PERCEIVING ROUGHNESS VIA A RIGID PROBE: PSYCHOPHYSICAL EFFECTS OF EXPLORATION SPEED AND MODE OF TOUCH[1]

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ABSTRACT

Two experiments investigated the psychophysical consequences for roughness perception of altering the speed of motion with which real textured surfaces are explored using a rigid probe. Two speed ranges were used: a 10-fold change (Experiment 1) and a 4-fold change (Experiment 2). Relative motion was altered both by moving the probe actively over a stationary surface (active mode) and by moving the surfaces under the stationary probe (passive mode). Substantial effects of speed were obtained relative to previous studies. The results are examined both in terms of the complex effects of speed on the psychophysical roughness functions and in terms of an increase in the size of the maximum speed effect as the range of speeds explored was reduced. We also consider how best to minimize potentially negative effects of speed on the haptic exploration of simulated textures. Two operator-training procedures are proposed to achieve effective haptic exploration strategies.

1. INTRODUCTION

While we most often interact manually with objects directly via our bare hands, we also frequently use intermediary links such as gloves and tools. In this paper, we report the results of a research study that is a part of an ongoing program that deals with how people perceive and manipulate the world indirectly via such intervening links. The current experiments psychophysically examine how people perceive surface texture via a rigid probe using different rates of probe movement, under both active and passive modes of exploration. As we discuss later, the results are relevant to fundamental psychophysical questions and to the production and exploration of real and simulated texture information via haptic interfaces for teleoperator and virtual-environment systems.

1.1 Perceiving roughness directly with the bare finger

To date, most psychophysical research on texture has focused on the perception of surface roughness, one of texture's most prominent perceptual attributes. Early research determined some of the primary physical determinants of perceived roughness. Surfaces included abrasive surfaces and more precisely controlled linear gratings and 2-dimensional raised dot patterns. For example, Lederman (e.g., [18] [14] [15]) showed that for engraved linear metal gratings with rectangular waveforms, the groove width between the ridges exerted by far the strongest effect on perceived roughness (see also [26] [1] [2] [23] [25]). The magnitude of this percept increased monotonically with increasing groove width. Increases in ridge width tended to decrease perceived roughness; however, this second stimulus parameter, when it had any influence at all, produced a considerably more modest effect than groove width. In addition, neither the groove-to-ridge ratio nor the spatial period (inverse of spatial frequency) of the gratings affected perceived roughness.

As texture perception has also been shown to involve complex interactions between the surface and the exploring end effector, it is also critical that we address potential effects of various exploration parameters. Two that have been considered previously are fingertip force and speed of relative motion between end effector and surface. Increasing applied fingertip force has been consistently found to produce increases in the magnitude of perceived roughness; the effect of finger force was about 25% that of groove width (e.g., [14]). The contribution of fingertip force to roughness perception via a probe will be the topic of a separate paper.

The speed of relative motion between bare finger and surface has produced a relatively small effect on perceived roughness. More specifically, Lederman showed that both 25-fold [14] and 12-fold changes [15] in finger speed

[1] A reduced version based on the active-touch results will be presented at the 1999 Annual Conference of the American Society for Mechanical Engineers, for the Haptic Symposium for Virtual Environment and Teleoperator Systems [11].

produced negligible effects on perceived roughness, when subjects moved their hands actively across the surfaces (active touch); a 12-fold change in hand speed also failed to produce noteworthy effects of speed when the surfaces were moved under the subject's fingers (passive touch). (The effect of a 25-fold change in speed was not tested with passive touch.)

Based on these earlier results, Taylor & Lederman [27] proposed a quasi-static model of perceived roughness based on a mechanical analysis of the skin deformation resulting from changes in groove width, fingertip force, and ridge width. The effects of speed were not modeled, as they were negligible relative to those just listed. Their model for perceived roughness of gratings suggested that perception mapped best to the mean deviation of the skin from its initial resting position, summed over the total area of skin contact. Such variation in the magnitude of skin deformation proved to be the best candidate parameter for predicting the empirical estimates of perceived roughness. Taylor and Lederman described the representation of roughness as "intensive", since the most viable skin-deformation parameter varied in magnitude along a single continuum. At the time, technological difficulties prevented them from further assessing the contribution of any spatial attributes pertaining to the skin deformation pattern.

More recently, Johnson, Connor and their colleagues [1] [2] have considered the underlying neural representation for coding roughness. Klatzky and Lederman [10] have described Connor et al.'s neural model as "spatial-intensive", because both spatial and intensive (i.e., unidimensional magnitude) codes are used, but at different levels in the somatosensory system. The latter's research implicates spatial coding of the textured surface first in terms of the relative activity rates of spatially distributed SAI mechanoreceptors. (Slowly Adapting Type I mechanoreceptors are the peripheral sensory population implicated in coding texture. For a discussion of the four populations of mechanoreceptors in hairless skin, see [6].) The spatial pattern in the activity in peripheral SAI units is preserved in SI (and more specifically, within areas 3b and 1) of the cortex, by neurally computing differences in activity of adjacent SAI units that are separated by about 1 mm. The SI neurons involved must possess receptive fields with adjacent excitatory and inhibitory zones to perform the appropriate difference operation. It was further proposed [4] that these differences in spatially distributed activity (i.e., a spatial code) are subsequently passed along to neurons in cortical area SII. These neurons serve to integrate the information across the entire regions activated in areas 3b and 1 into a single magnitude code. Accordingly, roughness switches to an intensive code in area SII of the cortex.

Although vibratory signals that arise from relative motion between bare skin and textured surface are potentially available, psychophysical studies by Lederman and her associates [14] [15] [17] concluded that humans usually tend not to use such information. This conclusion was based on three converging sets of empirical findings. First, subjects' judgments were unaffected by the spatial period of stimulus gratings, although spatial period partly determines the fundamental frequency of vibrations created during skin-surface contact [14]. Second, as previously mentioned, subjects were unaffected by the speed with which relative motion occurred ([9] [14] [15], but see [12]) using active and passive modes of touch. And third, subjects showed no effects of selectively adapting the fingertip to either a low-frequency (20 Hz) or high-frequency (250 Hz) stimulus of high amplitude on the magnitude of perceived roughness of linear gratings. (The adapting stimuli were applied to the fingertip in the normal direction.) In a separate experiment, the same subjects were asked to judge the perceived magnitudes of test vibrations varying in amplitude after adapting to either the same low- or high-frequency stimuli used in the roughness experiment. In contrast, subjects showed large and selective reductions in the perceived vibratory magnitudes of the test stimuli, depending on the frequency of both the adapting and test stimuli. (For further details on the selective-adaptation effects, see [17].) If the sense of vibration does underlie the perception of roughness of these surfaces, large adaptation effects should have been observed with perceived roughness as well. To conclude, the results of all three sets of empirical results suggested that subjects did not use vibration-based cues to judge the magnitude of roughness. We also note that Johnson and Lamb [8] drew a similar conclusion inasmuch as vibrating gratings on the fingertip at both 40 and 200 Hz did not show any appreciable effect on perceived roughness.

Most recently, Hollins, Bensmaia, and Rismer [3] have proposed a duplex model of roughness perception. Their experiments suggested that vibration is used for very fine surfaces. Johnson and Hsiao [7] have speculated this might be the case for surfaces with interelement spacings less than about 1 mm, the centre-to-centre spacing of SAI units on the fingertip. And LaMotte and Srinivasan [13] have suggested a role for PC or "fast-adapting Type II" units in coding very fine surfaces. For more coarsely spaced surfaces, however, Hollins et al.'s study showed that vibration did not appear to play a significant role, thus confirming the earlier conclusions of Lederman and her colleagues.

A separate issue addressed in the literature relates to the shape of the psychophysical function for perceived roughness as a function of interelement spacing. Early studies most commonly obtained power functions, which were linear on log-log scales (2D abrasive papers: [26]; unidimensional, engraved linear gratings: [14]). More recently, Connor and his colleagues have documented an inverted U-shaped function with the bare finger (2-D dot patterns: [1] [2]). The quadratic function has tended to peak around 3.5 mm. However, it is still unclear at this time whether the same heuristic was used to judge roughness across the entire interelement continuum. It is also possible that the declining portion was instead the result of subjects switching their coding strategy to accommodate a lack of confidence in making consistent roughness judgments about surfaces with widely separated dots.

1.2 Perceiving roughness indirectly using rigid finger covers and probes

While people may typically produce spatial-intensive representations of roughness via direct surface contact, they clearly can use vibration-based information to judge surface roughness when using an intervening tool that is grasped in the hand (e.g., [9]). We have now begun to systematically investigate how people perceive the world indirectly through the use of various intermediate objects, such as probes and finger coverings.

Klatzky and Lederman [10] had subjects explore raised-dot textures (for details, see Experiment 1 below) with two rigid stick-like probes that differed in the diameter of their tips. The two power functions (perceived roughness as a function of increasing interelement spacing) that were obtained with the probes rose less slowly than that obtained in a control condition with the bare finger. The differences in steepness between the direct- and indirect-touch (i.e., probe) conditions suggested that subjects were less capable of differentiating between textured surfaces via indirect contact. The small probe with a 2-mm contact diameter showed a maximum 0.95-fold change in perceived roughness for a 2-fold change in interelement spacing. The corresponding magnitudes of the effects on perceived roughness when using the larger probe (4-mm contactor diameter) and the bare finger were 1.39-fold and 1.97-fold changes, respectively.

