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Tactile roughness perception with a rigid link interposed between skin and surface

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Subjects made roughness judgments of textured surfaces made of raised elements, while holding stick-like probes or through a rigid sheath mounted on the fingertip. These rigid links, which impose vibratory coding of roughness, were compared with the finger (bare or covered with a compliant glove), using magnitude-estimation and roughness differentiation tasks. All end effectors led to an increasing function relating subjective roughness magnitude to surface interelement spacing, and all produced above-chance roughness discrimination. Although discrimination was best with the finger, rigid links produced greater perceived roughness for the smoothest stimuli. A peak in the magnitude-estimation functions for the small probe and a transition from calling more sparsely spaced surfaces rougher to calling them smoother were predictable from the size of the contact area. The results indicate the potential viability of vibratory coding of roughness through a rigid link and have implications for teleoperation and virtual-reality systems.

Perceived texture is a multidimensional concept that includes roughness, among many other percepts relating to the distribution of elements on a surface (see Hollins, Faldowski, Rao, & Young, 1993; Loomis & Lederman, 1986). Perceived roughness is arguably one of the most prominent aspects of texture perception, and certainly the one most commonly studied to date by scientists concerned with the sense of touch. This paper focuses on the perception of roughness when a rigid structure is interposed between the skin and the textured surface. We present psychophysical data comparing roughness perception with and without such a rigid link.

Representations of Roughness via Direct Contact

Over the years, psychophysicists and neurophysiologists have focused on different ways in which roughness may be represented or coded when the bare finger is used. For example, early psychophysical investigations (e.g., Katz, 1925/1989; Lederman & Taylor, 1972; Stevens & Harris, 1962) considered the nature of the representation in terms of the distal stimulus. Collectively, such research indicated that the magnitude of the roughness percept is a strongly increasing function of the separation between raised elements that form the textured surface. Subsequently, Taylor and Lederman (1975) investigated the nature of the representation for roughness in terms of the critical components of the proximal stimulus, considered in terms of various parameters of skin deformation. They found that roughness perception was directly related to the total area of skin that was instantaneously indented from a baseline resting position while in contact with linear gratings. Taylor and Lederman's skin-mechanics model accounted for the psychophysical effects of groove width, as well as smaller effects owing to the ridge width and the net contact force applied (Lederman, 1974). We refer to such coding, which represents a stimulus in terms of its magnitude, as *intensive*. If the roughness percept further varied between surfaces that produce identical magnitudes of skin deformation but different spatial deformation patterns, purely *spatial* parameters of the proximal stimulus would be implicated. To date, stimuli have not been developed that test the contributions of these spatial parameters.

In related work on roughness perception, neurophysiologists have focused on the underlying neural representations of roughness, rather than on the effects of the distal or the proximal stimulus. Neurophysiological coding may vary with the particular site in the nervous system being considered. Johnson and associates have recently offered a neural model of roughness perception (for a review, see, e.g., Johnson & Hsiao, 1994). At the peripheral level, the model computes what is essentially a measure of in-

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stantaneous variation in a spatial map of intensity values in slowly adapting (SA) units. It is further proposed that, at the cortical level, units in SI (area 3b) having receptive fields with excitatory/inhibitory subregions compute local differences in SA activity. Such activities are subsequently passed along to SII units, which spatially integrate the local differences (see Sinclair & Burton, 1991, 1993; Tremblay, Ageranioti-Bélanger, & Chapman, 1996, for investigations of responses to textured surfaces among cells in SI and SII). Accordingly, this model of roughness is most accurately described as *spatial intensive*, inasmuch as local spatial information is preserved only up to SI (area 3b); beyond this level (i.e., SII), the local differences are integrated and coded intensively. The term *spatial* is reserved for events in which the spatial layout of the elements that make up the code is represented.

At the perceptual level (cf. the proximal or the distal stimulus or the neural code), both psychophysicists and neurophysiologists agree that the roughness of a surface is best represented intensively (see, e.g., Johnson & Hsiao, 1992; Lederman & Klatzky, in press)—that is, in terms of its magnitude on a perceptual roughness continuum. We will use the term *spatial intensive* to describe the stream of processing that results in this intensive perceptual response.

Although neurophysiological work suggests that the intensive perceptual response originates in spatial coding, one might also propose that perceived roughness is based on a vibratory code. This proposal is derived from the following observation: When people judge the roughness of a surface, they typically move their fingers laterally across it, thus producing vibratory signals; rarely do they either press down in a direction normal to the surface or simply rest their fingers statically after contact has been made (Lederman & Klatzky, 1987). The need for relative motion between the skin and the textured surface may seem to suggest that roughness coding is based on the vibratory signals produced. This hypothesis was proposed early in the 20th century by Katz (1925/1989). However, published research to date has failed to find a role for vibration in perceiving the roughness of surfaces with interelement spacings of about 1 mm or more (macrotextures).

This conclusion is based on a number of convergent findings. First, changes in the speed of active and, perhaps more importantly, passive arm movements (10-fold by Katz, 1925/1989; 25- and 12-fold by Lederman, 1974 and 1983, respectively) have failed to alter perceived roughness in any meaningful way. Second, the roughness of these surfaces has also been shown to be unaffected by the spatial period of the elements, which, in part, determines the corresponding fundamental vibratory frequency (Lederman & Taylor, 1972). Finally, roughness judgments are unaffected by selective vibrotactile adaptation to low (20-Hz) versus high (250-Hz) frequencies applied normally to the fingertip surface (Lederman, Loomis, & Williams, 1982). A subsequent experiment by Kudoh (1988) showed that perceived roughness was modulated by direct manipulation of temporal frequency (perceived roughness proved slightly greater for 30 Hz than for 280 Hz); however, the effect only occurred for 2 out of 6 subjects.

Coding With the Skin Versus a Rigid Link

To reiterate, for macrotextures, those with element spacing above the limits of resolution imposed by the peripheral receptors (i.e., about 1 mm—see Phillips & Johnson, 1981), behavioral and neurophysiological evidence support the use of spatial-intensive coding, when the finger contacts the surface directly. By spatial intensive, we mean processing that begins with a representation of the layout of textural elements in space but culminates in an integrated representation of magnitude.

Although either spatial-intensive or vibration-based coding is possible when a textured surface is felt directly with the finger, only the latter is possible when a rigid link is interposed between skin and surface (e.g., when we write with a pencil or stir a pot with a spoon). When the finger directly contacts a textured surface, the spatial gradient on the skin is strongly correlated with the spatial gradient of the surface. But when the finger holds a probe that touches the surface, the correlation between the skin gradient (produced by points of contact with the probe) and surface spatial gradient is eliminated. However, variations in surface structure will alter the vibratory cues, which are transmitted to the skin along the rigid link. The temporally distributed pattern is again correlated with the geometry of the stimulus, although the spatial deformation pattern on the finger is not. In addition, there are likely to be intensive changes in the vibratory signal, produced by a number of possible factors, such as surface geometry, probe compliance, contact size, and contact shape.

The present paper constitutes the initial stage of a broader program of research on feeling the world through a probe; the program investigates performance across a range of perceptual tasks when forces on the finger arise from traveling waves along a rigid link (see, e.g., Lederman & Klatzky, in press). This research was motivated by two factors. First, we wished to extend our fundamental psychophysical knowledge of tactile texture perception. Second, we wished to consider the role of vibration-based coding in haptic perception, inasmuch as the development of sensory interfaces for teleoperator and virtual environment systems that display cutaneous and haptic feedback to the hand of a human operator has given it new significance. Vibration has proven to be important in teleoperated systems, which control exploration and manipulation of a remote site. To teleoperate effectively, the operator must also receive haptic feedback about the results of his or her commands—for example, to indicate that the remote tool has contacted a surface. Recently, teleoperator systems have been successfully developed to provide feedback about contact in the form of vibration normal to the skin (Kontarinis & Howe, 1995). Vibratory stimulation is also potentially important in creating virtual environments, which attempt to haptically render the texture of surfaces by applying temporally varying lateral forces (Minsky, 1995; Minsky & Lederman, 1996). In such applied contexts, it is critical to understand the role of vibratory cues in perceiving surface properties.

Coding Roughness at Macro and Micro Scales

As was indicated above, current theories of roughness perception implicate spatial-intensive coding for macrotextures. The contribution of concurrent vibratory signals for such surfaces is contraindicated by the psychophysical studies reported above. In contrast to spatial-intensive coding of roughness on the macrogeometric scale, vibratory coding of roughness does, in fact, occur with very fine *microtextures*, whose elements are on the order of microns in height. LaMotte and Srinivasan (1991) found that subjects could discriminate a texture from a featureless surface when the height of the elements forming the texture was only 0.06 microns for textures made up of bars and 0.16 microns for dotted textures. The subjects making these discriminations reported attending to the vibration they felt when stroking the texture. Moreover, measures of mechanoreceptor activity in monkeys passively exposed to the same surfaces showed that only the FAII units gave rise to a strong signal that differentiated not only flat from textured surfaces, but also textures made of bars rather than dots. The FAIIs are characterized by responses to relatively high-frequency vibrations, peaking in response in the region of 250 Hz (Johansson & Vallbo, 1983). The distinction between vibrotactile and spatial-intensive codes for microgeometric textures is further supported by work on texture discrimination in rats (Carvell & Simons, 1995), which are able to discriminate textures in the range of 0.05–0.5 mm with a single whisker but require two whiskers for discriminations of textures defined by separations greater than 1 mm.

