of force models was examined for the 3-DOF device, with the result that resolution of grating orientation was better for the damping model (f=bv) than for the stiffness model (f=kx). Because the selection of experimental parameters in this experiment was somewhat arbitrary, as befits an initial look, no firm conclusions about the superiority of one model over the other should be drawn.

At present we have no plausible explanation for the somewhat better resolution for sinusoidal grating stimuli over square-wave stimuli on the 3-DOF device observed in Experiment 2. It is possible that the velocity with which the user moved the thimble end-effector across the virtual surface may have impeded complete sensing of the grooves of the square gratings, but not affected the sensing of the grooves in the sinusoidal gratings because of their more gradual slopes. Movement velocity was completely unrestrained in the present study; users were instructed to find a movement velocity that gave them a “good” stimulus percept, and to maintain this velocity across conditions. Further work could focus more directly on the role played by movement velocity in the perception of surface features.

There are several other factors that should be considered. First, it is possible that differences in the end-effector used in the two devices may have had an effect on performance. The way in which the fingertip contacts the PHANToM’s thimble end-effector provides a very different proximal stimulus to the tactile mechanoreceptors than that provided when the thumb and several fingers grip the IE2000's stylus-like joystick. In one case, stimulation is confined to a single fingertip, whereas in the other, simultaneous stimulation of several fingertips occurs.

This issue was addressed in an experiment in our laboratory (Weisenberger, Krier, Rinker, and Kreidler, 1999). For the PHANToM, it is relatively simple to compare the thimble and stylus end-effector situations, as the manufacturer provides both elements for use with the interface. For the IE2000, we machined a thimble end-effector that can be substituted for the stylus joystick. In this way a direct comparison of end-effector types was possible for both devices. Although some data in the literature (e.g., Brisben et al., 1999) suggest that grasping a rod might produce different vibratory thresholds from touching a contactor, we did not find significant differences for our suprathreshold grating discrimination task. Thus, at least for the specific stimuli we employed, the type of end-effector does not seem to be a major contributor to the percept.

Finally, an issue of considerable interest for future work is whether the 3-dimensional surfaces generated on the PHANToM in the present experiments were perceived in some different fashion due to the "frictionless" nature of the z-vector forces employed. Experiments currently underway in the laboratory compare the perception of these z-vector frictionless surfaces to surfaces that include tangential as well as vertical force vectors, which would presumably be representative of more realistic surfaces (see Weisenberger, Krier, and Kreidler, 2000). Preliminary results suggest that observers are able to detect very small amounts of lateral friction force in contacting a surface. Although friction has not been demonstrated to play a role in the perceived roughness of real textured surfaces sensed with the fingertip (e.g., Taylor and Lederman, 1975), it seems plausible that the addition of a friction component might alter resolution of grating orientation, or other surface features, and thus some knowledge of perceptual thresholds for detection of friction are important for haptic rendering.

Overall, the findings from the present study support earlier reports of Massie (1996) and Minsky (1995), that very compelling virtual textures can be simulated with both 3-DOF and 2-DOF force feedback haptic interfaces. These results, together with ongoing work in our laboratory and other laboratories, should provide useful insights into the cues that underlie sensing of real surfaces. One particularly beneficial aspect of using haptic interfaces for such investigations is the ability with virtual stimuli to factor out individual cues (such as tangential friction forces) and present them separately, so that the contributions of individual cues can be determined. In addition, this work can yield guidelines for improvements in the design of new haptic interfaces.

NOTES

1. A portion of these results was presented at the 1998 meeting of the American Society of Mechanical Engineers, and published in the proceedings from that meeting.

2. Present address: Department of Psychology, Lamar University, Beaumont TX.

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