Despite the reduced effects with the stick-like probes relative to the bare finger, some roughness differentiation was clearly possible. Similar results were produced using rigid sheaths that covered the fingertip (see [10] [16]). Roughness differentiation was obtained with both magnitude-estimation and 2-alternative forced-choice (2-AFC) roughness-discrimination paradigms. Two intriguing findings from the 2-mm probe condition were as follows. First, in the magnitude-estimation experiment, the psychophysical roughness function for the narrow probe peaked at a certain interelement spacing, and then declined -- the log-log coordinate data were fit very well by a quadratic equation. Second, in the 2-AFC experiment, subjects showed a transition from calling wider interelement surfaces rougher to calling them smoother. Both findings just described could be predicted from the size of the probe-surface contact diameter. In addition, overall surface roughness proved to be greatest with the 2-mm probe, less rough with the 4-mm probe, and least rough with the bare finger.

To continue our initial psychophysical investigation of the primary determinants of roughness perception via a probe, in the current paper, we evaluated the influence of relative speed of motion between probe and surface in both active- and passive-touch modes. Recall that earlier work with the bare finger indicated that despite substantial changes in relative speed, perceived roughness was relatively little affected, if at all, compared to the effect of interelement spacing. The direction of that small speed effect was to reduce the magnitude of roughness perceived as participants actively moved their fingers more rapidly across the textured surfaces [14] [15]. It is possible that speed had little influence when subjects actively moved their own hands because they could compensate for any effects of changing speed -- that is, subjects may have used kinesthetic feedback about their hand movements to counteract any changes in cutaneous cues (intensive, spatial or temporal) produced by changes in speed. However, despite the fact that such kinesthetic information was presumably unavailable when the surfaces were moved across the subjects' stationary fingers ([15]: 12-fold variation in speed), there was still relatively little alteration in perceived roughness. On the basis of results from this study and others outlined above, Lederman concluded that the concomitant vibratory signals did not play a primary role in her studies with the bare finger; rather, observers were using the spatial and intensive cues available in the proximal skin-deformation pattern.

However, when a rigid probe is used, people presumably must rely on the vibrotactile signals, since the spatial deformation pattern on the fingertips no longer correlates with the geometric properties of the textured surfaces. We therefore predicted that larger speed effects would be obtained when participants contacted spatially jittered, raised 2D dot patterns indirectly with a stick-like probe rather than with the bare finger. And indeed, we will demonstrate that the magnitude of speed effect obtained with a probe can be substantial.

We also anticipated more complex effects of speed in the current experiments, inasmuch as the psychophysical functions obtained with probes by Klatzky and Lederman [10] were quadratic in shape. More specifically, the functions were inverted U-shaped (log perceived roughness as a function of log interelement spacing), particularly for the smaller probe. We will confirm that the probe functions are best fit by quadratic equations. We will also show that increasing speed tends to decrease the magnitude of roughness perceived. However, unlike the direction of the small speed effect obtained in the bare-finger experiments, this pattern actually reverses itself -- that is, perceived roughness increases with increasing speed -- beyond some point along the interelement-spacing continuum. We will show that such a reversal is produced by a corresponding shift in the quadratic peak toward the higher end of this continuum with increasing speed.

In the current study, subjects judged surface roughness in both active- and passive-touch conditions. We presumed that cutaneous and kinesthetic cues would be available in the active-touch condition, while sensory information about the textured plates would be limited to cutaneous feedback alone in the passive condition. Therefore, we predicted -- and will confirm -- that speed effects are larger for passive than for active touch.

Finally, the range of speed of relative motion was varied across the two experiments reported here. A 10-fold range was used in Experiment 1 to approximate the 12-fold range used by Lederman [15] with the bare finger. The magnitude of the speed effect obtained proved to be considerably larger than the negligible effect obtained earlier by Lederman [14] with a 25-fold range of speeds; however, it was only a little larger than that obtained in the Lederman [15] study. Recall the previous two studies both used direct contact between finger and surface. We hypothesized that the effect of speed would increase as the range of speeds decreased across experiments, for both active- and passive-touch conditions. To test this hypothesis, in Experiment 2 we predicted that if a considerably smaller, 4-fold speed range is used, we should obtain still larger speed effects. This prediction will be confirmed. More precisely, we will show a strong linear relationship between the magnitude of the maximum speed effect and the ratio of speeds employed across all experiments that have investigated the effect of speed on perceived roughness. This relationship will be shown to occur for both active and passive touch.

The current psychophysical findings therefore provide important information concerning the complex role that relative speed plays in perceiving roughness with a rigid probe. To conclude the paper, we will propose ways in which such undesirable perceptual effects may be avoided or minimized when haptic interfaces are used to explore real and simulated surface textures.

2. EXPERIMENT 1

In Experiment 1, we investigated the effect of speed of relative motion between probe and surface on the magnitude of perceived roughness. Both active- (hand moves, surface stationary) and passive- (hand stationary, surface moves) touch conditions were employed. As mentioned earlier, we assumed that cutaneous and kinesthetic cues would both be present in the active-touch condition, while only cutaneous feedback about the surfaces would be available in the passive condition. We therefore predicted limited or no effects due to changes in speed when subjects used active touch, because, as observed previously when the bare finger was used, subjects were likely to use kinesthetic cues to achieve roughness constancy. In addition, we anticipated larger speed effects with passive than with active touch, inasmuch as the kinesthetic cues to speed were unavailable in the former case.

2.1 Method

Participants. Forty first-year psychology students (25 females, 15 males) participated in the experiment for course credit. Their mean age was 23 years, ranging from 19 to 40 years. The participants were randomly assigned to either active- or passive-touch conditions, for a total of 20 per group. All participants defined themselves as "right-handed", and reported no known cutaneous or kinesthetic problems.

Apparatus and stimuli. A force-control balance apparatus, designed like a classical balance scale, was used in the current study (Figure 1; see also [15]). A detailed description of an earlier version of the apparatus may be found in Lederman and Taylor [18]. The textured plates were fixed (in turn) upon a stimulus platform, which was mounted toward the front end of a balance arm. The position of the platform could be adjusted along the length of the balance arm to accommodate varying arm lengths. Subjects rested their elbows on a padded elbow rest, which was located above the fulcrum of the balance arm toward the back of the apparatus; to eliminate vibratory noise, it was physically isolated from the apparatus. A padded wrist rest was used for passive-touch trials. The wrist rest extended forward from the elbow rest, and could also be adjusted for differences in arm length.

In both active and passive conditions (described below), the subject was instructed to keep the balance arm steady throughout the trial. With the balance arm steady, the moments of the two ends about the fulcrum had to be equal. Thus, the subject had to apply a well-defined force via the probe on the front arm, to balance the weight on the back arm. The constancy of the force of the probe on the stimulus arm was disturbed only by the small acceleration forces as the balance arm moved up and down. This variation was a small proportion of the total force applied via the probe. Simulation tests in which a force gauge was substituted for the probe indicated that the applied force remained within about 20% of the nominal value. To set the required force more easily from the front of the apparatus, the experimenter adopted the following procedure. She balanced the balance arm initially with a large weight that was mounted along a threaded metal shaft at the back of the apparatus. The shaft was connected to the balance arm. Smaller counterweights totaling that of the large one at the back were placed on a metal tray toward the front of the apparatus. The tray was connected to the balance arm, at a position directly beneath the center of the stimulus platform. The counterweights, which were more easily accessible to the experimenter, were ultimately used to set the required force. After the balance arm was balanced with the back and front weights in place, the experimenter removed a small weight (.29N) from the weight tray, so that the subject had to apply equivalent counter force to maintain the balance arm steady.

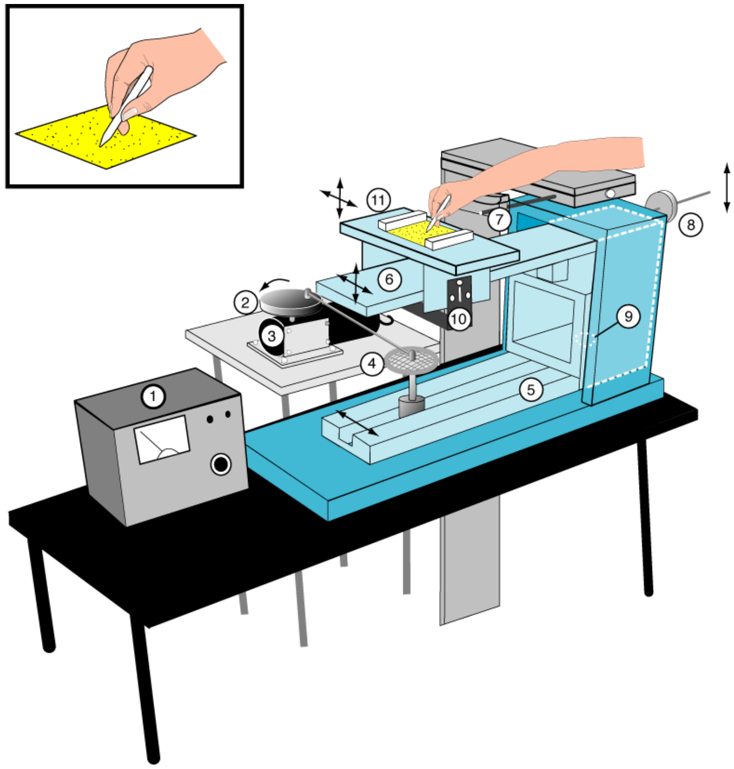

Figure 1. The apparatus used to control force (active and passive touch) and speed (passive touch only). 1. tachometer; 2. cam; 3. variable-speed motor; 4. rubber connector; 5. rotating base; 6. balance arm; 7. adjustable wrist support; 8. weight; 9. pivot point about which base rotates (shown as white dotted circle); 10. weight tray; 11. stimulus platform. The inset shows the subject contacting textured surface with a probe (for details on operation, see text). Note that the balance arm is moved sideways by the rotating base, to which it is attached (passive touch only). The balance arm independently moves up or down, whenever the counter-force applied to the textured surface by the subject is less or more, respectively, than the targeted .29N force (both active and passive touch).

