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Tactile perception of nonpainful unpleasantness in relation to perceived roughness: Effects of inter-element spacing and speed of relative motion of rigid 2-D raised-dot patterns at two body loci

Ryo Kitada, Norihiro Sadato, Susan J Lederman§
Division of Cerebral Integration, National Institute for Physiological Sciences, Okazaki 444-8585, Japan; e-mail: kitada@nips.ac.jp; § Department of Psychology, Queen's University, Kingston K7L 3N6, Canada
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Abstract. Rigid surfaces consisting of spatially jittered 2-D raised-dot patterns with different inter-element spacings were moved back and forth across the skin at three different speeds (10-fold range). Within each psychophysical experiment, participants numerically estimated the perceived magnitude of either unpleasantness (nonpainful) or roughness of 2-D raised-dot surfaces applied to two stationary body sites (experiment 1: fingers; experiment 2: forearm). The psychophysical functions for the two types of perceptual judgment were highly similar at both body loci; more specifically, the perceived magnitude of unpleasantness and roughness both increased monotonically as a power function of increasing inter-element spacing, with the rate of growth declining at the upper end of the continuum. These results suggest that inter-element spacing is a critical determinant of the perceived magnitude of unpleasantness (nonpainful), as well as of roughness. Each perceptual judgment also increased as a function of increasing relative speed at both body loci. However, the magnitude of this effect was significantly greater for perceived unpleasantness than for perceived roughness; conversely, the speed effect was significantly greater on the forearm than on the fingers. Several possible explanations for these findings are considered.

Keywords: touch; roughness; pleasantness; somatosensory; material perception

1 Introduction

When we touch objects, in addition to perceiving and discriminating their physical properties, we may also experience associated affective sensations, such as pleasantness and unpleasantness. Interest in the mechanisms that underlie the affective aspects of touch has grown because the latter are critical for good quality of life and for our general sense of well-being (Field 2001; McGlone et al 2007; Essick et al 2010). Conducted at both peripheral and central levels, neurophysiological studies have revealed the existence of different (although possibly overlapping) neural mechanisms for the mediation of affective and discriminative touch (McGlone et al 2007). However, to date we know relatively little about the corresponding psychophysical properties of affective touch.

Our current approach to this topic is to psychophysically examine the extent to which several critical parameters previously assessed with respect to their influence on discriminative touch influence corresponding affective percepts. We address these affective judgments in their own right, and in relation to perceived roughness, an aspect of discriminative touch that has been extensively investigated because it constitutes a reliable and prominent dimension of texture perception (Hollins et al 1993). We employ rigid surfaces comprised of raised 2-D dot patterns because such stimuli can be precisely controlled and have been most commonly used in previous studies of tactile roughness perception (eg Connor et al 1990; Klatzky and Lederman 1999; Meftah et al 2000). While contact with compliant surfaces (eg textiles and brushes) is typically considered in terms of pleasant sensations, contact with rigid surfaces (eg a brick; our current stimuli) more typically elicits unpleasant (nonpainful) sensations. Accordingly, in the present study, we address unpleasantness, as opposed to pleasantness, as a prominent dimension of affective perception. We have chosen to experimentally manipulate three parameters of critical interest in previous studies of tactile roughness perception that pertain to the nature of the stimulus surface, the type of skin-surface interaction, and the actual site of skin stimulation (ie inter-element spacing, relative speed of motion between skin and surface, and body locus, respectively). We compare the magnitude estimates of perceived unpleasantness to those for perceived roughness under identical parametric conditions.

We begin by introducing the relevant background literature on tactual roughness perception. Previous psychophysical and neurophysiological studies have manipulated a variety of physical parameters associated with stimulus surfaces such as linear unidimensional gratings (eg Lederman and Taylor 1972; Sathian et al 1989; Lawrence et al 2007) and 2-D raised-dot patterns (eg Connor et al 1990; Connor and Johnson 1992; Blake et al 1997; Meftah et al 2000). These studies have consistently demonstrated that inter-element spacing, one of three parameters of interest in the current study, is arguably the strongest physical determinant of roughness perception by touch: whether passive or active touch is used, the magnitude of perceived roughness increases as inter-element spacing is increased.