Vibration-Based Coding of the Roughness of Macrogeometric Surfaces

It is, therefore, possible that vibrotactile coding can be used to estimate and discriminate even macrotextural properties, albeit less effectively than can spatial-intensive coding. One way to examine the effects of vibration is to evaluate roughness perception when surfaces are explored with a rigid probe. As was described above, a probe will transmit vibratory information to the skin that reflects the perturbations of the probe as it moves across the surface over time. Katz (1925/1989) reported that subjects could discriminate the roughness levels of different types of paper surfaces quite well while exploring them with a wooden rod. This suggests that vibrotactile coding could prove useful for roughness perception, despite the fact that people do not normally use such cues when exploring with the bare finger.

The present experiments were designed to explore this suggestion. Rigid links, in the form of hand-held probes and sheaths, were interposed between textured surfaces and the skin to alter the manner in which people coded roughness—that is, from spatial-intensive to vibrotactile coding. These links precluded any direct correlation between distal stimulus properties and spatially distributed forces on the skin. Any spatial gradient imposed on the skin would reflect only the properties of the exploring tool itself—for example, the shape and compliance of a probe's handle. The result of using a rigid link would be, we assumed, to force the perceiver to use vibration-based codes for judging roughness. In contrast, from the literature reviewed above, perception with the bare skin or a compliant link (e.g., a thin glove) was assumed to use spatial-intensive coding.

We investigated two issues. The first was how the nature of the link affects the psychophysical relationship between perceived roughness and the geometry of the textured surface. This relationship was assessed with two types of psychophysical functions. One function was obtained using a magnitude-estimation procedure; it related the subjective roughness of a stimulus to the spacing between raised elements in its surface. We use the relative rate of growth of this function as an indication of relative sensitivity: the steeper the rise, the more sensitive subjects are to differences between stimuli differing in interelement spacing. The second psychophysical function was obtained from a comparative-roughness task, in which subjects were presented with pairs of stimuli differing in interelement spacing and were asked which member of each pair was rougher. In the analysis of interest, the difference between members of a pair was held constant; what varied among pairs was their position on the interelement-spacing dimension. The proportion of responses where the stimulus with greater spacing was judged to be rougher was plotted as a function of the level of interelement spacing of the pair. We expected the nature of the skin-to-stimulus link to affect these psychophysical functions. In particular, the size of the contact surface provided by a rigid link should be critical, because the vibrations resulting from contact are produced by the combination of the exploring effector and the raised elements within the surface that is explored. This point will be discussed in more detail below.[1]

The second issue addressed here is related to the first; it concerns the relative sensitivity of vibrotactile versus spatial-intensive codes for roughness, where sensitivity is defined by both the subjective magnitude of perceived roughness and the level of roughness discrimination that is possible. The evidence that spatial-intensive information is usually relied on for roughness perception at the macroscale suggests that spatial-intensive coding should be more sensitive than vibrotactile coding. But relatively, how effective can the latter coding be?

Our experiments involved two types of rigid links, as was indicated above. One was implemented by having a subject explore the surfaces, using a stick-like probe held in the fingertips. The other involved exploring through a fiberglas sheath, molded to the ventral surface of the fingertip. Two stick-like probes were used, which differed in the size of the contact surface; however, both were smaller than the surface of the sheath. We compared contact via these links to more direct contact between the surface and the skin, which was either bare or covered with a thin, com-

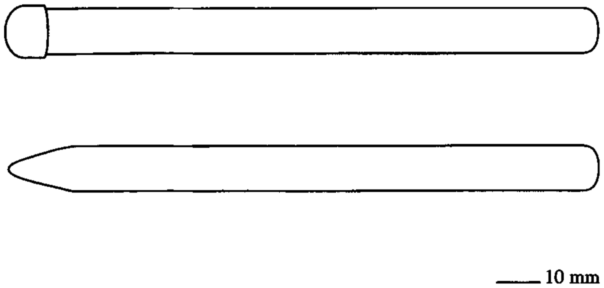

Figure 1. Illustration of probes used in Experiments 1 and 2.

pliant glove. Although a glove will affect friction at contact, Taylor and Lederman (1975) have found no effect of friction on perceived roughness. We provide converging evidence for this fact with a control experiment.

In this initial psychophysical inquiry into feeling textures with a rigid probe, we performed a set of four formal experiments and one control manipulation. The first two experiments compared the perceived roughness of a set of raised-dot patterns when subjects used the bare finger with perceived roughness when they used two probes with different sized tips: Experiment 1 required magnitude estimates of surface roughness, whereas Experiment 2 required roughness comparisons between pairs of textured surfaces. Experiments 3 and 4 used the same methods as those in Experiments 1 and 2, respectively; this time, however, subjects judged roughness while wearing just a thin latex glove with that when the molded sheath was inserted into the tip of the same latex glove. Finally, the control experiment comparing bare-finger with gloved-finger conditions confirmed that the glove used in Experiments 3 and 4 did not itself alter the estimated magnitude of perceived roughness.

EXPERIMENT 1

Magnitude Estimation of Perceived Roughness, Using Finger and Rigid Probes

The subjects provided magnitude estimates of the perceived roughness of a set of raised-dot patterns that varied in interelement spacing. Traditional psychophysical functions were obtained for the bare finger and for two rigid, stick-like probes, which varied in the diameter of the contact area. We presumed that the bare-finger function would be based on spatial-intensive coding of roughness, whereas the probe functions would be based on vibratory cues, as affected by both interelement spacing and probe size.

Method

Subjects. The subjects were 12 university undergraduates, 7 female and 5 male, who received credit for a course requirement. All chose to use their right hand in the experiment, and no effects of exploring hand on perceived roughness were demonstrated in previous research on this issue (Lederman, Jones, & Segalowitz, 1984). None of the subjects in this or subsequent experiments reported cutaneous or motor impairments. Different subjects participated in each experiment reported here.

Stimuli and Manipulanda. The stimuli were plastic plates with raised dots photoengraved with the nyloprint technique (Lederman, Thorne, & Jones, 1986). Each dot diameter was approximately 1 mm (and owing to the fabrication process, covaried with separation over approximately a 0.5-mm range). The interelement spacing was produced by a computer algorithm that began with a matrix at a specified interdot spacing (inner edge to inner edge), then, randomly, spatially (radially and angularly) jittered each dot within a predetermined circular area, so as to maintain the mean interelement spacing at the same level as that in the original dot matrix. The interelement spacings for the plates used in each of the experiments are given in the Appendix. Nine plates were used in the present experiment, with interelement-spacing values ranging from 0.5 to 3.5 mm, in 0.375-mm increments.

The subjects explored with the bare index finger and with each of two rigid probes made of delrin plastic, shown in Figure 1. Each had a cylindrical shaft 15 cm long. The large probe terminated in a half-ellipse shape that was slightly rounded at the tip; the small probe terminated in a conical shape with a rounded tip. The contact diameter was measured by inking the probe tip and pressing it lightly on a rigid surface, then rotating the wrist without allowing slip. The measured contact diameter was approximately 4 mm for the large probe and 2 mm for the small. Thus, both probes had larger surfaces than the smallest of the interelement-spacing values of the stimuli (0.5 mm), but only the small probe had a surface size that fell within the stimulus range of interelement spacing. For purposes of comparison, the fingertips of 8 separate subjects were inked, and they were instructed to apply pressure as they had during the roughness judgments. The resulting contact area averaged 9 × 13 mm.

Procedure. The subjects were blindfolded and fitted with wax ear plugs, over which were placed headphones of a tape recorder. Background noise was played over the headphones, in order to cover the sounds from exploring the plates. The noise was created by recording samples of sounds produced by scanning across the plates with the two probes. The sample sounds were looped to create a continuous sound and summed with white noise to muffle any rhythm from repetition. A rubber mat under the plates prevented slipping during exploration.

The subjects rated the roughness of the surfaces after exploring with the bare finger or a probe. They were told to lightly scan across the surface "about an inch" (2.54 cm) on each side of the center. An absolute-magnitude-estimation procedure (Zwislocki & Goodman, 1980) was used, in which the subjects were instructed to use any starting point and to designate a number that best described the subjective roughness of the plate (using whole numbers, decimals, or fractions, excepting zero). The nine stimuli were presented three times within each end effector (finger, large probe, or small probe), in random order. The order in which the end-effector blocks were presented was counterbalanced across subjects. Practice trials without feedback preceded each block of trials.