During the passive-mode trials, the textured stimuli were moved underneath the probe by driving the balance arm from side to side via a linear metal rod. (Subjects were instructed to hold the probe as stationary as possible.) The metal rod was connected horizontally at one end via a rubber connector -- to reduce extraneous vibrations created by the activity of the motor -- to a vertical rod, which was in turn connected to the rotating base of the apparatus. The other end of the horizontal rod was connected to a cam that was attached to a variable-speed motor positioned on an adjacent steel table. The circular motion of the cam was converted to sideways, linear motion of the moveable base, and likewise of the balance arm to which it was attached (at the back of the apparatus). The speed of motion varied sinusoidally. A tachometer was used to control the mean speed of the textured surface under the probe. The table legs were set in sand to minimize extraneous vibrations along the balance arm.

In the passive mode, the stimulus was moved back and forth under the probe, approximately 80mm in both directions. In the active mode, participants were instructed to move the probe the same distance across the stationary plate, using a sideways, back-and-forth motion (as in the passive condition). The three speeds (mean) used in both active and passive conditions were approximately 20.5 mm/s (“slow”), 73.2 mm/s (“medium”), and 207.3 mm/s (“fast”).

While the control of speed was not as precise as we intend for future work, the speed values were sufficiently different that we could reasonably assess the effect of speed on perceived roughness via a probe in this initial study. In order to match the speed of exploration between the active and passive modes, a computer-generated metronome was used during the active-mode trials. The metronome produced a series of clicks during each trial. The subject was trained to stroke the plate so that the beginning and end of a single stroke coincided with two successive clicks.

We elected to use the 2D, raised-dot surfaces described below, as they have been used in much of the recent psychophysical and neurophysiological work on roughness perception with the bare finger. The stimuli (also used by [10] and [16]) were produced using the Nyloprint photoengraving technique (see [19]). The plastic polymer plates contained raised dots in the form of truncated cones. Dot height was 0.52mm; the base diameter of the dots varied between .72 and .98 mm as a function of the shoulder angle of the cone sides. A computer algorithm was used to spatially jitter the elements within a given matrix in which the interelement spacing was a constant value. The position of each dot was jittered angularly and radially within a defined circular region surrounding the dot's position in an initially defined regular matrix. Thus, the dots appeared randomly spaced on the plate, yet maintained the original mean interelement spacing (inner edge to inner edge) in x and y. The stimulus set consisted of 7 interelement spacings ranging from 0.500 to 2.75 mm, in 0.375mm increments. The 2.75mm plate was the largest interelement spacing that our pilot subjects were not reluctant to judge at 20.5 mm/s in terms of perceived roughness.

All contact between the participants' hands and the stimulus plates was effected through a rigid probe made of delrin plastic. Its cylindrical shaft was 110 mm long and 1cm in diameter; the probe terminated in a spherical bulb that was 3 mm in diameter. The actual contact diameter of the probe tip, however, was measured by inking the tip and rotating it about the contact point on a surface. By this measure, the probe tip's functional diameter was 2 mm.

An audiotape of background masking noise was used to eliminate any auditory feedback produced by the probe. This was achieved most effectively by using superimposed sounds of probes being scanned back and forth across the stimulus plates. The acoustic frequency of each click of the metronome used to control speed of movement (1000 Hz with duration of 1 ms) was outside the range of frequencies within the masking noise, rendering the click clearly audible. The participants were fitted with pliable wax-cotton ear plugs, a blindfold, and a headset through which the background noise was played.

Experimental Design. A one between-subject, three within-subject design was used, with modes of touch as the between-subjects factor, and interelement spacing, speed, and repetitions all within-subjects factors. Participants were randomly assigned to active or passive modes of touch. The order in which the seven interelement spacings and the three speeds were presented was randomly determined for each of two replications per subject, such that each speed/stimulus combination was presented once within each replication. Applied finger force was held constant at 0.29 N in both active and passive conditions by instructing participants to apply a force that would maintain the balance arm level.

Experimental Procedure. Participants were seated on a stool with the apparatus to their right. Roughness was estimated using an absolute magnitude-estimation procedure [29]: participants were instructed to choose any positive, non-zero number (decimal, fraction, or whole number) that best matched the perceived roughness of the surface. Neither modulus nor standard was used. All participants wore both earplugs and a blindfold, and were fitted with the headset through which the background noise was played.

Participants in the passive mode were trained to maintain the balance arm steady and level, and then were presented with a sample of 12 stimulus interelement spacing/speed combinations from across the full stimulus range. To prevent participants devising a fixed response range, they were informed that they might experience rougher or smoother plates in the actual experiment than in the training. In the actual experiment, each stimulus was presented in random order at each of the three speeds. The experimenter informed participants that she would touch their hand to signal them at the start of a trial and would gently raise the stimulus platform up until they could counterbalance it with the probe. The participant was given a short break followed by retraining between replications.

Participants in the active mode of touch were shown the distance and direction they were required to move, and were permitted to trace that distance with their finger. They were then fitted with earplugs, a blindfold, and a headset. Training was then provided to teach participants to maintain the balance arm level, and to move the specified distance. This distance was chosen based on the mean distance moved by the apparatus in the passive condition. Next, participants were trained to control speed with the computer-generated electronic clicks. A random sample of speeds was presented until the participant had mastered the technique. As in the passive mode of touch, all participants were familiarized with the magnitude-estimation procedure using a sample of surfaces and speeds. The same set of randomized stimulus/speed samples was provided in the passive- and active-mode conditions. Throughout training, the experimenter provided feedback on the speed, distance and direction the probe was moving, as well as on the appropriateness of the force applied to the plates (see Section 5.1) .

With both modes of touch, subjects were instructed to hold the probe lightly in the same manner as a pencil; they did not explore it prior to use. In order to dampen movement of the top end of the probe, the probe was grasped part way up such that its top end rested in the fleshy web between the thumb and forefinger. Subjects were instructed to maintain the same grasp configuration throughout the experiment. In the active condition, subjects moved the probe back and forth across the plate, rotating their hand/forearm about the elbow. The stimulus plates and probe were hidden from view both prior to and upon completion of the experiment. A session lasted approximately 45 minutes.

2.2 Results

To begin our data assessment, we performed traditional univariate Analyses of Variance tests using the magnitude-estimate responses. However, meaningful interpretation of these data proved to be somewhat limited -- it was inappropriate to put much weight on significant main effects, when the ANOVA also identified significant interactions between speed and interelement spacing. Moreover, these interaction terms reflect complex patterns in the data that cannot be succinctly described. We therefore subsequently performed several additional analyses, as required, using measures derived from the magnitude estimates. As will become evident, these analyses allowed us to meaningfully address issues relating specifically to the effect of speed on the shape of the psychophysical functions (peak shift, crossover effects), to the effect of mode of touch, and finally to compare speed effects across experiments.

To assess any effects of repetitions, separate Analyses of Variance (ANOVA) with a three-factor, repeated-measures design were initially performed on the raw data from both active and passive conditions. The three within-subject factors were speed (three levels), interelement spacing of the stimulus (seven levels), and repetitions (two levels). As neither the main effect of repetition nor any interaction involving this factor was statistically significant in either the active- or passive-touch analyses, we will not consider this effect further.

To reduce variability, the data from the two replications were combined for use in all subsequent analyses. These data were normalized within each mode to eliminate possible biases due to the subjects' use of different number ranges. Finally, to provide a more normal distribution of the magnitude estimate scores (see e.g., [20]), the scale-equated scores were logarithmically transformed (base 10). The transformed data served as the basis of all subsequent data analyses.

Effect of interelement spacing, speed and mode of touch: Active touch. A two-factor repeated measures ANOVA was performed on the active-touch data. The Greenhouse-Geisser adjustment for degrees of freedom was used to assess the two main effects and their interaction. The F value for the main effect of interelement spacing was $F(6, 27.2) = 85.05$, $p < .0001$. Figure 2a shows perceived roughness as a function of interelement spacing on logarithmic scales for each of the three speeds. Quadratic fits to the individual data points are shown for all three psychophysical roughness functions, for reasons discussed shortly. In general, perceived roughness tended to increase with interelement spacing, approaching a peak within or beyond the range of spacings used in this experiment. The main effect of speed was highly significant, $F(2,23) = 21.23$, $p < .0001$: the mean estimates of roughness decreased with increasing speed. However, the interaction term was highly significant as well, $F(12, 90.2) = 4.74$, $p < .0008$: the effect of speed tended to decrease with interelement spacing, and to reverse direction at the wide end of the spacing continuum.