Research has also shown that the speed of relative motion between skin and surface, our second parameter of interest, produces negligible if any effects on perceived roughness magnitude, whether passive or active contact via the fingers is used (Lederman 1983; Meftah et al 2000). For instance, Lederman (1983) conducted an experiment in which linear gratings were moved from side to side beneath the participant's left middle finger at three different speeds across a 10-fold range. Although the speed of relative motion significantly influenced the magnitude of perceived roughness, it accounted for only 2% of the overall variance, which was substantially smaller than the corresponding effect of inter-element spacing (41%). Speed had no influence on the perceived roughness of 2-D raised-dot patterns as well (Meftah et al 2000). Collectively, the available empirical results support the occurrence of perceptual roughness constancy despite alterations in the relative speed of motion between finger(s) and surface.

In the current study, we further explore the influence of relative speed of motion on perceived roughness by manipulating a third parameter, body locus of skin stimulation. Does relative speed of motion influence roughness judgments of perceived magnitude at sites other than the hand (ie the volar forearm)? The only study to previously assess tactile roughness perception at different body loci was conducted by Stevens (1990). Participants provided magnitude estimates of roughness when grooved metallic surfaces were manually stroked across ten different body parts. The degree of roughness sensitivity was expressed as the exponent of the psychophysical power function relating perceived roughness magnitude to groove width. The value of this measure was greater for the glabrous skin (ie lip, finger) than the hairy skin (ie forearm, upper arm, belly), suggesting greater roughness sensitivity on glabrous, as opposed to hairy, skin. However, because speed of relative motion in that study was neither controlled nor systematically varied, its effects on tactile roughness perception at body loci other than the fingers remains current unknown.(1)

We turn now to the psychophysics of affective touch, the primary focus of our current study. In contrast to discriminative touch, which focuses mainly on stable external objects and their various properties, affective touch relates to how physical

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(1) Previous psychophysical studies (Lederman and Taylor 1972; Lederman 1974, 1983) using the finger(s) have demonstrated that increasing the force applied to a textured surface increases the magnitude of perceived roughness. Closer examination of the relevant data indicates that this effect appears to be most evident when the force variation considerably exceeds normal levels (Lamb 1983; Smith et al 2002). Accordingly, in our first psychophysical study on affective touch, we restricted our focus to relative speed of motion, while maintaining finger force constant at 0.29 N, a level that previous studies have determined to be 'comfortable' (eg Lederman and Taylor 1972).

contact affects the internal state of the body (Craig 2002). In addition to eliciting roughness percepts, contact with physically rough, rigid surfaces may also be experienced as unpleasant. It is this subjectively based affective percept that we have chosen to explore in the current study, on its own and in comparison to the more externally referred roughness percept.

As the inter-element spacing between the rigid texture elements increases, the skin becomes progressively more indented (up to some maximum) relative to the tops of the textured elements. As the sharp edges of those rigid texture elements are pushed deeper into the skin, the possibility of causing skin damage during relative motion also increases. We assumed that contact with a raised-dot surface would feel more unpleasant as such contact becomes more likely to damage the skin. Accordingly, we expected that the perceived magnitude of unpleasantness experienced during contact with rigid raised-dot surfaces would also increase as inter-element spacing was increased. Preliminary confirmation with abrasive surfaces comes from the results of two psychophysical studies (Ekman et al 1965; Verrillo et al 1999). For example, in Ekman et al (1965), the participants were asked to actively scan a pair of textures with their two index fingers and to numerically estimate the ratio of the magnitude of smoothness and pleasantness for one surface relative to the other. Textures used in this study were different types of paper (cardboard, writing, and abrasive). The magnitudes of pleasantness and roughness were highly related to each other; that is, the smoother a surface felt, the more pleasant it was judged to be. Verrillo et al (1999) required participants to actively scan abrasive surfaces with the pad of the index finger and to numerically estimate the magnitude of both perceived pleasantness and roughness. As the grit value [1/(particle diameter)] was increased, the magnitude of perceived roughness monotonically declined, while corresponding estimates of pleasantness increased. Unfortunately, abrasive surfaces, as well as cardboard and writing papers, are not well-controlled stimuli; moreover, neither study above included objective statistical analysis regarding the relationship between pleasantness and perceived roughness. As such, the Ekman and Verrillo et al studies provide interesting, although limited, background data for the current study.