Results

To control for differences in numerical scale, the magnitude estimations for each subject were first normalized by dividing each one by the subject's mean within a condition, then multiplying by the grand mean. The data were then logarithmically transformed to produce more nearly normal distributions. Finally, the three estimates given by a subject within each condition were averaged.

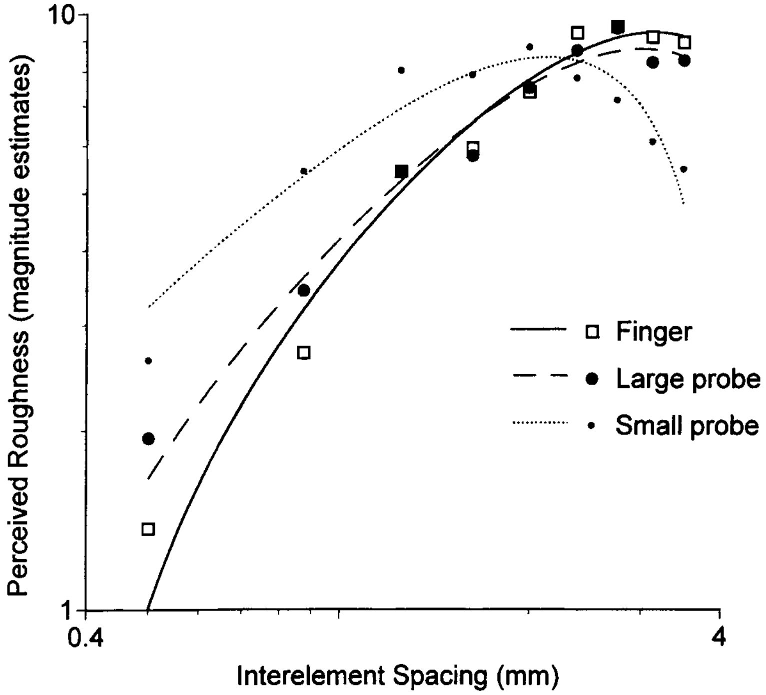

Figure 2. Geometric mean magnitude estimate as a function of interelement spacing of the stimulus in Experiment 1 on log scales, for the three end effectors. Quadratic functions fit to the log–log data were as follows. Small probe, $y = -0.93 * x^2 + 1.26 * x + 0.58$; large probe, $y = -0.70 * x^2 + 0.98 * x + 0.63$; finger, $y = -1.79 * x^2 + 0.84 * x + 0.82$. The r value in all cases was .99.

In Figure 2, the geometric means for the magnitude estimates are shown as a function of interelement spacing (log scales), for each end effector. Linear functions fit to the log–log values for the finger and the large probe produced reasonable fits (slope = 1.00 and .79, and $r = .96$ and .96, respectively). However, the fit was poorer for the small-probe function, which showed a tendency to decrease with higher interelement spacing (slope = .35, $r = .60$). Because there was an apparent tendency for all of the functions to be negatively accelerated, we fit quadratic functions relating log magnitude to log spacing, as is shown in the figure. The functions tended to be increasing, with the degree of steepness greatest for the finger and least for the small probe. As was noted above, the rate of increase indicates the extent to which stimuli varying in interelement spacing can be differentiated. The height of the function at low levels of interelement spacing indicates the magnitude of perceived roughness with the smoothest stimuli; this was greatest for the small probe and least for the finger.

A within-subjects analysis of variance (ANOVA) was performed on the log-normalized magnitude estimates, with factors of end effector (three levels), and interelement spacing (nine levels). In describing these and subsequent ANOVA results, all significant effects will be reported; nonsignificant effects ($p \geq .05$) will not be reported or discussed further. There were main effects of end effector [$F(2,22) = 8.56, p < .01$] and interelement spacing [$F(8,88) = 53.34, p < .00001$], and an interaction [$F(16,176) = 9.33, p < .00001$], reflecting the obvious differences in the shapes of the magnitude-estimation functions.

By taking the derivative of the quadratic function fit to the data in Figure 2 (i.e., log magnitude estimate as a function of log interelement spacing) and setting it to zero, one can determine at what interelement spacing the function would theoretically peak. This procedure resulted in an estimate of 4.8 mm for the finger, 5.0 mm for the large probe, and 1.7 mm for the small probe. In theory, the function would begin to turn down at the estimated peak; beyond this point, perceived roughness would decrease with larger interelement spacing, rather than increasing, as in the earlier part of the function. The estimated spacing values at which the small-probe function peaked (1.7 mm) was relatively close to the measured contact diameter (2 mm). For the large probe, the corresponding values were 5.0 and 4 mm, respectively, indicating a relatively small discrepancy as well. However, since the linear fit to the large-probe function was excellent over this stimulus range, determining the position of the quadratic peak may not be overly meaningful, as was likewise the case for the bare finger. In the latter condition, there was a considerably greater discrepancy between the estimated peak and the contact diameter (4.8 mm for the peak vs. 9 mm for the minor axis of the bare-finger contact).

Discussion

This experiment yielded three major psychophysical results from exploring with a probe, as compared with the bare finger. When described as a power function in the traditional manner (a linear function on log–log scales), the exponents of all three functions were positive. The shallower rates of growth observed in the magnitude-estimation functions for the two probes, as opposed to the bare finger, indicate that roughness perception was less sensitive to interelement spacing when a rigid link was used. Presumably, the difference in rates reflects the relative efficacy of spatial-intensive coding with the finger, as opposed to vibrotactile coding required by the intervening probe. Second, quadratic fits produced differences between the functions with respect to the point of downturn, indicating that the relation of perceived roughness to interelement spacing was altered by the method of exploration. The peak of the functions was clearly lowest for the small probe. The higher peak values were about the same for the large probe and the bare finger but are difficult to interpret, because of the excellent linear fits and because the estimated peaks fall outside the range of stimuli used here. Earlier research with the bare finger and a larger range of stimuli (e.g., Connor, Hsiao, Phillips, & Johnson, 1990; Lederman et al., 1986) has found that the psychophysical roughness functions peak at about 3.5 mm. It is not surprising that the bare-finger function in Experiment 1 did not peak, given that the interelement stimulus range only went up as high as 3.5 mm. Third, although the finger produced the greatest sensitivity to interelement spacing (as is indicated by the slopes), the five narrowest stimuli actually produced higher subjective roughness estimates when the narrowest probe was used, followed by the large-probe and then the bare-finger conditions.[2]

Next, we speculate on how the vibratory signals produced during contact with a probe might be affected by interelement spacing and probe size, in interaction with one another. In subsequent research, we plan to measure the signals directly and then predict how subjects might use such information to judge roughness. In this initial assessment, we consider the amplitude and fundamental frequency of the vibratory signal resulting from exploration, both of which are potentially salient cues.

Consider first the joint effects of interelement spacing and probe size on the amplitude of the vibratory signal. When the diameter of the probe is wider than the smallest interelement spacing in the textured surface, vibrations will be produced as the probe contacts the tops of the elements, perhaps catching on their edges as well. These signals presumably will be of relatively low amplitude, because the distance the probe can rise and fall must be minimal. When the probe size is intermediate, relative to the spacing, it will move part way down into the troughs between some, but not all, of the elements. Thus, it will produce vibration not only when it rides along the tops of the elements, but also each time it contacts the base of the surface, when it moves to varying degrees along the base surface between raised elements, and when it catches on the leading edges of each subsequent element that is contacted. Such vibration will therefore be of relatively higher amplitude. With extremely wide interelement spacing (i.e., wider than the probe tip), the probe will produce vibrations whose average amplitude (over space and/or time) is determined primarily by relatively extensive contact along the smooth base surface between raised elements. Thus, the amplitude of the vibratory signal can be hypothesized to first increase, then decrease, with interelement spacing for a given probe size, and the point of maximum amplitude will be at greater spacing values for larger probes.

Next, consider the potential use of the fundamental frequency of the vibratory signal to code roughness. For a given spatial frequency (i.e., the inverse of interelement spacing) and a given exploratory speed, there will be a particular fundamental temporal frequency. (Transients will also exist, of course, but we focus here on the fundamental.) The relation between spatial and temporal frequency is likely to depend on the contact area of the effector, relative to the textured surface elements. The relation is most straightforward when the probe is small enough, relative to the interelement spacing of the surface, that it falls between elements, and thus, the frequency of contact with an element decreases with increasing interelement spacing. Over the range in which the spacing is so small that the probe rides above the surface elements, the relation between spatial and temporal frequency is less obvious and may well be attenuated. We therefore speculate that vibratory frequency will be a monotonically decreasing function of interelement spacing that is likely to be flatter at low values of spacing. The relationship between perceived roughness and vibratory frequency is yet more uncertain. On the basis of the small and inconsistent effects found by Kudoh (1988), one could predict that perceived roughness would be inversely related to frequency and, hence, directly related to interelement spacing. The same relation would be predicted if perceived roughness with a probe were to parallel judgments of roughness that were based on the frequency of sounds produced by someone else touching (Lederman, 1979). However, there is simply too little extant data to reach any conclusion about the dependence of perceived roughness on the fundamental frequency of vibration when exploring with a probe.