Table 1: Linear fits, quadratic fits and peak of the quadratic functions fit to data in Experiment 1

Condition	Speed		Linear fit (r^2)	Quadratic fit (r^2)	Peak (mm)
ACTIVE:	Slow	(20.5 mm/s)	.73	.98	1.82
	Medium	(73.2 mm/s)	.85	.98	2.26
	Fast	(207.3 mm/s)	.91	.98	2.97
PASSIVE:	Slow	(20.5 mm/s)	.78	.98	1.96
	Medium	(73.2 mm/s)	.87	.97	2.59
	Fast	(207.3 mm/s)	.94	.96	5.74

The three psychophysical roughness functions for active touch based on aggregated participant data were initially fit with linear and quadratic equations (see Table 1 and Figure 2a). The r^2_{linear} values for the slow, medium and fast speeds were .73, .85 and .91, respectively. Therefore, the associated % non-linear, residual variance was 27%, 15% and 9% respectively. As the $r^2_{quadratic}$ values were .98 .98 and .98, the corresponding quadratic fits accounted for 93%, 87% and 78% of the residual, non-linear variances. Therefore, the quadratic fits were better than the linear fits (see Section 5.2).

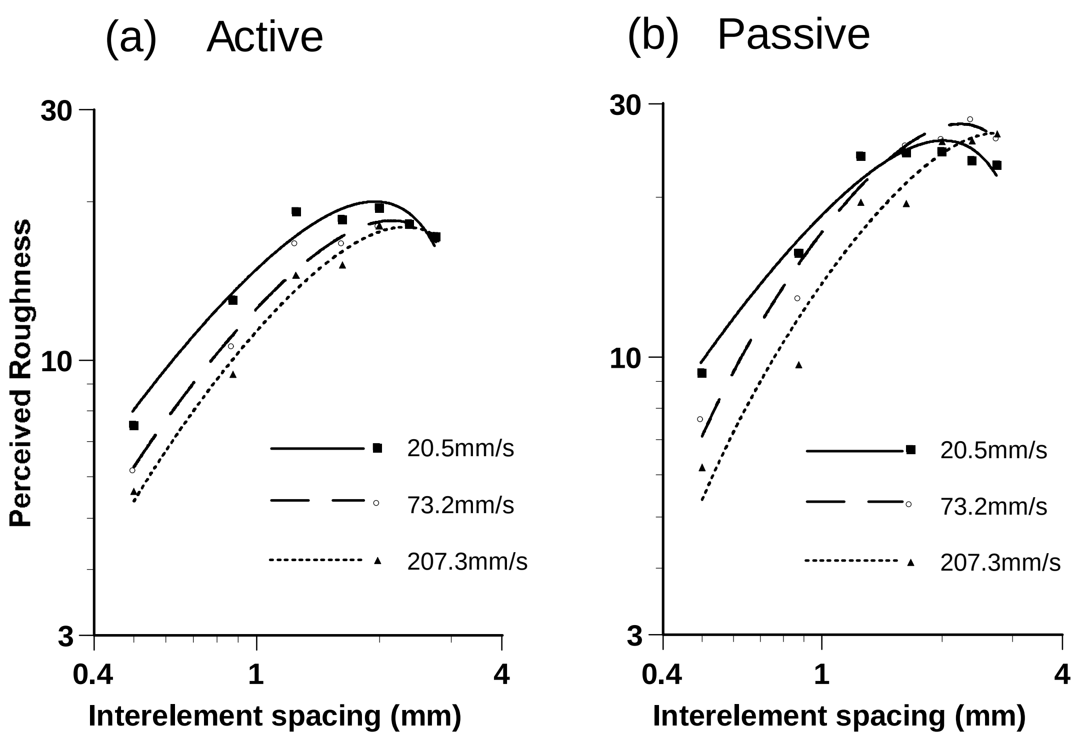

Figure 2. Experiment 1: Mean $\log_{10}$ normalized roughness magnitude estimates as a function of interelement spacing under: (a) active and (b) passive modes of touch for slow (20.5 mm/s), medium (73.2 mm/s) and fast speeds (207.3 mm/s). The data points for each speed condition have been fit with a quadratic function. Each data point is based on 20 observations. Note that each observation is the mean of two replications. Figure 2a is reprinted with permission from [11]).

Effect of interelement spacing, speed and mode of touch: Passive touch. For the two-factor ANOVA performed on the passive-touch data, the F value for the main effect of interelement spacing was highly significant, $F(6, 26) = 97.99$, $p < .00001$: perceived roughness tended to increase with increasing interelement spacing. The main effect of speed was highly significant, $F(2,22.9) = 9.11$, $p < .005$: mean roughness estimates tended to decrease with increasing speed. The two-way interaction term was also statistically significant, $F(12, 104.4) = 9.44$, $p < .00001$, and was similar to that obtained in the active touch condition.

Each of the three psychophysical roughness functions based on aggregated participant data was initially fit with both linear and quadratic equations (see Table 1 and Figure 2b). The r^2_{linear} values for the slow, medium and fast speed conditions were .78, .87, and .94, respectively; thus, the associated percent residual variance not accounted for by the linear fit was 22%, 13%, and 6%. As the corresponding $r^2_{quadratic}$ values were .98, .97 and .96, the quadratic fits accounted for 91%, 69%, and 33% of the residual non-linear variances for slow, medium and fast speed conditions. We conclude that quadratic equations fit the data obtained better than did linear equations (see Section 5.2).

Active vs. passive touch. Initially, we attempted to compare the relative magnitude of speed effects in active- versus passive- touch conditions, by combining the two separate ANOVAs (above) into a single ANOVA with one additional between-group factor (mode of touch). However, the significant higher-order interactions were too complicated to interpret. To address this question more directly, we therefore adopted a different procedure. We began by deriving, for the active condition, seven difference scores, one per interelement spacing. For each interelement spacing, we considered the speed conditions that produced the highest and the lowest roughness estimates. The absolute value of the difference between these two estimates (i.e., the higher estimate minus the lower estimate), was used to obtain -- for the given interelement spacing -- the largest unsigned difference in perceived roughness from among all three possible speed pairs. Thus, the unit of observation was interelement spacing. An identical procedure was used to calculate the seven largest unsigned difference scores for the corresponding passive-touch data, again one per interelement spacing.

Next, we performed a one-tailed t-test for independent groups (mode of touch; see Section 5.3) with the absolute difference between the extremes in perceived roughness due to speed (calculated above) as the dependent variable. The mean difference between the active and passive absolute difference scores proved to be statistically comparable, $t(12) = -0.93$, $p > .05$. We do note, however, that with the exception of the 1.25-mm and 2-mm interelement spacings, the speed effect in the passive-touch condition was larger for each of the remaining five interelement spacings than it was for the corresponding interelement spacings in the active-touch condition. Thus, although not statistically significant, passive touch tended to produce a larger effect of speed than did active touch.

Position of peak roughness in quadratic function. Klatzky and Lederman [10] found that the quadratic function peaked near the point where the interelement spacing exceeded the diameter of the probe tip. As the interelement spacing increased beyond this point, the magnitude-estimate values decreased. To determine any effect of speed on peak shift, we determined the interelement spacing at which the quadratic functions in Figure 2 peaked. These functions were all based on aggregated subject data, to reduce any influence due to extreme scores from individual subjects. The peak value consistently shifted along the interelement spacing continuum toward the higher end with increasing speed in both active-and passive-touch conditions. In the active condition, the peaks for the slow, medium and fast speeds were 1.82, 2.26, 2.97 mm (Table 1, Figure 2a), respectively. In the passive condition, the corresponding values were 1.96, 2.59, and 5.74 mm (Table 1, Figure 2b), respectively.

We also examined the peak values for the 40 individual subjects, with 20 different subjects in each of the active and passive conditions. While the very large majority of values ranged overall between about 1.5 and 7, we did in fact note three or four (out of 20) unusually high peaks in the high-speed conditions (active and passive touch), as well as two very high values (out of 20) for the medium speed (passive touch only). We believe that the excessively high peaks were due, at least in part, to excellent linear fits for these data. (In support of this interpretation, two additional one-way ANOVAs were performed on the r^2_{linear} values, one for active- and one for passive touch, with subject as the unit of observation. These both revealed that the linear fit statistically improved with increasing speed.) Accordingly, we tested the differences among the peaks produced by the three speed conditions with a non-parametric test, the Friedman two-way ANOVA. The dependent variable was peak rank value. Within each subject, we rank ordered by size the peaks obtained in the three speed conditions: a 1 was assigned to the speed with the lowest peak value, a 2 for the speed with the intermediate peak value, and finally a 3 for the speed with the largest peak value. Subject was the unit of observation. The test was performed separately for active and passive conditions.

For the active condition, the summed ranks were 23.5, 43, and 53.5 for the slow, medium and fast conditions, respectively (cf. 20, 40, and 60 if the peak orders were consistent for every subject). The effect of speed was significant, $\chi_r^2\ (2) = 23.17$, $p < .001$. Planned comparisons of the slow vs. medium and slow vs. fast speed conditions were both statistically significant, $p < .05$.

For passive touch, the summed ranks were 29, 42.5 and 48.5, respectively, ordered from low to high across slow, medium and fast speeds. The effect of speed was again significant, $\chi_r^2\ (2) = 9.97$, $p < .01$. However, planned comparisons among the pairs of speed scores for passive conditions showed a significant difference only for the difference in rank peak values between the slow and fast conditions, $p < .05$.