We further explored possible effects of manipulating the relative speed of motion between skin and rigid textured surfaces on perceived unpleasantness at two body loci. To our knowledge, no previous study has directly compared the effects of speed of relative motion on affective touch (perceived unpleasantness) with discriminative touch (perceived roughness) using the same experimental conditions.

As a raised-dot surface moves across the skin, the latter can snag on the sharp leading edges of the rigid elements that form the textured patterns (Smith et al 2002). Because increasing speed will cause even greater snagging, we predicted that perceived unpleasantness would monotonically increase with increasing speed. Previous psychophysical experiments have investigated the differential effects of relative speed of motion on perceived pleasantness of compliant surfaces (soft brushes and textiles) presented to hairy versus glabrous skin sites (Essick et al 1999, 2010; Löken et al 2009). For example, Löken et al (2009) showed that a slow (1 to 10 cm s^{-1}) brush stroke on the forearm produced more pleasant percepts than faster (30 cm s^{-1}) or slower (below 0.3 cm s^{-1}) stroke speeds, this psychophysical relation being fit best by a negative quadratic function. In contrast, varying the speed of relative motion of brush strokes on the palm did not relate strongly to the magnitude of perceived pleasantness (neither linear nor quadratic fits were statistically significant). Although the previous study was primarily concerned with which mechanoreceptor population(s) subserve the experience of pleasantness (see section 4), the results with compliant surfaces reveal a stronger effect of speed on the forearm than on the palm. Will speed of relative motion affect the forearm (hairy) more strongly than the fingers (glabrous) in the current study when rigid textured surfaces are presented?

To summarise, we conducted two experiments in which rigid surfaces consisting of non-compliant, spatially jittered 2-D raised-dot patterns were stroked at three different speeds across the stationary skin of three middle fingers and ventral forearm (experiments 1 and 2, respectively). In both experiments, after each textured surface was presented, participants were asked to numerically estimate the perceived magnitude of either unpleasantness or roughness. The mean speeds ranged from 1.3 to 14.2 cm s^{-1}, and overlapped ranges used earlier by Lederman (1983) for judging perceived roughness (1.7 to 20.6 cm s^{-1}) and by previous studies of affective touch that examined the perceived pleasantness of compliant materials (Essick et al 1999, 2010; Löken et al 2009).

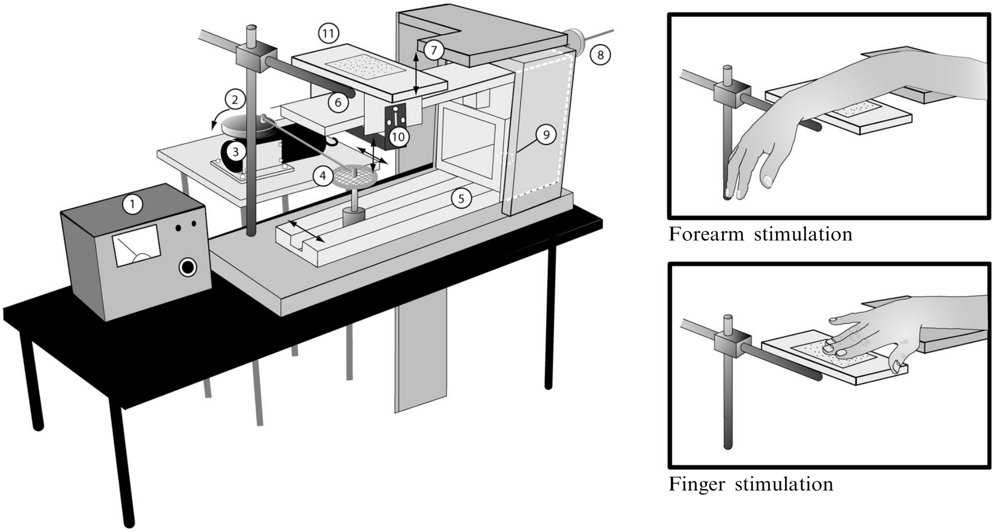
2 Experiment 1: Perceived unpleasantness and roughness of rigid textured surfaces applied to the fingers