In short, to the extent that subjects use the amplitude of the vibratory signal, we might predict a U-shaped function relating perceived roughness to interelement spacing, with the peak of the function being at lower spacing values as the probe is smaller. The inverted-U–shaped function predicted by amplitude variations should be obtained particularly when the range of interelement spacings incorporates values both larger and smaller than the probe tip. Over the range of interelement spacings presented in this experiment, this is, in fact, what we observed for the small probe. The large probe failed to show a downturn in the function, which is in keeping with its being larger than any of the spacing values used here. We find it more difficult to predict effects of the fundamental frequency of vibration. The data provide no support for the idea that, if frequency mediates roughness perception, magnitude estimations should be directly related to spacing in the stimulus range in which the probe tip is smaller than the average interelement spacing. However, such an effect might be overshadowed by effects of amplitude, which we expect to be in the opposite direction.

Finally, in agreement with previous experimental results, we assume that, when exploring with the bare finger, the subjects used a spatial-intensive code (not vibration) to produce the obtained psychophysical power function with a positive exponent. The use of nonvibratory coding may reflect not only the availability of spatially distributed forces at the fingertip, but also the tendency of the compliant skin to damp low-level vibration and catch less on the edges of protruding surface elements than do the probes.

EXPERIMENT 2

Roughness Differentiation With Finger Versus Probes, Using a Roughness-Comparison Task

Experiment 2 used a roughness-comparison task in which the two stimulus plates presented on each trial were always different and a judgment was made as to which was rougher. Again, exploration was either with the bare finger or with the large or small probe. This task allows us to determine not only sensitivity to the degree of difference in the stimuli, but also the nature of the underlying function relating comparative roughness to interelement spacing. In theory, if subjective roughness first increases, then decreases, with increasing interelement spacing, comparative roughness judgments should shift in direction at some point along the spacing dimension. That is, whereas greater interdot spacing is judged to be rougher when spacing values are low, there should be a point on the interdot spacing dimension at which a stimulus with greater interdot spacing is judged to be smoother, for reasons explained above. The magnitude estimations of Experiment 1 suggest that such a shift in comparative judgments would be evident particularly with the small probe, if not with the larger probe or bare finger, over our range of stimulus values. Estimation of the shift point is likely to be less reliable in the case of the large probe and finger, because the derived peaks of the corresponding magnitude-estimation functions in Experiment 1 occurred beyond the end of the stimulus range and because the linear fits to the log–log functions were excellent.

Method

Subjects. The subjects were 24 right-handed university students or staff, who were compensated for their participation. Eighteen were female and 6 were male. The subjects were randomly assigned to two groups of 12 each, according to the size of the probe to be used. Each subject took part in two conditions, one with the bare index finger and one with a probe. Half the subjects used the small probe, and half the large probe.

Procedure. The study used 23 plates with interelement spacings ranging from 0.5 to 3.5 mm. The plates were assigned to pairs, so that 20 pairs differed in spacings by 0.125 mm, two pairs differed by 0.25 mm, three differed by 0.375 mm, two differed by 0.5 mm, and one differed by 0.625 mm (see the Appendix.). Using 0.125 mm as a baseline difference in interelement spacings between items in a pair, these groups will be called the one-step pairs, the two-step pairs, the three-step pairs, the four-step pairs, and the five-step pair, respectively. The single five-step pair was ultimately combined with the four-step pairs for data analysis.

The subjects were blindfolded and fitted with foam ear plugs that were worn under headphones. The same tape as that used in Experiment 1 was played through the headphones at a comfortable level, in order to mask the sounds of exploration. On each trial, two plates were placed on the desktop directly in front of the subject, approximately 3 cm apart (center-to-center distance of 14 cm). The subjects applied either the probe or the distal phalanx of the index finger, as designated for the given condition, with a light sweeping motion from left to right across each plate in turn. They could reexamine the stimuli as many times as desired with the same motion. They then indicated which member of the pair was rougher. No definition of roughness was provided.

The subjects explored each pair twice with the finger and twice with a probe. The pairs were presented in one of two orders, PFFP or FPPF, where P stands for a block of trials in which the plates were explored with the probe and F stands for a block in which exploration was with the finger. Within each block, there was a randomly ordered run through the 28 pairs. Both orders were used equally often with each probe, across subjects. Five practice pairs preceded the experimental trials, with feedback; no feedback was given during the experimental trials.

Results and Discussion

An initial ANOVA was conducted on comparison accuracy. For this purpose, a response was considered correct if the stimulus with greater interelement spacing was called rougher. The ANOVA was directed at the effects of the difference between the stimuli on comparative-roughness judgments. It included factors of end effector (probe vs. finger), probe size (large or small), pair difference (difference in interelement spacings of the two plates in 0.125-mm steps: one step, two steps, three steps, or four and five steps combined), and replication (first vs. second presentation of a pair). Only the probe size factor was manipulated between subjects.

Figure 3 (top panel) shows the mean accuracy as a function of pair difference for each combination of end effector and probe size. For this analysis, proportion correct was determined for the items within a given level of pair difference (combining four- and five-step pairs), within each subject. Overall, performance was best with the bare finger and worst with the small probe, producing a significant effect of end effector [$F(1,22) = 21.68, p < .001$]. This is what was expected from the magnitude-estimation functions in Experiment 1. Accuracy increased with increasing pair difference for all end effectors; thus, the main effect of pair difference was significant [$F(3,66) = 360.80, p < .001$]. There was also an interaction between end effector and pair difference [$F(3,66) = 4.21, p < .01$], reflecting the fact that the effect of the end effector was primarily observed for the one-step pairs. The interaction between end effector and probe size was also significant [$F(1,22) = 9.05, p < .01$]. The analysis also revealed a

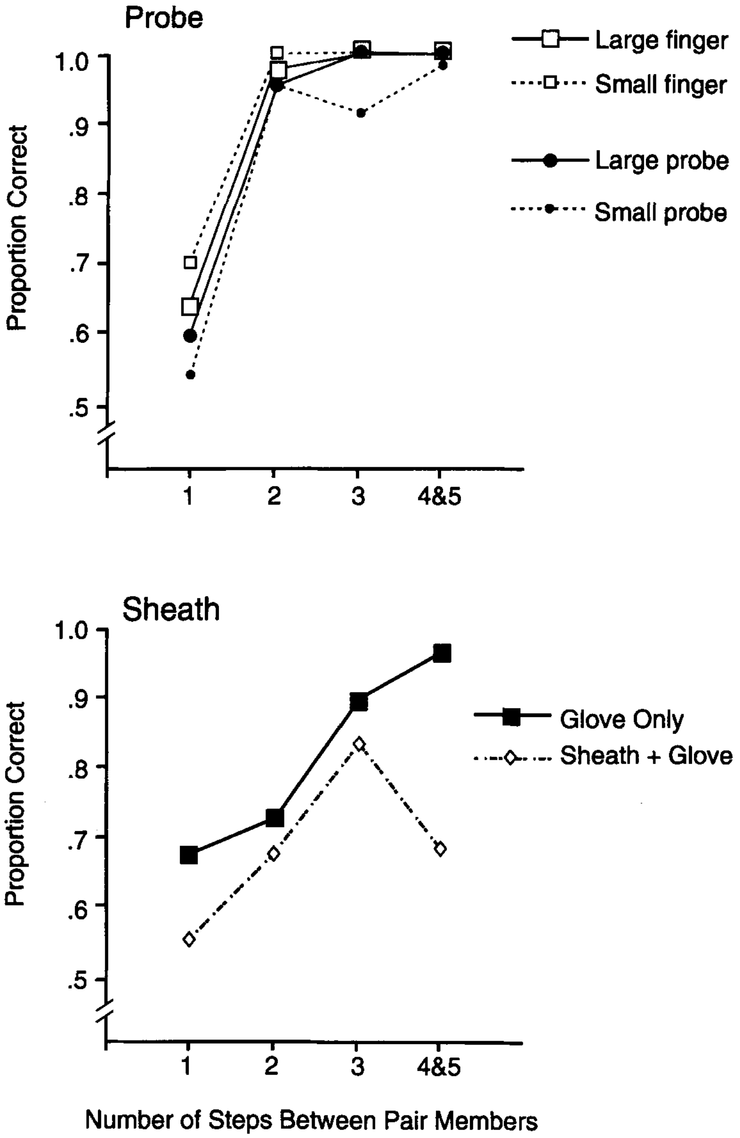

Figure 3. Proportion correct on roughness comparisons of Experiment 2 (top panel) and Experiment 4 (bottom panel), as a function of number of 0.125-mm steps between the stimuli with respect to interelement spacing. In Experiment 2, different groups of subjects explored with a large or a small probe or with the bare finger. The legend subscript refers to the size of the probe used in the group. In Experiment 4, the end effectors were sheath + glove or glove only.

three-way interaction involving replication, pair difference, and probe size [$F(3,66) = 3.54, p < .05$]. However, replication did not alter the qualitative pattern of results and was not significant in the supplementary analyses, so it will not be considered further.