In Experiment 1, therefore, we may conclude that increasing speed from slow to fast consistently and significantly shifted the peak position toward the wider end of the interelement spacing axis. The peak position of the medium speed also consistently increased; as the differences were somewhat smaller, however, the results of the planned comparisons usually proved to be non-significant. We consider the reason for the peak-shift effect in the General discussion.

Magnitude of "maximum speed effect". Finally, to assess the influence of speed on perceived roughness, we developed a new comparative measure that assessed the maximum effect of speed within any interelement spacing, relative to the maximum effect of interelement spacing within any speed. We selected this "worst-scenario" case to consider the greatest possible influence that speed might have on perceived roughness. We chose interelement spacing for comparison inasmuch as it has been repeatedly shown to be the most prominent determinant of perceived roughness. The ultimate goal was to calculate what we call the "doubling ratio" -- the ratio consisting of the largest absolute change in perceived roughness obtained by doubling speed relative to the largest absolute change in perceived roughness obtained by doubling interelement spacing. We could then use this measure to compare relative maximum speed effects across all experiments that, to date, have manipulated speed. A detailed description follows as to how this comparative ratio measure was derived (see Section 5.5).

The ratio was derived in a series of steps, as described in Equations 1-7 below. The steps were: (1) Compute the largest variation in mean roughness attributable to speed at each level of spacing, i.e., the effect due to speed, SPEEDEFFECT. (2) Compute the maximum of all SPEEDEFFECT values calculated in (1), MAXSPEEDEFFECT. (3) Compute the largest variation in roughness attributable to spacing at each level of speed, i.e., the interelement spacing effect, SPACINGEFFECT. (4) Compute the maximum of all SPACINGEFFECT values calculated in (3), MAXSPACINGEFFECT. (5) and (6) Rescale the MAXSPEEDEFFECT or MAXSPACINGEFFECT values according to the range of the manipulated variable, speed or spacing, in order to determine the effects of doubling the value of that variable. (7) Compute the DOUBLING RATIO, which indicates the change in perceived roughness due to doubling speed relative to the change in perceived roughness due to doubling interelement spacing.

We began by determining the maximum variation in roughness attributable to speed, as follows. For each level of the interelement spacing variable, the largest variation in roughness attributable to speed, SPEEDEFFECT, was computed as the maximum perceived roughness (log units) minus the minimum perceived roughness (log units). That is, where i indexes a level of interelement spacing,

$$\text{SPEEDEFFECT}_i = (\log_{10}(\text{max perceived roughness}) - \log_{10}(\text{min perceived roughness})|, \text{ where the roughness values considered are those obtained for the three speeds at spacing level I} \quad (1)$$

Next the maximum of these SPEEDEFFECT effects, across all interelement spacing levels, was computed to be the largest SPEEDEFFECT. That is,

$$\text{MAXSPEEDEFFECT} = \max \text{SPEEDEFFECT}_i \text{ over all i} \quad (2)$$

Similarly we quantified the largest absolute change in perceived roughness due to doubling speed. First, we determined the largest change in perceived roughness due to spacing across the levels of speed. That is, where j indexes a level of speed,

$$\text{SPACINGEFFECT}_j = (\log_{10}(\text{max perceived roughness}) - \log_{10}(\text{min perceived roughness})|, \text{ where the roughness values considered are those obtained for the seven interelement spacings at speed level j} \quad (3)$$

$$\text{MAXSPACINGEFFECT} = \max \text{SPACINGEFFECTj over all j} \quad (4)$$

Next, the MAXSPEEDEFFECT and MAXSPACINGEFFECT values were converted to antilogs and rescaled to reflect the observed changes in perceived roughness due to an arbitrary 2-fold change in the given independent variable, speed or interelement spacing. That is, given the obtained relation, y:x (where y is the obtained y-fold change in perceived roughness due to an x-fold change in manipulated speed or interelement spacing), z : 2 reflects the corresponding z-fold change in perceived roughness (i.e., the speed-doubling effect) due to a 2-fold change in speed or interelement spacing. The scaling factor normalized the MAXSPEEDEFFECT and MAXSPACINGEFFECT according to the range of values over which the associated variable was manipulated (i.e., maximum:minimum speed ratio).

For speed, the scaled perceived roughness value was:

$$\text{Speed doubling effect} = 2 * \frac{\text{antilog(MAXSPEEDEFFECT)}}{\text{max speed/min speed}} \quad (5)$$

For interelement spacing, similarly, the scaled perceived roughness value was:

$$\text{Spacing doubling effect} = 2 * \frac{\text{antilog(MAXSPACINGEFFECT)}}{\text{max spacing/min spacing}} \quad (6)$$

The doubling effects for speed and interelement spacing are shown in Table 2, along with the associated ratios of the parameter ranges for speed and interelement spacing used in the scaling procedure (i.e., the denominators of equations 5 and 6).

Finally, we devised a single descriptive statistic -- the doubling ratio -- for purposes of comparing the relative effects of speed to interelement spacing across a number of experiments, including those in the current study.

$$\text{DOUBLING RATIO} = \text{speed doubling effect/spacing doubling effect} \quad (7)$$

The doubling ratios for Experiment 1 were substantial, that is about 24% and 21% of the corresponding effect of interelement spacing for active- and passive-touch, respectively. Corresponding values based on data from the two previous experiments that investigated the effect of speed of relative motion on perceived roughness using the bare finger are also shown in Table 2. The doubling ratios in Experiment 1 were a little larger than those pertaining to the Lederman [15] study, and considerably larger than the value for active touch that was based on the Lederman [14] study. Note that unlike the ANOVA analysis, the doubling ratio pertains specifically to the largest difference between speed conditions across the three possible pairs, without regard to sign. Also different is the fact that the doubling ratio takes the range of speeds into account in its derivation. Such differences likely account for the large doubling ratios obtained in Experiment 1, which indeed highlights the maximal effect of speed range on perceived roughness that the ANOVA analysis cannot uncover.

Table 2: Parameters and doubling ratios across experiments that have investigated the effects of speed. Reprinted with permission from [11].

Experiment	Maximum speed/ Minimum speed (denom.of eqn. 5)	Speed doubling effect (eqn. 5)	Maximum spacing/ Minimum spacing (denom. of eqn. 6)	Spacing doubling effect (eqn. 6)	Doubling ratio (eqn. 7)
Lederman '74	25	.10	5.7	1.4	.07
Lederman '83					
Active	12	.28	8	2.21	.13
Passive	12	.28	8	1.93	.15
Current study:					
Expt. 1					
Active	10	.28	5.5	1.17	.24
Passive	10	.32	5.5	1.54	.21
Current study:					
Expt. 2					
Active	4	.59	6.25	1.47	.40
Passive	4	.72	6.25	1.88	.38

We will discuss the results of Experiment 1, together with those of Experiment 2, in the General Discussion.

3. EXPERIMENT 2

Based on the order of magnitude of doubling ratios in Table 2 for the first three studies shown ([14] [15] Expt. 1, current study), an intriguing hypothesis is that the strength of the speed effect varies inversely with the size of speed range, as measured by the maximum:minimum speed ratio. This hypothesis seems reasonable, inasmuch as such a relation might reflect a decreased capacity to determine relative speed when the range of speeds experienced is smaller. To the degree that observers can estimate probe speed less accurately as the range of explored speeds decreases, they might also be less able to adjust their roughness estimates to compensate for the effects of changing speed.

To test our hypothesis, in Experiment 2 we substantially reduced the range of speeds from a 10- to a 4-fold change. The following three speeds were used: 55, 114 and 222 mm/s. Finger force was again 0.29 N. The methodology, number of subjects, subject population, data transformations and analyses were identical to those in Experiment 1. Different subjects participated in the two experiments. We begin by making the same predictions as in Experiment 1, with respect to interelement spacing, speed and mode of touch. In addition, we predict that with the substantially reduced range of speeds in Experiment 2, its effects should prove to be even larger than those documented in the previous experiment. Eight interelement spacings were used in Experiment 2, with the mean (base) interelement spacing increasing from 0.500 to 3.125 mm, in increments of 0.375 mm. The 3.125-mm interelement spacing was added because unlike the previous experiment, pilot subjects were comfortable making roughness judgments with all speeds selected for use in Experiment 2.

3.1 Results

As in Experiment 1, initial analyses of the effects of repetitions failed to reveal any statistical significance for either active- or passive-touch conditions; hence, the means of the scores for the two replications for all conditions were used as the input data for subsequent analyses of variance. ANOVAs performed separately on the log normalized roughness estimates for active and passive touch showed psychophysical patterns in the data that were similar to those obtained in Experiment 1. However, unlike Experiment 1, the main effect of speed was not statistically significant for either active or passive modes of exploration.

Effect of interelement spacing, speed and mode of touch: Active touch. A two-factor, repeated-measures ANOVA was performed on the active-touch data. As expected there was a significant effect of interelement spacing, $F(7, 30.6) = 60.84$, $p < .00001$: roughness initially increased as a function of interelement spacing, and subsequently declined. There was no statistical main effect of speed, $F(2,33.8) = 1.05$, $p > .05$. However, the interelement-spacing x speed interaction term was significant, $F(14,113.2) = 3.08$, $p < .01$, as shown in Figure 3a. The mean data points were fit with quadratic functions. Increasing probe speed tended to shift the roughness function lower on the perceived-roughness axis, particularly for the narrowest spacings. Toward the wide end of the interelement-spacing continuum (between about 1.1 and 1.7mm), the relative ordering of the functions by perceived roughness reversed. The fast-speed function now tended to produce the highest roughness estimates across the wide end of the spacing continuum, followed in turn by the medium- and then the slow-speed functions.