2.1 *Materials and methods*

2.1.1 *Participants.* Twenty-four naive psychology students (eighteen females, six males) participated in the experiment for course credit or $10 compensation. Their mean age was 19.4 years (range: 17–23 years). Half of the participants were pseudorandomly assigned to one of two groups (nine females, three males in each group). All were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield 1971), with no injury on the fingers. Written informed consent was given at the start of the experiment. The study was approved by the local ethics committee of Queen's University (Canada).

2.1.2 *Stimuli.* We used rigid 2-D raised-dot surfaces that had been employed in previous studies (eg Klatzky and Lederman 1999; Lederman et al 1999; Lederman and Klatzky 1999). These surfaces were produced using the Nyloprint photoengraving technique. The plastic polymer plates contained raised dots in the form of truncated cones. The dot height was 0.52 mm. The base diameter of the dots varied between 0.72 and 0.98 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. 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 across the plate, yet maintained the original mean inter-element spacing (inner edge to inner edge) in x and y. The stimulus set consisted of 8 inter-element spacings ranging from 0.500 to 4.00 mm, in 0.500 mm increments. An audiotape of background masking noise (pink noise) was used to eliminate any auditory feedback produced by the fingers.

2.1.3 *Apparatus.* A force-control balance apparatus, designed like a classical balance scale, was used in the current study (figure 1). This apparatus has been already utilised in previous studies (eg Lederman and Taylor 1972; Lederman 1974, 1983; Lederman et al 1999; Lederman and Klatzky 1999). The textured plates were fixed (in turn) upon a stimulus platform, which was mounted toward the front end of a balance arm. The elbow rest was located above the fulcrum of the balance arm toward the back of the apparatus; it was physically isolated from the apparatus. When their fingers were stimulated with the texture, participants rested their forearm on the rest. In both conditions, the participant 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 participant had to apply a well-defined force via his or her skin on the front arm, to balance the weight on the back arm. The applied force was set at 0.29 N in order to make our result comparable to previous studies on roughness (0.41 N—Lederman 1983) and on pleasantness (0.2 N and 0.4 N—Löken et al 2009). The constancy of the force was disturbed only by the small acceleration forces as the balance arm moved up and down. However, as mentioned earlier (Lederman and Taylor 1972), these variations were no more than about 20% of the nominal value.



Forearm stimulation

Finger stimulation

Figure 1. The apparatus used to control force and speed: 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 participant contacting textured surface with fingers or forearm. Note that the balance arm is moved sideways by the rotating base, to which it is attached. The balance arm independently moves up or down, whenever the counter-force applied to the textured surface by the participant is less or more, respectively, than the targeted 0.29 N force. The experimenter confirmed that fingers or forearm did not contact the stimulus platform outside of the surface for each trial.

The textured stimuli were moved back and forth beneath the skin by driving the balance arm from side to side via a linear metal rod. To reduce extraneous vibrations created by the activity of the motor, the metal rod was connected horizontally at one end via a rubber connector 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 to further reduce extraneous vibrations. 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 skin. The table legs were set in sand to minimise extraneous vibrations along the balance arm. The stimulus was moved back and forth under fingers, approximately 5.5 cm in both directions. The three speeds (mean) were approximately 1.3 cm s^{-1} (slow), 3.7 cm s^{-1} (medium), and 14.2 cm s^{-1} (fast). These velocities were chosen for two main reasons. First, we endeavored to make our result comparable to our previous work (Lederman 1983). Moreover, these velocities overlap with range of speeds tested in previous studies on tactile pleasant perception (Löken et al 2009; Essick et al 2010).