A supplementary ANOVA on the pairs separated by more than one step showed no effect of end effector, pair difference, probe size, or replication, reflecting ceiling effects with these larger pair differences. An ANOVA within the one-step pairs showed that the effect of end effector was significant [$F(1,22) = 21.53, p < .001$], as was the interaction between end effector and probe size [$F(1,22) = 7.14, p < .05$]. The accuracy difference between the bare finger and the small probe was significant [$t(11) = 5.92$, $p < .01$], but the other comparisons of end effectors did not reach significance.

We next examine how roughness judgments varied with the position of the stimuli on the interelement-spacing dimension. Figure 4 shows proportion of correct responses (i.e., the stimulus with the larger space value was judged rougher) on a given one-step pair, as a function of the spacing in the lower valued member of the pair. For this

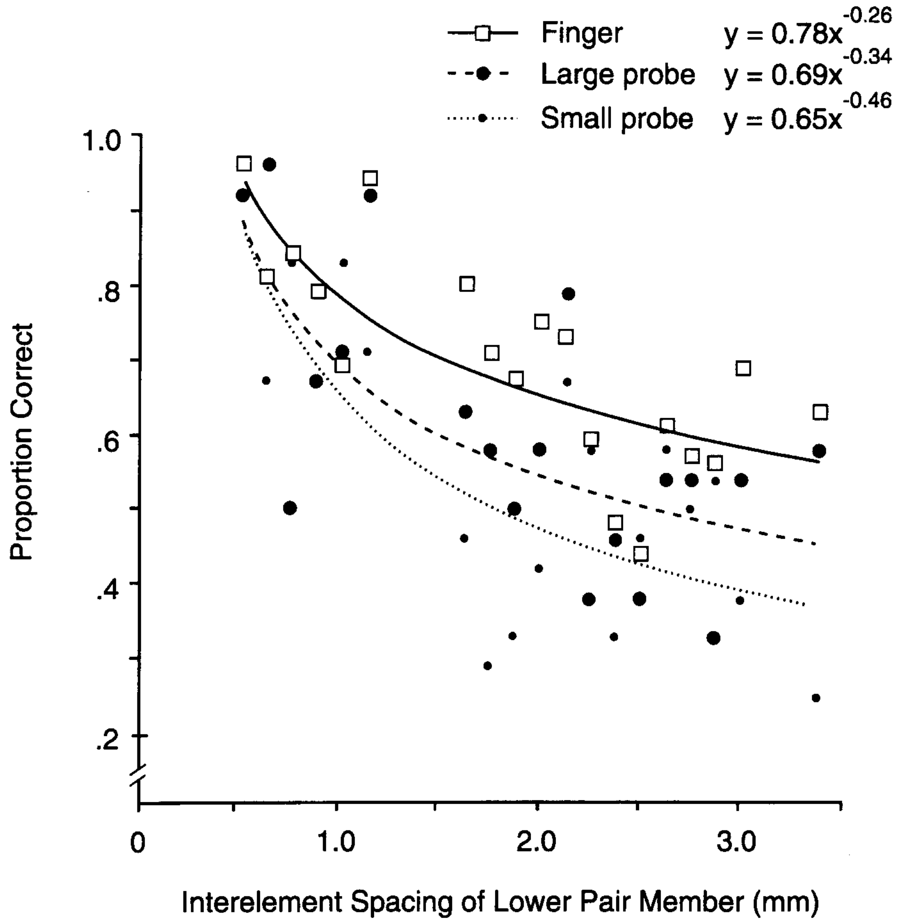

Figure 4. Proportion correct in roughness comparisons of Experiment 2, where the correct response is defined as choosing the stimulus with lesser interelement spacing. All the pairs were separated by 0.125 mm in interelement-spacing values; the abscissa represents the lesser value of the pair. The subjects explored with the bare finger, a large probe, or a small probe; a power function has been fit to each condition.

analysis, the observations of a given pair (two per subject within a condition) were pooled across subjects. One pair of stimuli, with interelement-spacing values of 1.25 and 1.375 mm, proved to produce anomalously low accuracy (relative to neighboring pairs) when explored with the finger (23%). Exclusion of this pair did not alter the significance of statistical tests. However, the pair was excluded for purposes of fitting functions to the one-step pairs. The figure shows power functions fit to the data for each probe and the finger (averaging over the finger data from the large- and small-probe groups). As was predicted by Weber's law, the functions show a decline in performance as the interelement spacing increases, with the steepness of the decline (as determined by the exponent, which would be the slope of the function in a log–log plot) decreasing from the small probe to the large probe to the finger. The multiplicative factor (which would correspond to the intercept of a linear function on a log–log plot) increased from the small probe to the large probe to the finger. The r^2 associated with the function is .58 for the finger, .48 for the large probe, and .58 for the small probe, indicating a not inconsiderable amount of variability.

Given the strong downturn in the small-probe magnitude-estimation function, we may now ask whether, for the corresponding function in Figure 4, there is some point of interelement spacing at which there would be a reversal in the direction of comparative roughness judgments. That point can be estimated by the x-value at which the function crosses the 50% accuracy level. For the small probe, the value of the average spacing (for the lower member of the pair) is 1.9 mm. Corresponding values for the large-probe and the bare-finger functions are 2.6 and 5.4 mm, respectively. The value for the small-probe function corresponds almost exactly with the point at which subjective roughness peaks, estimated, from Experiment 1, to be 1.7 mm. Recall that it is at this point that perceived roughness stops increasing with interelement spacings and begins to decrease, and thus, it is at this point that the stimulus with greater spacing should begin to be called smoother rather than rougher. (Parallel comparisons for the

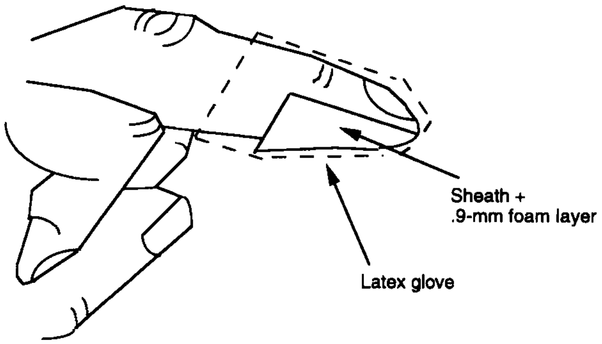

Figure 5. Illustration of the sheath used in Experiments 3 and 4.

large probe and the finger are questionable, given the excellent fits obtained with linear, as well as quadratic, fits in Experiment 1.)

To summarize, the data in Figure 3 (top panel) verify that roughness can be discriminated quite well with vibrotactile cues. With stimulus differences in interelement spacing of 0.25 mm or greater, both probes achieved performance levels that were not statistically differentiable from that for the bare finger. With a difference of 0.125 mm, the mean accuracy was ordered as would be expected from the steepness of the magnitude-estimation functions in Experiment 1: The finger performed best and the small probe worst.

However, the relative inaccuracy with the small probe doubtless reflects another mechanism as well. With that probe, judgments appeared to shift from more sparsely dotted surfaces being rougher to their being smoother, causing a drop to below 50% performance. This shift occurred at about 2-mm spacing. This was expected from the downturn in the magnitude-estimation function with the small probe in Figure 2. The shift in the psychophysical relation contributed to the lower accuracy for step-one pairs observed with the small probe, because the judgments that more sparsely dotted pairs were smoother would be counted as errors.

EXPERIMENT 3
Magnitude Estimation With Sheathed Versus Unsheathed Finger

We now turn from using a stick-like probe as a rigid link between skin and textured surface to using a sheath that covers the entire distal phalanx of the finger. This experiment replicated the magnitude-estimation procedure of Experiment 1, but with the finger covered by a rigid sheath inserted into a snug-fitting latex glove (*sheath + glove* condition—see Figure 5) or only by the glove (*glove-only* condition). The thin (0.17-mm), compliant glove should alter the friction of the surface interaction, but this should not have a substantial effect on roughness perception (Taylor & Lederman, 1975). To confirm this finding, however, we performed an additional control experiment, which compared roughness perception with and without the glove. In support of Taylor and Lederman's original result, no differences were obtained.[3] (See, also, Thompson & Lambert, 1995, for a null effect of a latex glove on two-point threshold and detection of fibers.) The sheath provides not only a rigid but a large contact surface, one that is larger than any of the interelement spacings. As a result, it should not ride up and down on the elements at any spacing, which would presumably reduce the amplitude of vibratory cues to texture, relative to the probes used in Experiments 1 and 2. The question is whether the vibratory cues provided by the sheath will be adequate to judge texture.