Table 3: Linear fits, quadratic fits and peak of the quadratic functions fit to the data in Experiment 2

Condition	Speed	Linear fit (r^2)	Quadratic fit (r^2)	Peak (mm)
ACTIVE:	Slow (55.4 mm/s)	.79	.97	2.28
	Medium (114.6 mm/s)	.83	.97	2.53
	Fast (222.4 mm/s)	.87	.96	3.05
PASSIVE:	Slow (55.4 mm/s)	.77	.97	2.07
	Medium (114.6 mm/s)	.86	.98	2.67
	Fast (222.4 mm/s)	.89	.97	3.28

Each of the three psychophysical roughness functions for active touch based on aggregated participant data was initially fit with linear and quadratic equations (see Table 3 and Figure 3a). The r^2_{linear} values for the slow, medium and fast speeds were .79, .83, and 87, respectively. Accordingly, the associated percent residual variances not accounted for by the mean linear fits were 21%, 17%, and 13%. As the corresponding $r^2_{quadratic}$ values were .97, .97 and .96, the quadratic fits accounted for 86%, 82%, and 69% of the residual non-linear variances for the slow, medium and fast speeds, respectively. We conclude that the addition of a quadratic term substantially improves the fit relative to the linear equation, indicating that the underlying function is quadratic (see Section 5.2). Further details concerning the shape of these quadratic functions will be considered in a separate section.

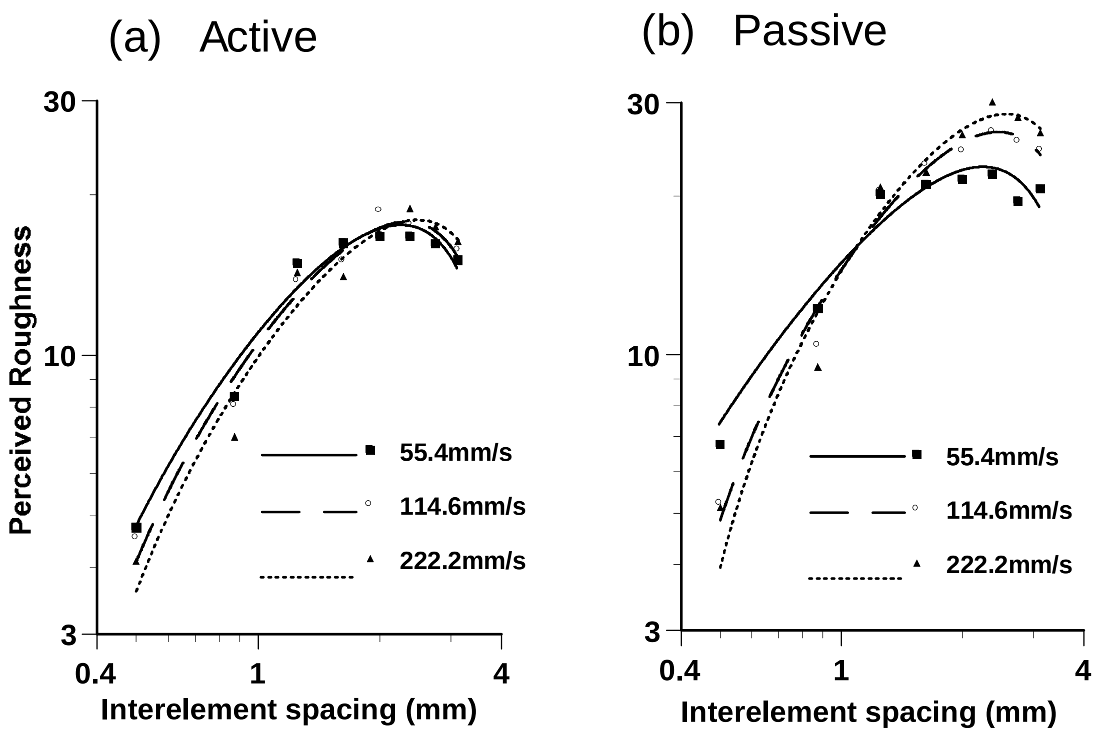

Figure 3. Experiment 2: Mean $\log_{10}$ normalized roughness magnitude estimates as a function of interelement spacing under: (a) active and (b) passive modes of touch for slow (55.4 mm/s), medium (114.6 mm/s) and fast speeds (222.4 mm/s). The data points for each speed condition have been fit with a quadratic function. Each data point is based on 20 observations; each observation is the mean of two replications. Figure 3a is reprinted with permission from [11].

Effect of interelement spacing, speed and mode of touch: Passive touch. The same two types of ANOVA were performed on the passive-touch data. The 2-factor (interelement spacing, speed) ANOVA results were similar to those for the active mode. The main effect of interelement spacing was highly significant, $F(7, 35.8) = 75.68$, $p < .00001$: roughness estimates tended to increase as a function of speed until they reached a peak and subsequently declined. The main effect of speed was not statistically significant, $F(2,22.4) = 2.02$, $p > .05$. However, once again the interelement spacing x speed interaction was highly significant, $F(14, 88.6) = 5.69$, $p < .0005$. The interaction is shown in Figure 3b, with quadratic functions fit to the mean data points. The fast-speed function tended to be positioned lowest on the Y axis, particularly for the narrowest spacings; the medium-and slow-speed functions lay in turn somewhat above. The three speed functions reversed themselves at about 1 mm on the interelement-spacing continuum.

Each of the three psychophysical roughness functions based on aggregated participant data was initially fit with linear and quadratic equations (see Table 3 and Figure 3b). The r^2_{linear} values for the slow, medium and fast speeds were .77, .86, and .89, respectively. Accordingly, the associated percent residual variances not accounted for by the linear fits were 23%, 14%, and 11%. As the corresponding $r^2_{quadratic}$ values were .97, .98 and .97, the quadratic fits accounted for 87%, 86%, and 73% of the residual non-linear variances for the slow, medium and fast speeds, respectively. We conclude that the addition of a quadratic term substantially improves the fit relative to the linear equation, indicating that the underlying function is quadratic (see Section 5.2).

Active vs. passive touch. To compare the magnitude of the speed effects obtained in the active versus passive conditions, we performed another one-tailed t-test for independent groups i.e., mode of touch (see Section 5.3). The absolute difference between the extremes in perceived roughness due to speed was the dependent variable (for details, see Experiment 1). In Experiment 2, the mean difference between these two sets of absolute difference scores proved to be highly significant, t (14) = -2.48, p < .015, indicating that speed had a greater effect in the passive-touch condition, regardless of the direction of the speed effect.

Effect of speed on peak roughness. To determine any effect of speed on peak shift, once again we determined the interelement spacing at which the quadratic functions peaked (Figure 3). These functions were all based on aggregated subject data, to minimize the effect of extreme scores from individual subjects. As previously found in Experiment 1, the peak value consistently shifted along the interelement spacing continuum toward the higher end with increasing speed in both active-and passive-touch conditions. In the active condition, the peaks for the slow, medium and fast speeds were 2.28, 2.53, and 3.05 mm (Table 3, Figure 3a), respectively. In the passive condition, the corresponding values were 2.07, 2.67, and 3.28 mm (Table 3, Figure 3b), respectively.

Once again, there were several unusually high participant peak values in the high-speed conditions for both active and passive modes. As before, we attribute these to the improved linear fit as speed increased. (A one-way ANOVA with speed as a within-subject factor, r^2_{linear} as the dependent variable, and participant as the unit of observation, indicated that the linear fit significantly improved with increasing speed for both active- and passive-touch conditions.) Hence, we used the non-parametric Friedman two-way ANOVA to test for the effects of speed on peak position. The unit of observation was subject. The test was performed separately for active and passive conditions. For the active condition, the summed ranks were 27, 40 and 53 for the slow, medium and fast conditions, respectively. The effect of speed was significant, χ_r^2 (2) = 16.9, p < .001. Planned comparisons of the differences between the three speed conditions indicated that the slow condition produced lower peak ranks than did the high speed condition, p < .05. Neither of the other two comparisons, slow vs. medium and medium vs. fast, was significant. For the passive condition, the summed ranks were 36, 37, and 47, respectively. Although the trend toward a shift in the quadratic peak in the passive condition was similar to that observed in the active condition, the differences were smaller and the effect of speed was not significant, χ_r^2 (2) = 3.7, p > .05. We conclude that increasing speed significantly produces, or tends to produce, an increase in the peak position along the interelement spacing axis. This peak shift, in turn, might account for the observed cross-over in the direction of the speed effect, i.e., the significant interaction terms involving speed and interelement spacing in the ANOVAs for active and passive touch. It might also explain the increasing linearity with increasing speed, as the peak shifts toward and beyond the wide end of the interelement-spacing continuum.

Effect of speed range on perceived roughness. To evaluate the effect of speed range on perceived roughness, the doubling ratios for active- and passive-touch conditions were calculated as in Experiment 1: the corresponding values were .40 and .38 (see Table 2), that is, the speed variable produced about 40% of the corresponding effects due to interelement spacing. As predicted, therefore, the effect of speed, as measured by the doubling ratio, increased markedly when the range of speeds was reduced to a 4-fold change.