2.1.4 *Experimental design.* We employed an experimental design with three within-subject and one between-subject factors. More specifically, we treated inter-element spacing, speed, and repetition as within-subject factors, whereas percept (unpleasantness, roughness) was designed as the between-subject factor to avoid the participant treating the two percepts as identical. The order in which the eight inter-element spacings and three speeds were presented was pseudorandomly determined for each of four repetitions per participant, such that each speed/stimulus combination was presented once within each repetition. The first repetition was considered practice and excluded from statistical analysis.

2.1.5 *Experimental procedure.* Participants were seated on a stool with the apparatus to their right. An absolute magnitude-estimation procedure was utilised to estimate either the roughness or unpleasantness of each surface (Zwislocki and Goodman 1980). In one group, the participants were instructed to choose a number that best matched the perceived roughness of the surface. In the other group, participants were instructed to choose a number that best matched the magnitude of unpleasantness associated with each surface. Participants were allowed to use any number (decimal, fraction, or whole number), as long as the number was above zero. Neither modulus nor standard was used. All participants were blindfolded, and fitted with a headrest through which background pink noise was played.

Participants were trained to maintain the balance arm steady and level. They were also instructed to keep their three fingers together. Each trial started when the experimenter would gently raise the stimulus platform up until they could counterbalance it with the three fingers. During practice, all participants were familiarised with the magnitude-estimation procedure using a sample of surfaces and speeds. A session lasted approximately 50 min. Participants were allowed to take short break after the two repetitions of trials were complete. After the experiment ended, the experimenter confirmed that none of the participants experienced painful sensations throughout the experiment.

2.2 *Results and discussion*

To assess any effects of repetitions, separate analyses of variance (ANOVAs) using a three-factor, repeated-measures design were initially performed on the raw magnitude estimates for both unpleasantness and roughness conditions. The three within-subject factors were speed (three levels), inter-element spacing (eight levels), and repetitions (three levels). The Greenhouse – Geisser correction was used for degrees of freedom in all analyses. As neither the main effect of repetition nor any interaction involving repetition was statistically significant in either roughness or unpleasantness conditions ($ps > 0.1$), the effects of these terms were not considered further.

To reduce variability, the data from the three replications were combined for use in all subsequent analyses. These data were normalised within each perceptual condition to eliminate possible biases due to the participants' use of different number ranges. This normalisation procedure was performed by dividing each data point by the participant's mean and then multiplying by the grand mean for the group (roughness or unpleasantness). Finally, to provide a more normal distribution of the magnitude-estimate scores (see eg Marks 1982; Gescheider 1997), the scale-equated scores were logarithmically transformed (base 10). The transformed data served as the basis of all subsequent data analyses.(2)

2.2.1 *Effects of inter-element spacing and relative speed of motion.* Unpleasantness and roughness are qualitatively different perceptual dimensions. Moreover, the different groups of the participants may have chosen to use different number ranges to estimate magnitude. Thus, we did not initially directly compare the magnitude estimates for the two percepts within the same analyses. We began by analysing the data for each percept condition separately, and subsequently compared the two percepts directly in terms of the perceptual effects of inter-element spacing and relative speed of motion at two body loci. The results of the latter analyses are presented in sections 3.2.3 and 3.2.4.

(2) In the method of magnitude estimation, it is recommended to employ geometric means, rather than arithmetic means, to combine data from different participants (Gescheider 1997). Indeed, previous psychophysical studies have shown that inter-element spacing of 2-D raised-dot patterns can reasonably account for the magnitude estimates of perceived roughness, which were calculated as geometric mean (Klatzky and Lederman 1999; Lederman et al 1999). However, relatively little is known about the magnitude-estimate patterns as a function of speed. Accordingly, in our analyses of the effect of speed on magnitude estimates, we conducted an additional analysis using arithmetic mean of normalised magnitude estimates to confirm our result obtained from geometric mean.