Method

Subjects. The subjects were 10 right-handed university students, 4 female and 6 male, who received credit for participation.

Procedure. The procedure was the same as that in Experiment 1, except that the subjects explored the plates while wearing a latex glove that covered either a rigid sheath molded to the fingertip or the bare fingertip, as is shown in Figure 5. The middle finger was used in both conditions, for greater stability when exploring with the sheath. (This may have reduced sensitivity somewhat, relative to the index finger used in Experiments 1 and 2; see Lederman, 1976.) The sheath was made of fiberglass (approximately 1 mm thick), covered with a 1-mm layer of pliable foam to prevent extremely high frequency vibration (chatter) during contact; this did not alter the vibratory threshold. It extended from the fingertip to approximately the proximal interphalangeal joint and had a semicircular cross section, so that it covered the ventral surface and sides of the finger but left the nail and the dorsal surface exposed. The size of the sheath was selected for each subject so that it fit the contour of the index finger without slipping. The subject wore a 0.17-mm-thick latex glove over the sheath as a lightweight support. In the glove-only condition, only the glove was worn, to equate for friction with the sheath + glove condition while being compliant enough that the pressure gradient would be transmitted. The instructions were identical to those for Experiment 1, except that a light stroke with the finger was emphasized, to avoid tearing the glove. Eight practice trials with the appropriate exploratory mode preceded each block of trials.

The subjects participated in one of two orders: SGGS or GSSG, where each letter represents a block, within which type of exploration was held constant and there were two presentations per plate. The S stands for a block of exploration with the sheath + glove and G stands for a block with the glove only. Presentations within a block were randomized.

Results and Discussion

The magnitude estimates were first normalized, as in Experiment 1, and then log transformed. Figure 6 shows the geometric mean of the magnitude estimates of roughness, as a function of the interdot spacing, for the two conditions (log scales). All the statistical analyses were performed on the log-normalized data. A paired t test indicated that the slopes of linear functions fit to the data differed significantly between sheath + glove and glove-only [$t(9) = 3.88, p < .01$]. There seemed to be no point in fitting a quadratic function to the log–log data, since linear functions accounted for 96% and 95% of the variance in the glove-only and sheath + glove conditions, respectively. (The additional parameter in the quadratic only

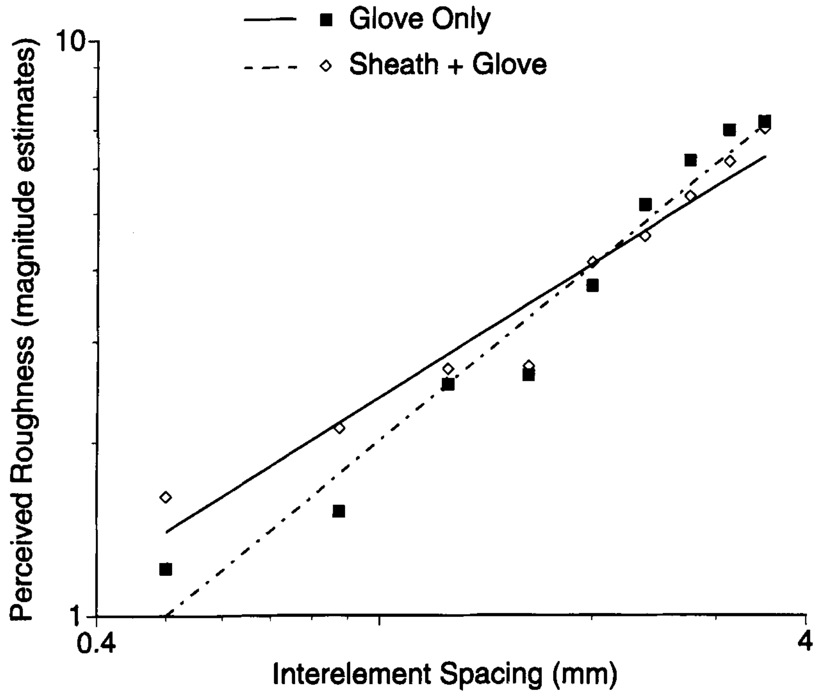

Figure 6. Geometric mean magnitude estimate as a function of interelement spacing of the stimulus in Experiment 3 (on log scales), for the two end effectors—sheath + glove or glove only. Linear functions have been fit to the log–log data.

slightly increased the explained variance, to 98% in both conditions.) The slopes of the present linear functions, 1.01 for the glove-only condition and 0.77 for the sheath + glove condition, are comparable with slopes of linear functions fit to the Experiment 1 log–log data for the finger (slope = 1.00) and large probe (slope = 0.79). (Linear functions provided reasonable fits to the data for those two conditions in Experiment 1.)

Moreover, when the low values of interelement spacing are considered, the sheathed finger actually led to higher magnitude estimates than did the glove only. This is consistent with the results of Experiment 1, where again, at the lower values of interelement spacing, using the probes produced higher magnitude estimates than did using the bare finger. In both studies, it appears that the subjective roughness of the smoothest stimuli was enhanced by a rigid link.

As is indicated by the scant improvement when fitting a quadratic, there was no apparent downturn in the magnitude-estimation functions in this experiment. We have taken the downturn to indicate the point at which the exploring effector makes the transition from riding along the tops of the protrusions in a surface to riding down into and along the substrate below them. At that point, the relationship between interelement spacing and perceived roughness should become reversed. The failure of the present functions to indicate a reversal was not unexpected, since the exploring surface in both the sheath and the finger conditions was larger than the largest interelement-spacing value (3.5 mm).

EXPERIMENT 4

Roughness Differentiation With Sheathed Versus Unsheathed Finger, Using a Roughness-Comparison Task

In this experiment, we evaluated roughness comparisons in the sheath + glove and glove-only conditions. The task was directly analogous to that in Experiment 2.

Method

Subjects. The subjects were 10 right-handed university students, 7 female and 3 male, who received credit for participation.

Procedure. The stimuli were identical to those of Experiment 2, except that 2 additional one-step pairs were used, for a total of 30 (see the Appendix). The subjects wore a blindfold and cotton in the ears, over which sound-attenuating headphones were placed. No background noise was imposed. The sheath + glove and glove-only conditions were like those of Experiment 3; again, the middle finger was used. As in Experiment 2, two block orders were used: SGGS or GSSG. One randomly ordered run through the stimuli occurred in each of the four blocks. The instructions were identical to those for Experiment 2, except that a light stroke with the finger was emphasized, to avoid tearing the latex glove. Eight practice trials were presented, with feedback, before each block.

Results

Figure 3 (bottom panel) shows mean accuracy in the sheath + glove and glove-only conditions, as a function of pair difference. The sheath + glove condition was clearly worse at all levels of pair difference. An initial ANOVA included factors of end effector (sheath + glove and glove-only), pair difference (difference in interelement spacings

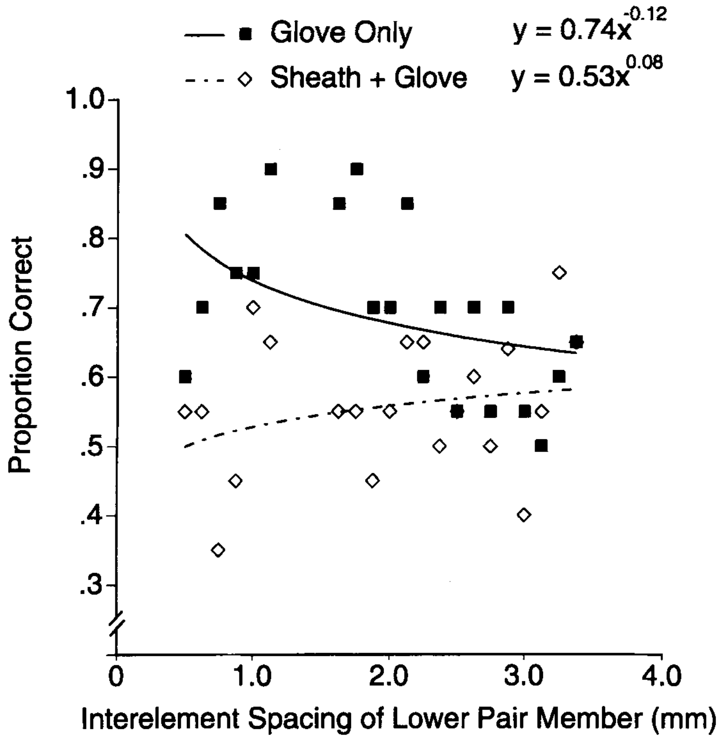

Figure 7. Proportion correct in roughness comparisons of Experiment 4, where the correct response is defined as choosing the stimulus with lesser interelement spacing. All the pairs were separated by 0.125 mm in interelement-spacing values; the abscissa represents the lesser value of the pair. The subjects explored with the sheath + glove or glove only. A power function has been fit to each condition.

of the two plates in 0.125-mm units: one, two, three, or four and five steps combined), and replication (first vs. second presentation of a pair). All three main effects were significant: end effector [$F(1,9) = 9.59, p < .05$], pair difference [$F(3,27) = 6.92, p < .01$], and replication [$F(1,9) = 7.68$, $p < .05$]. Although the interaction between replication and pair difference was not significant, the replication effect was not observed in the one-step pairs (accuracy = .61 on replication 1 and .62 on replication 2). With larger step sizes, accuracy decreased from replication 1 to replication 2 (average proportion decrease = .09), contraindicating practice effects. There were no interaction effects, so replications will not be considered further. Supplementary ANOVAs showed that the main effect of end effector—that is, the sheath disadvantage—was significant both within the one-step pairs [$F(1,9) = 19.74, p < .01$], and within pairs separated by more than one step [$F(1,9) = 6.25, p < .05$].