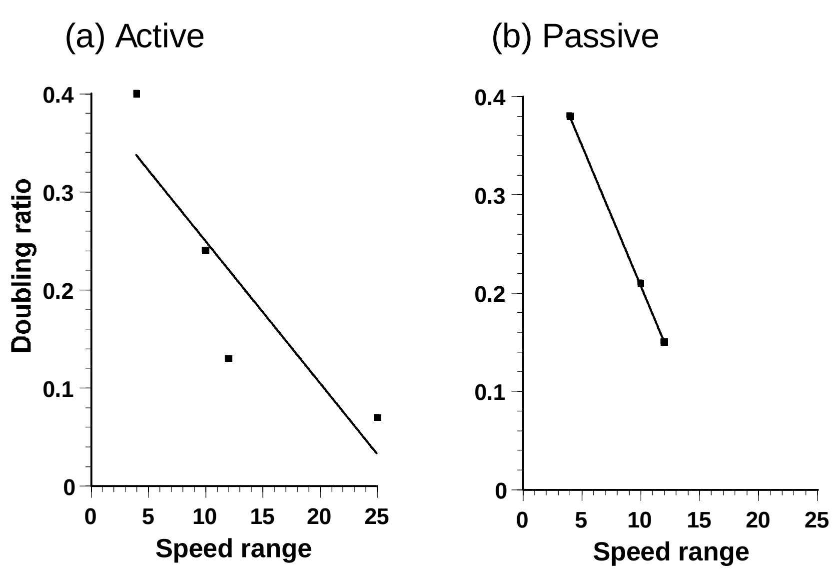

Figure 4. Doubling ratio as a function of ratio of speed range for all experiments: (a) active, (b) passive. A value of zero indicates no effect of speed, i.e., total speed constancy. The data have been fit with a linear function.

In the introduction to Experiment 2, we suggested that the strength of the speed effect might vary inversely with the size of speed range, as measured by maximum:minimum speed ratio. To quantitatively evaluate this idea, linear fits were applied separately to the active and passive conditions relating the doubling ratio (y-axis) to the maximum:minimum speed ratio (x-axis) (Figure 4). All experiments by Lederman and her colleagues that have examined the effect of speed on perceived roughness were included (see Table 2), regardless of the type of end effector used. In support of our prediction, a linear fit to the functions provided good to excellent results, with r^2 values of .78 and 1.00 for active and passive touch, respectively. We did not believe that it was appropriate to use the doubling-ratio measure to directly compare the two modes of touch within each experiment for reasons explained in Section 5.6.

4. GENERAL DISCUSSION

The current study investigated the influence of a potentially critical manual-exploration parameter -- speed of relative motion -- on roughness perception via a rigid probe. Performances under active and passive modes of touch were both considered. The current results address several important issues. First, they reveal significant differences in the nature of the psychophysical functions for roughness obtained with a rigid probe versus earlier work with the bare finger. Second, they highlight the fact that speed affects roughness perception via a probe in several complex ways. Third, and finally, the psychophysical findings provide valuable information concerning possible effects of speed of exploration on the perceived roughness of real or simulated textured surfaces using point-contact haptic interfaces for teleoperation and virtual environments. We will address each of these topics in turn.

4.1 Shape of the psychophysical function for roughness as a function of interelement spacing

Earlier experiments with the bare finger (e.g., 2D abrasive surfaces: e.g., [26]; 1D metal gratings: e.g., [18]) confirmed that a power function, which is best described by a linear function when log scales are used, provided excellent fits to the psychophysical data. Such linear functions have been shown to apply well to a wide variety of prothetic (i.e., intensive) dimensions, including perceived roughness. In contrast, Connor and his associates [1] [2] found that an inverted U-shaped function best fit the perceived roughness of 2D raised, plastic dot patterns, with a peak roughness occurring with an interelement spacing of about 3.5 mm. It is less clear that Connor et al.'s quadratic function, which was obtained with a bare finger, was due to a decline in perceived roughness along a single intensive dimension. We suspect the decline might rather have been the result of subjects switching their heuristic when the upper boundary of the perceived roughness continuum was encountered. For example, in our lab, subjects have frequently indicated that surfaces with interelement spacings greater than about 3.5 mm did not appear to lie along the same "perceived roughness" continuum as the others; rather, these surfaces felt smooth with a limited number of raised dots on them. In current pilot work with the rigid probe, we documented a similar effect, although the upper bound now tended to occur somewhat below the 3.5 mm value usually obtained with the bare finger. It was for this reason that we chose to eliminate the interelement spacings that subjects could not comfortably evaluate in terms of roughness (Experiment 1).

The psychophysical roughness functions in Experiments 1 and 2 (Figures 2 and 3, respectively) plotted as a function of interelement spacing, were very well fit by quadratic equations. A substantial percentage of the residual non-linear variance was accounted for by a quadratic fit. These data confirmed earlier findings by Klatzky and Lederman [10], which showed good quadratic fits to the psychophysical roughness functions obtained when rigid probes were used, particularly the smaller one. We therefore currently believe that a linear function (log scales) best describes the surface roughness perceived with a bare finger up to about 3.5 mm; in contrast, we believe a quadratic function best describes the nature of the psychophysical relation obtained with a rigid probe, especially when it is relatively narrow relative to the interelement spacings used. The increasing linearity in the psychophysical functions with increasing speed is likely due to a rightward shift in the peaks of the quadratic functions, together with an upper bound on the spacing values that can be tested while subjects still report perceiving roughness.

4.2 Psychophysical effects of speed on perceived roughness

Shift in peak roughness. The point at which the quadratic functions peaked in the Klatzky and Lederman [10] study shifted toward the wider end of the interelement spacing continuum as the size of the probes increased. We argued that one possible reason for the shift might be due to the fact that as probe size increased, so too did the minimum value of interelement spacing into which the probe could first fully penetrate.

In the current experiments, increasing speed produced a similar effect -- the peak roughness value tended to shift toward the wider end of the interelement-spacing for both active- and passive-touch conditions. To account for the shift in peak position in these experiments, we suggest that increasing speed had the effect of increasing the minimum size of interelement spacing into which the probe could fully fit -- presumably, the probe could descend less and less completely into the gaps between elements as speed increased up to some very high value, at which point the probe could only ride across the tops of the raised elements.

Overall, the results tend to support our inference from previous data that the geometry of the probe/surface interaction, and its effects on vibratory patterns, are critical to the perception of roughness via a rigid probe.

Direction of speed effects. Recall that in Lederman's earlier studies [14] [15] with the bare finger, the slight effect of speed was the result of a small decrease in perceived roughness as speed increased; this pattern was most evident for the gratings with the narrowest groove widths. How do those results compare with the current ones?

In the current experiments, speed clearly influenced the direction of the subjects' roughness judgments, as indicated by the results of the analyses of variance performed in both Experiments 1 and 2. As with earlier bare-finger experiments, both the active-and passive-touch psychophysical functions for the fast-speed condition tended to produce the lowest roughness estimates across the narrow end of the interelement-spacing continuum. However, as significant higher-order interactions between speed and interelement spacing were always present, it was considered inappropriate to interpret any significant main effect of speed. The interaction effect indicated that unlike the bare-finger experiments, the functions crossed over at the wider end, such that the fastest speed produced the roughest estimates of the wider interelement spacings. The points of transition tended to occur closer to the wide end of the continuum in Experiment 1 than in Experiment 2. We have suggested that such cross-over effects may be due to a shift in the quadratic peak toward the wide end of the interelement-spacing continuum. In future work, we plan to consider the basis of this cross-over effect observed when a rigid probe, as opposed to the bare finger, is used by obtaining precise measurements of the actual vibratory signals.

Mode of touch. We initially anticipated that the effect of speed on perceived roughness would be larger when passive, as opposed to active, touch was used. We argued that there should be less kinesthetic information in the passive touch condition that could be used to compensate for alterations in perceived roughness resulting from changes in the speed of relative motion. This prediction was generally confirmed. A 1-tailed t-test was used to compare the magnitude of the speed effect for active versus passive touch. The input data consisted of the differences in the maximum speed effects for all interelement spacings. (Direction was ignored because of observed crossover effects.) The results revealed a significant mode effect in Experiment 2, and a non-significant trend in experiment 1. Both effects were in the predicted direction.

It is possible that the active-passive difference was more substantial in Experiment 2 (than in 1) because the corresponding kinesthetic (and possibly cutaneous) feedback about the speed of relative motion was less discriminable. After all, the ratio of maximum to minimum speeds was substantially reduced from 10 (Experiment 1) down to 4 (Experiment 2).

Magnitude of speed effect: Speed vs. interelement spacing -- the doubling ratio. Lederman previously [14] [15] showed a relatively negligible effect of speed of motion on roughness perception when the bare finger was used. In these earlier studies, the effect of speed was assessed by comparing the proportion of the overall sum of squares due to treatments contributed by speed, as compared to that due to the primary determinant of roughness -- groove width. In the current experiments, we derived a new measure -- the "doubling ratio". This measure was intended to provide us with a "standard" measuring tool with which we could compare "worst-scenario" speed effects across experiments, both past and present. Accordingly, the measure was based on the maximum contribution of speed relative to that of interelement spacing, the most influential determinant of perceived roughness documented to date. The maximum contribution of speed for any single interelement spacing was selected from among the set of all interelement spacings used, without regard to which two (of three possible) speeds produced the maximum speed effect. (There were a few inconsistencies in the direction and magnitude of speed effects for a few subjects; however, the majority of subjects gave fairly similar results.) Sizeable effects of speed were observed in the current experiments, as revealed by relatively large doubling ratios.