Unpleasantness. A two-factor repeated-measures ANOVA on inter-element spacing (8 levels) and speed (3 levels) with magnitude estimates of perceived unpleasantness as the input data yielded a highly significant main effect of inter-element spacing ($F_{1.5,\,16.2} = 91.7$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.89$). Figure 2a shows perceived magnitude of unpleasantness as a function of inter-element spacing on base-10 logarithmic scales for each of the three speeds. In general, the magnitude of unpleasantness tended to increase with inner-element spacing and to level off at the higher values. As this flattening occurs at the top end of the stimulus range, linear trends account for most of the variance; R^2 values (coefficient of determination) for the slow, medium, and fast speeds are all above 0.97 (table 1). The main effect of speed is also highly significant ($F_{1.3,\,14.3} = 17.4$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.61$); the mean estimates of unpleasantness increase with increasing speed. The interaction term is not statistically significant ($p = 0.37$). A posteriori paired comparisons (with Bonferroni correction) of the mean estimates for the inter-element spacings at each speed show that the fast speed produces significantly greater unpleasantness estimates than either of the other two speeds (ps < 0.01), which are not significantly different ($p = 0.25$).

Roughness. A similar two-factor repeated-measures ANOVA on inter-element spacing (8 levels) and speed (3 levels), with magnitude estimates of perceived roughness as the input data likewise reveals a highly significant main effect of inter-element spacing ($F_{1.3,\,14.4} = 102.8$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.90$); the magnitude of roughness also increases with increasing inter-element spacing, leveling off at the upper end (figure 2b). The R^2 values

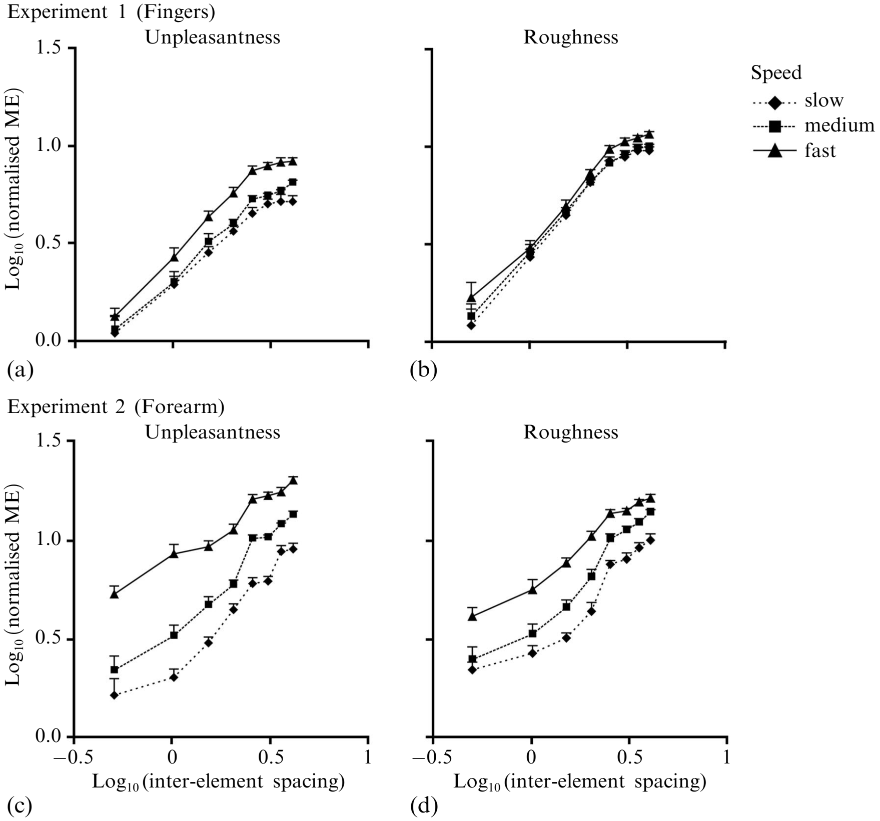


Figure 2. Mean $\log_{10}$ normalised magnitude estimates (ME) of roughness and unpleasantness as a function of inter-element spacing for slow (1.3 cm s^{-1}), medium (3.7 cm s^{-1}), and fast speeds (14.2 cm s^{-1}). Each data point is based on twelve participants (each with mean of three replications). Each data point indicates mean ± SEM.