Figure 7 shows accuracy on the one-step pairs as a function of the interelement spacing in the lower valued member of the pair for each method of exploration. It can be compared with Figure 4, which shows corresponding data for the bare finger and the stick-like probes. Again, the pair of stimuli with spacing of 1.25 and 1.375 mm produced anomalously low accuracy, this time with the glove (20%; cf. 23% for the corresponding finger accuracy in Experiment 2). Exclusion of this pair did not alter the outcome of statistical tests, but the pair was eliminated for purposes of fitting power functions to the one-step pairs. The r^2 values associated with the functions were very low and are included here only for comparison with Experiment 2; they were .06 for the sheath + glove condition and .15 for the glove-only condition.

The function fit to the glove-only data showed a decline in performance as the interdot spacing increased, although it was less steep than the corresponding functions from Experiment 2. Given that the magnitude-estimation function for the glove-only condition did not have a downturn, we did not anticipate that the function in Figure 7 would cross the 50% point. Therefore, no projection of the point of reversal was done; moreover, the goodness of fit of the power function was low. It is interesting that, despite the obvious difference in rate of decrease for the functions fit to the bare-finger data (Figure 4) and the glove-only data (Figure 7), the accuracy scores were correlated across the two conditions [$r(18) = .71$ over the one-step pairs common to both studies].

With pairs differing by only one step, performance with the sheath + glove was near chance, on average (55%). This phenomenon cannot be attributed to the subjects' shifting from calling more sparsely spaced pairs rougher to calling them smoother (which occurred with the small-probe condition in Experiment 2), because the function fit to the sheath + glove data in Figure 7, relating accuracy to interelement spacing in the lower pair member, was essentially flat or slightly increasing. Apparently, when members of a pair were close in interelement spacing, roughness discrimination with the sheath was uniformly insensitive across the stimulus range.

Comparing Experiments 2 and 4, the gloved middle finger (Experiment 4) and bare index finger (Experiment 2) led to similar accuracy with the one-step pairs (.68 and .67, respectively). Also, with one-step pairs, the small probe and the sheath + glove led to similar, but low, accuracy (.54 and .55), with the large probe being intermediate (.60). With the two-step pairs or higher, performance with the probes and the bare finger in Experiment 2 reached levels of 90%, regardless of the method of exploration. The glove-only accuracy in Experiment 4 reached 90% with three-step differences, but the sheath + glove accuracy remained below that level even with differences greater than three steps. These observations support the assumption that performance with the sheath is considerably below that achieved with the more stick-like probes, which are closer to perception with the finger in terms of supporting discrimination accuracy.

GENERAL DISCUSSION

The findings of the present experiments indicate that vibrotactile coding of roughness through a rigid link can be highly sensitive. Moreover, the nature of the link—particularly at the site of contact with the surface—affects the functional relationship between surface properties and perceived roughness. Subsequent discussion expands on these points and relates the findings to applied contexts.

Relation of Perceived Roughness to Interelement Spacing

The present studies asked whether vibrotactile and spatial-intensive coding mechanisms show common psychophysical functions relating perceived roughness to the interelement spacing of the stimulus surface. In Experiment 1, the data relating subjective roughness magnitude to interelement spacing in the stimulus were fit well by quadratic functions, although the quadratic trend was considerably more evident with the small probe than with the large probe or the finger. Moreover, the peak of the function—taken to indicate a shift from a tendency to perceive more sparsely dotted surfaces as rougher to perceiving them as smoother—occurred at a lower interelement-spacing value for the small probe than for the other conditions (if it occurred at all in those cases).

We attribute the difference between the large and the small probe to effects on vibratory intensity arising from the scale of the probe, relative to the spacing of surface elements. Larger spacing at first produces more buffeting of the probe and greater perceived roughness, up to the point at which the spacing is so large that the probe can ride along the underlying substrate. The small probe reaches the point of peak perceived roughness at a more dense spacing level than does the large probe. In contrast, the difference between the probes and the bare or gloved finger seems best attributed to the use of vibrotactile coding with the probe and of spatial-intensive coding with the finger, given the evidence that vibration is not the basis for normal roughness perception at this (macro) stimulus scale.

Extending the argument about stimulus size to the sheath, given its large contact area, it is clear that it does not ride between elements at any value of stimulus spacing within the range used here. Accordingly, the magnitude-estimation functions for the sheath + glove condition were strongly linear and had no downturn. We would expect the direction to become reversed, however, if sufficiently wide dot spacing were introduced and the exploring effector rode along the bottom of the plate.

Turning from magnitude estimation to the roughness-comparison task of Experiments 2 and 4, the bare finger, gloved finger, and hand-held probes led to qualitatively similar psychophysical functions. When accuracy was considered as a function of interelement spacing, the function decreased in all these cases, although less so for the glove-only than for the other conditions. This overall decrease is expected from the quadratic functions obtained with the magnitude-estimation task, if some straightforward assumptions are made. Assume, first, that the subjective difference between two stimuli decreases with their increasing position on the interelement-spacing dimension, holding the objective difference between the stimuli constant. This is indicated by the negative acceleration in the magnitude-estimation function. Assume next that the closer two stimuli are in subjective magnitude, the less certainty there will be as to which is rougher. Assume, finally, that the level of certainty in any one roughness judgment translates into a percentage agreement, when multiple judgments of the same stimulus pair are aggregated. That is, the less certainty associated with any judgment as to which member of a pair is rougher, the lower the consistency across judgments will be. Under these assumptions, as interelement spacing increases, pairs of stimuli with equal objective differences will be subjectively closer in roughness and, hence, will produce less consistency in the comparative-roughness judgment. This relation holds up to the point at which the magnitude-estimation function reaches a peak. At this point, subjective roughness shifts from treating more sparsely dotted plates as rougher to treating them as smoother, and comparative-roughness judgments should also become reversed, causing the accuracy of roughness comparison (under a criterion of *sparser spacing is rougher*) to fall below chance.

By our reasoning, the size of the exploring effector determines the level of interelement spacing at which (1) the magnitude-estimation function peaks and (2) the roughness-comparison function falls below 50% accuracy. Both the peak of the magnitude-estimation function and the 50% accuracy point in roughness comparison should occur at approximately the interelement spacing at which the effector shifts from rising and falling with the raised surface elements to predominantly riding along the substrate. This level of spacing is determined by the size of the end effector. One can ask, then, how well the function parameters and effector size agree. For the small probe, the contact diameter was approximately 2 mm, as was the estimated peak of the magnitude-estimation function and the 50% accuracy point in comparative-roughness judgments. As the critical points in the psychophysical functions for the large probe and sheath fall near or beyond the range of samples used, estimation of the parameter values becomes more problematic.

The roughness-comparison task with the sheath + glove produced quite a different psychophysical function with one-step pairs than it did with the other exploratory conditions. Accuracy was relatively invariant (and near chance) across the interelement spacing dimension. This is in contrast to the decreasing functions obtained in other conditions; however, the magnitude-estimation task with the sheath + glove did not produce a negatively accelerated function, which we assume underlies the decrease in comparative-roughness accuracy in other conditions. The glove-only condition fell between the sheath + glove condition and the others. Like the sheath + glove condition, it did not produce a negatively accelerated magnitude-estimation function, but like the finger and probe conditions, it did produce a decreasing comparative-roughness function. The decrease was relatively shallow, but it does indicate an underlying tendency for relative magnitudes to become less differentiable at higher spacing levels, under exploration with the gloved finger. Apparently, this tendency was not measurable with the stimulus spacing used in the magnitude-estimation task.