Implications of doubling-ratios for initial predictions. In this next section, we use the doubling ratios to interpret the relative size of speed effect obtained as a result of the nature of the end effector (compliant finger vs. rigid probe) and the size of speed range employed.

We begin first by considering maximum speed effects due to the end effector. Recall that we predicted that speed might exert a relatively greater influence on perceived roughness than it did in the previous studies with the bare finger. This is because speed affects the vibratory signals that are likely to prove even more important when exploration is limited to the use of a rigid probe. Indeed, the doubling ratios initially seem to confirm our prediction, inasmuch as they are considerably larger than those for the bare-finger experiments when the ratios in Table 2 are expressed as percentages (cf. ratios of 21 to 40% vs. <1% to15%, for probe and finger, respectively). The use of doubling ratios to assess the maximum effect of speed relative to interelement spacing on perceived roughness further confirms our earlier conclusion concerning the relatively negligible effects of speed on perceived roughness with the bare finger. However, the bare finger/probe difference in doubling ratios may be explained better by changes in the size of the speed range, a parameter with which it is confounded. Further research is needed to determine if the type of end effector (bare finger vs. probe) makes an independent contribution to the effect of speed on perceived roughness.

Let us turn now to the effect of size of speed range. In Experiment 1, the doubling ratios (active and passive) were about .20, which was about one-fifth that due to a corresponding change in interelement spacing. When the range of speeds was reduced even further (Experiment 2), these values increased substantially to about .40, which means that the maximum effect of speed in both active and passive conditions was now about 40% that due to interelement spacing. While clearly less than the maximal effect due to interelement spacing, the effect of speed is still clearly noteworthy.

The results reported in Experiment 1 led us to speculate further that the magnitude of the speed effect would vary inversely with the size of speed range, as measured by maximum:minimum speed ratio. Experiment 2 confirmed this prediction (see Table 2, column 2). We noted that linear equations applied to the doubling ratio as a function of maximum speed:minimum speed ratio produced good to excellent linear fits for both active and passive modes of touch (Figure 4). These functions highlight the fact that regardless of the touch mode employed, the effect of speed increased as the range of speeds declined.

Might this reflect an decreased ability to determine relative speed when the range of speeds is smaller? To the extent that subjects were less able to estimate probe speed accurately when the range of explored speeds narrowed, they may also have been less able to adjust their roughness estimates to compensate for effects resulting from changes in speed (whether active- or passive- touch was used).

Summary of psychophysical findings. The current study confirmed that when a rigid probe was used, a quadratic equation generally described the psychophysical functions (perceived roughness by interelement spacing on log scales) better than did a linear equation. Previous research indicated that a linear equation best fit the psychophysical roughness functions when the bare finger was used.

The effects of speed of relative motion on perceived roughness proved to be multiple and complex. First, the quadratic functions tended to peak further toward the upper end of the interelement-spacing continuum as speed increased. This pattern of results occurred regardless of the mode of touch employed. Presumably, this also explains why the functions became more linear with increasing speed. Second, increasing speed tended to render surfaces as "smoother"; however, unlike earlier experiments that investigated the effect of speed using the bare finger, the current effect tended to reverse itself as the interelement spacing increased. Beyond this point of transition, surfaces tended to feel rougher with increasing speed. Such a transition is likely also the result of the shift in peak roughness just described. Third, with respect to mode of touch, the passive condition produced larger effects of speed on perceived roughness than did active touch, although substantial effects were obtained with the latter. These effects were either statistically significant (Experiment 2) or tended in that direction (Experiment 1). And fourth, the maximum-speed effect on perceived roughness -- as measured by the doubling ratio – was inversely proportional to the maximum:minimum speed ratio (Figure 4). That is, the smaller the range of speeds used, the larger the influence of speed on perceived roughness, relative to that of interelement spacing. This appeared to be true whether the bare finger or a rigid probe was used, and is likely attributable to the reduced discriminability of sensory (kinesthetic, cutaneous) cues about the speed of motion..

4.3 Implications for designing haptic interfaces for teleoperation and virtual environments.

The results of the present study also contribute to the growing psychophysical literature on perceiving roughness via a haptic interface (see, e.g., [5] [21] [22] [28]). Our initial study in this research program [10] indicated that while perceiving surface roughness via a rigid probe is not quite as precise as when the bare finger is used, it can still be reasonably effective in discriminating amongst real textures. The same study also raised the possibility that simulated textures -- produced by altering corresponding vibratory input -- may prove discriminable.

Such textural differentiation could prove useful in a variety of CAD and medical applications. For example, in telemedicine, plastic surgeons could learn to evaluate with a probe the extent to which a new skin graft has properly taken, or to differentiate between healthy and burned skin. And simulated information about the textural properties of various tissues and diseased masses might be accessed using virtual training systems for open and minimally invasive-surgical procedures.

The designer should keep in mind, however, that the quadratic shape of the psychophysical roughness functions obtained with point contact devices (such as a rigid probe) may limit to differing extents the functional domain of unambiguous information about surface roughness. The extent of constraint would be determined by the width of the interelement continuum that lies below the position of the peak. Recall that the perceived roughness of some surfaces with physically different interelement spacings was perceived to be identical. As the control characteristics of haptic interfaces necessarily vary, it is important to predetermine for each an unambiguous domain of roughness stimuli. More specifically, one must find a range of interelement spacings that produces a monotonically increasing roughness percept as a function of increased spacing. Our data suggest that this pattern is most likely to occur when a high exploration speed is used.

The human operator must also be capable of differentiating vibration-based changes due to differences in enduring texture properties from those brought about by changes in the speed of exploration. The current results highlight the fact that the relative speed of motion can affect perceived roughness quite substantially. However the magnitude of the effect is reduced proportionally as the range of speeds that are sampled widens. Presumably, with the narrowest ranges, people have less precise kinesthetic information about the consequences on the vibratory signal of altering speed. We also documented that the peak roughness value tends to shift toward the wider end of the interelement - spacing continuum as a function of increasing speed.

How might one minimize these speed effects? One possibility would be to create software that would nullify any effects of speed on the vibratory signals. However, given the variability of the speed effects across observers, this approach is likely to prove problematic. As explained earlier, some of the individual psychophysical functions (log-log) were best fit by a linear function, although most were described best by a quadratic function. Furthermore, the position of the peaks tended to vary across subjects, which in turn affected the extent to which the direction of the speed effect on perceived roughness reversed itself. In contrast, we believe that operator-training procedures may yield more promising results, and propose the following two exploration procedures.

The first involves maintaining a single, very high speed while exploring various surface textures. According to the current experimental results, to the extent that this speed does not fluctuate, the maximum speed effect -- measured by the doubling ratio and produced by altering speed during exploration -- would be eliminated. Nor would there be any peak-shift effect. Finally, surface discrimination would be maximized because the operator would be working from the broadest possible linear range of perceived roughness -- recall that when the highest speed was used, the psychophysical functions (log perceived roughness as a function of log interelement spacing) were reasonably close to linear. (Indeed, some subjects' high-speed functions showed excellent linearity.) Thus, to the extent that any downturn in roughness occurs, it should lie beyond the range of interelement spacings appropriate for producing an intensive continuum of perceived roughness.

A second and complementary strategy would be to train the operator to vary the range of speeds widely between medium and high values when exploring a single texture. Such a procedure would presumably minimize speed effects on the perceived roughness of a single surface, provided that a sufficiently wide range of speeds at the high end can be effected with a point-contact end effector. Collectively, these two exploration heuristics should help to eliminate or minimize possible harmful effects of changing speed on perceiving surface textures via a haptic interface. As emphasized above, however, it is critical that designers both know in advance the control characteristics of the particular haptic interface and select an appropriate range of stimuli.

5. NOTES

5.1. We believe the speed manipulation was sufficient for purposes of this initial investigation of the effects of speed on perceived roughness via a probe. If there had been substantial overlap among the three selected speeds in Experiment 2 (which used only a 4-fold range, we would not have expected to find significant effects of speed. Nor was a 20% change in the targeted force value (.29N) expected to have any substantial effect on perceived roughness [14] .

5.2. For several reasons, we did not believe that a standard trend analysis of the linear and quadratic components of the main effect of interelement spacing or its interaction with speed was appropriate. First, the assumption of equal parameter spacing was violated with respect to the interelement spacing factor, whose values increased logarithmically. Second, the typical contrast assumes a symmetric quadratic; however, it is not possible to know a priori the shape of the quadratic function in the current study

5.3. We felt that it was more appropriate to use a t-test for independent means despite the fact that the same set of interelement spacings was used in both active and passive conditions. Our decision was based on the fact that the mean values for the corresponding active and passive conditions for each interelement spacing were in fact based on different subjects.

5.4. We view the new doubling ratio measure as a valuable heuristic that allows us to compare the effects of speed on perceived roughness across experiments. While we do not know at this point whether speed is a ratio scale, we do know that the units used to relate physical magnitude to psychological magnitude both use ratio scales for a wide range of continua (e.g. [24]).

5.5. We believe that within-experiment differences between active versus passive touch are best analyzed statistically using a t-test that accepts, as input, data from all interelement spacings. The ratio measure is used as a means of comparing the effects of speed across different experiments with varying speed ranges. It is based on comparative data from the single interelement spacing with the largest absolute difference in perceived roughness. Thus, the ratio measure may be less discriminating than the t-test when comparing the speed effects using the two modes of touch.

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