Table 1. Parameters and goodness of fit of linear functions fitted to the data.

Experiment	Speed	Unpleasantness			Roughness		
		slope	intercept	R^2	slope	intercept	R^2
1 Fingers	slow	0.80	0.30	0.982	1.04	0.44	0.972
	medium	0.87	0.33	0.985	1.01	0.47	0.982
	fast	0.93	0.44	0.974	1.00	0.53	0.981
2 Forearm	slow	0.91	0.39	0.952	0.82	0.49	0.906
	medium	0.94	0.56	0.967	0.91	0.59	0.955
	fast	0.64	0.91	0.969	0.73	0.80	0.976

for all speeds are above 0.97 (table 1). The main effect of speed is also highly significant ($F_{1.1,\,12.5} = 15.1$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.58$); the mean of the roughness estimates increases monotonically with increasing speed. Finally, the interaction term is not significant ($p = 0.21$). We averaged estimates over inter-element spacings at each speed and performed paired comparisons (with Bonferroni correction) among the three speed conditions. This a-posteriori test reveals that the fastest motion produces significantly greater roughness magnitudes than either of the other two speeds (ps < 0.01), which are not significantly different from each other ($p = 0.08$).

2.2.2 *Psychophysical functions: perceived unpleasantness versus perceived roughness as a function of inter-element spacing.* As the figures 2a and 2b show, the psychophysical functions for unpleasantness and roughness judgments are highly similar; the magnitude estimates of both percepts monotonically increase with inter-element spacing and then flatten at the higher values of inter-element spacing. Figures 3a–3c show the relationship between the mean magnitude estimates of unpleasantness and perceived

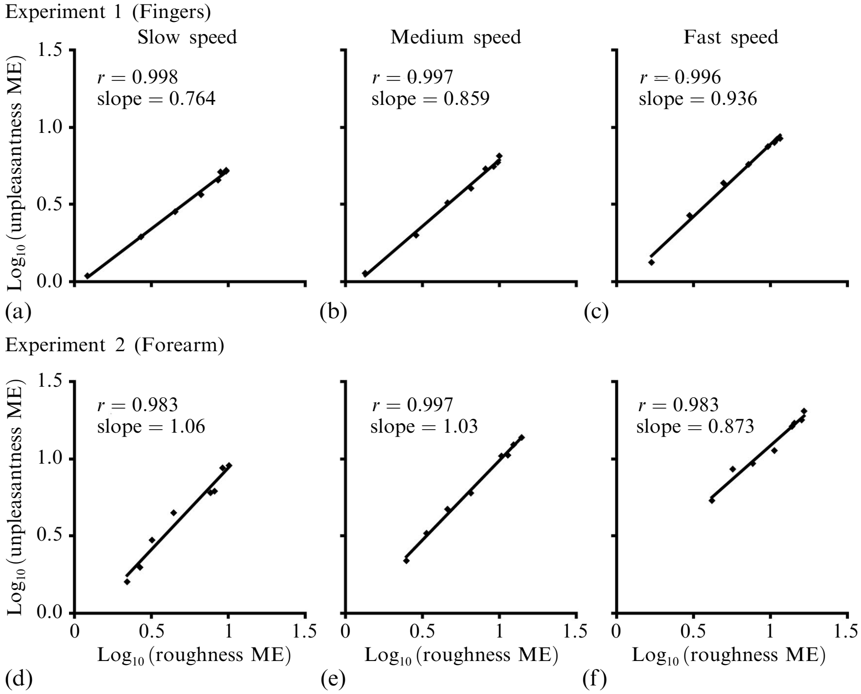


Figure 3. Relationship between $\log_{10}$ normalised magnitude estimates (ME) of roughness and unpleasantness. Each data point indicates mean data of each inter-element spacing of stimuli. Note that the magnitude estimates of roughness and unpleasantness were obtained from different subject groups.

roughness as a function of inter-element spacing on $\log_{10} - \log_{10}$ scales for slow, medium, and fast speeds, respectively. Each dot indicates corresponding scores for unpleasantness and roughness judgments at each inter-element spacing.