Sensitivity of Vibrotactile Roughness Coding

On the whole, it appears from these experiments that vibrotactile coding of roughness is effective to a substantial extent. One indication of its sensitivity is simply the magnitude of subjective roughness when a surface is explored through a rigid link between skin and surface. The greater the reported level of perceived roughness for a given objective value, the more intense the internal response to the explored surface. We consistently found that, at lower levels of interelement spacing (i.e., with the stimuli perceived to be smoothest), subjective roughness was actually higher with a rigid link than with the bare finger or a compliant link (the latex glove). Possibly, the compliant surface of the skin or the glove leads to lower perceptual values with low-intensity stimuli because of its damping characteristics. It is also possible that the compliant surface catches less on the edges of raised elements than does the rigid surface. It is interesting in this regard that, in our related study assessing perception through a sheath (Lederman & Klatzky, in press), we found that vibratory thresholds were very similar for the sheath + glove and the glove-only conditions. The present difference between the subjective magnitudes at low levels of interelement spacing must, then, reflect suprathreshold mechanisms that differ with compliant versus rigid links.

Another indication of sensitivity to vibrotactile-coded roughness is the degree of increase in the function relating subjective roughness to interelement spacing in the explored surface, as was assessed in Experiments 1 and 3. The rate of increase indicates how much the internalized roughness response differs, in relation to an objective difference in the stimuli. The greater the increase, the greater the internal differentiation corresponding to stimulus variation. In general, the subjective-magnitude function was increasing for all exploratory conditions, although some functions showed a downturn with the stimuli having largest interelement spacings. However, the magnitude of the increase (even excluding the region of downturn) was less for the conditions with rigid links than for the bare or the gloved finger. This indicates that vibrotactile coding provides lower precision in differentiating stimuli than does spatial-intensive coding.

The level of performance in the roughness-comparison tasks used in Experiments 2 and 4 provides further measures of roughness differentiation. As we have noted, accuracy in the roughness-comparison task is more difficult to interpret, because below-chance accuracy in some conditions may reflect reversals in how comparative roughness was related to interelement-spacing differences. That is, the assumption underlying scoring was that more sparsely dotted surfaces were to be called rougher throughout the range tested, but for some conditions, what the experimenters called a correct response did not match consensus beyond a certain point in that range. Despite the possibility that the probe conditions were penalized by such reversals, Experiment 2 showed above-chance performance with a large stick-like probe even for stimuli that were quite similar in interdot spacing (one-step pairs). For more differentiable surfaces (two-step pairs or greater), performance with both large and small probes reached levels that were indiscriminable from performance with the bare finger.

The sheath + glove condition in the roughness-comparison task of Experiment 4, in contrast, remained inferior to the stick-like probes or the finger (bare or gloved), even when the judged surfaces differed substantially with respect to interdot spacing. Moreover, in the case of the sheath, the poor performance cannot be attributed to reversals in the directions of judgments at a critical point in the stimulus range, since close discriminations led to poor performance across the entire range tested.

Probe Versus Sheath as a Rigid Link for Exploring Surface Roughness

What is the difference between a sheath over the fingerpad and a hand-held probe? One difference, which we have emphasized, is the size of the contact surface, which affects vibratory magnitude. The nature of feedback to the skin should also differ between probe and sheath. The sheath has one continuous contact surface with the skin on a single finger, whereas the probe has multiple discrete contact points. Both probe and sheath could potentially produce traveling waves as the basis for a vibrotactile signal to roughness. But the greater vertical translation of the probe during exploration may provide additional vibrotactile cues, such as gross skin deformation from contact with the handle and joint movements as the probe tip rides the raised elements in the stimulus.

On the motor side, the control over exploration is another potential difference between probe and sheath, this time apparently in the sheath's favor. The unpredictable rise and fall of the probe as surface elements are contacted should perturb its sweep. Also, the probe's small contact surface and shaft length combine to produce ambiguity in how the plate is being contacted. At an extreme, if the probe end approximates a sphere, so that contact is at a single point, the shaft could move within a cone around the surface normal without changing the position of the contact point. (The size of the cone would be determined by the coefficient of friction.) With its larger surface, the sheath does not produce the same ambiguity. A coarse pressure gradient along its length and around its edge are likely to allow explorers to maintain an unambiguous position, relative to the explored surface. Despite these arguments suggesting a relative advantage for the sheath in maintaining, controlling, and monitoring exploration, it is at a clear disadvantage in roughness perception. Apparently, an advantage in motor control is outweighed by the failure of the sheath to provide temporal cues to the skin.

As was noted above, we have found that vibratory thresholds are very similar for the sheath + glove and the glove-only conditions. Vibratory cues transmitted through the sheath presumably underlie the relatively high subjective magnitudes for the smoother stimuli, as well as the positive slope in the magnitude-estimation function. The differential vibration through the sheath is not, however, sufficient for precise roughness discrimination.

Application to Teleoperation and Virtual Environments

From an applied perspective, it is important that people experience a strong sense of surface roughness from a rigid link between surface and skin. Moreover, all the links we tested allowed substantial roughness discrimination. These findings support the use of vibrotactile cues to roughness in environments in which direct skin contact is precluded.

Vibratory cues can have various applied functions. In teleoperation, they can be used to convey contact between a remote end effector and an object's surface, by feeding back the vibratory signal that occurs. An implication of our results is that, to maximize such vibratory feedback, the scale of a remote probe should be fit to the geometric properties of the probed surface. Fortunately, it seems likely that, in many contexts, the telemanipulated end effector will require a small surface for functional reasons (e.g., a surgical scalpel).

Vibration is also used to render surface texture for purposes of teleoperation and virtual environments. In teleoperation, texture cues could provide information about the coefficient of friction on the surface of a manipulated object, which could direct the magnitude of forces to be applied in a natural way. Degrees of roughness could also be used to differentiate between surfaces—for example, between types of tissue in telesurgery. And in virtual environments, texture cues promote a greater sense of "presence."

Our results indicate that a rigid link between skin and environment does not preclude access to rich vibrotactile cues that signal environmental events and surface textures. Along with other results suggesting that haptic exploration through a rigid probe can provide extensive information about the distal environment (Barac-Cikoja & Turvey, 1991), these findings are encouraging with respect to the utility of haptic cues for remote and virtual manipulation.

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NOTES

1. The textured surfaces used in the study spanned a range of average interelement spacing from 0.5 to 3.5 mm. A broad range was used because the resolution constraints of the finger do not apply when a surface is explored with a rigid link. However, the use of finely spaced (i.e., <1 mm) and more widely spaced elements would presumably create a transition from vibrotactile to spatial coding when explored directly with the finger. We cannot speculate on the implications of this coding transition for the data.

2. The same pattern of results was confirmed in an undergraduate honors thesis by Andrea Swanson (Experiment 1), where the bare finger was always performed first, followed by the two probe conditions in counterbalanced order (Swanson, 1996).

3. The control experiment was performed to determine whether wearing a thin latex surgical glove altered perceived roughness judgments, as compared with when the bare finger was used alone. A total of 12 subjects gave magnitude-estimation judgments of all nine plates used in both Experiment 1 and Experiment 3. Each plate was judged three times within both end-effector conditions. The resulting 27 trials per condition were presented in random order. The order in which the end-effector conditions occurred was alternated across subjects. There was no effect of the mode of exploration (bare finger vs. glove, $p > .15$).

APPENDIX

Stimuli Used in Each Experiment

Plate Number	Average Dot Separation (mm)	Plate Number	Average Dot Separation (mm)
1	0.500	14	2.125
2	0.625	15	2.250
3	0.750	16	2.375
4	0.875	17	2.500
5	1.000	18	2.625
6	1.125	19	2.750
7	1.250	20	2.875
8	1.375	21	3.000
9	1.500	22	3.125
10	1.625	23	3.250
11	1.750	24	3.375
12	1.875	25	3.500
13	2.000		

Experiment 1 (magnitude estimation with probe)

Judged plates:	1, 4, 7, 10, 13, 16, 19, 22, 25

Experiment 2 (roughness comparison with probe)

One-step pairs:	1/2, 2/3, 3/4, 4/5, 5/6, 6/7, 7/8, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16, 16/17, 17/18, 18/19, 19/20, 20/21, 21/22, 24/25
Two-step pairs:	1/3, 4/6
Three-step pairs:	1/4, 2/5, 4/7
Four-step pairs:	1/5, 3/7
Five-step pair:	1/6

Experiment 3 (magnitude estimation with sheath)

Judged plates:	1, 4, 7, 10, 13, 16, 19, 22, 25

Experiment 4 (roughness comparison with sheath)

One-step pairs:	1/2, 2/3, 3/4, 4/5, 5/6, 6/7, 7/8, 10/11, 11/12, 12/13, 13/14, 14/15, 15/16, 16/17, 17/18, 18/19, 19/20, 20/21, 21/22, 22/23, 23/24, 24/25
Two-step pairs:	1/3, 4/6
Three-step pairs:	1/4, 2/5, 4/7
Four-step pairs:	1/5, 3/7
Five-step pair:	1/6

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