The Pearson's correlation coefficient between unpleasantness and roughness estimates is above 0.99, regardless of speed level. The mean slope value of the function averaged across the three speeds was 0.85, which is nominally below 1.0 (figure 3). It is not possible to directly assess whether this difference was statistically significant because the data for the two percepts are obtained from different subject groups. However, as shown in section 3.2.3, we showed that the slope values for the linear functions fit to the data relating perceived roughness versus unpleasantness (magnitude estimate) to inter-element spacing are not statistically significant.(3) We therefore confirm indirectly that the slope value in figure 3 (averaged across speed) is comparable to 1.0. We will statistically compare the effect of speed on perceived unpleasantness and perceived roughness at both body sites in section 3.2.4.

3 Experiment 2: Perceived unpleasantness and roughness of rigid textured surfaces applied to the forearm

3.1 *Methods*

Twenty-four experimentally naive psychology students (eighteen females, six males) participated in the experiment for course credit or $10 compensation. These participants did not participate in experiment 1. Their mean age was 19.0 years (range: 17 – 22 years). Participants were pseudorandomly assigned to either roughness- or unpleasantness-conditions, for a total of twelve per group (nine females and three males in each group). Thus, the ratio of gender and mean age were matched for all groups across experiments. All were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield 1971), with no injury in the area of skin stimulated. They provided written informed consent at the start of the experiment. The experiment was approved by the local ethics committee of Queen's University (Canada).

The stimuli, apparatus, experimental design, and procedure were identical to experiment 1 except for the skin area stimulated. Unlike experiment 1, participants rested their wrist and elbows on different rests (figure 1). The surfaces contacted the volar side of the right forearm, stimulating a section 7.5 – 17.5 cm proximal to the wrist. After the experiment was completed, the experimenter confirmed that none of the participants experienced any painful sensations during the experiment.

3.2 *Results and discussion*

We followed the same procedures for data analysis as in experiment 1. As neither the main effect of repetition nor any interaction involving this factor was statistically significant in either the unpleasantness or roughness analyses ($ps > 0.1$), the data from the three replications were combined. These data were normalised and then logarithmically transformed for subsequent analyses.

3.2.1 *Effects of inter-element spacing and speed*

Unpleasantness. The two-factor repeated-measures ANOVA [(8 levels of inter-element spacing) × (3 levels of speed)] on the $\log_{10}$ magnitude estimates of unpleasantness reveals a highly significant main effect of inter-element spacing ($F_{2.5, 27.0} = 91.9$, $p < 0.001$, $\eta_p^2 = 0.89$). Unpleasantness magnitude also increases as a power function of

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(3) It is inappropriate to interpret or compare the intercepts of the inter-element spacing functions, because the two percepts and two body loci were treated as between-subject factors. As participants were free to choose the numbers that best represent perceived magnitude, the intercept of the linear function remains affected by the group grand mean (ie mean of all data in a group), even after normalisation and log transformation of the input data. Accordingly, any intercept differences observed may simply reflect disparities in the number sets selected by the groups being compared.

inter-element spacing (figure 2c), with R^2 values for linear trends plotted on $\log_{10}$ scales for the slow, medium, and fast speeds all above 0.95 (table 1). The main effect of speed is also highly significant ($F_{1.1,\,12.1} = 37.0$, $p < 0.001$, $\eta_p^2 = 0.77$); the magnitude estimates of unpleasantness increase monotonically with increasing speed. The interaction term is also statistically significant ($F_{4.9,\,53.6} = 4.3$, $p < 0.01$, $\eta_p^2 = 0.28$).

As the interaction term was significant, we performed paired comparisons (with Bonferroni correction) among mean estimates for the three speed conditions at each inter-element spacing. This a-posteriori test confirms that the magnitude estimates of unpleasantness increase with speed. More specifically, fast motion produced significantly greater unpleasantness than the other two speeds (ps < 0.05) at all inter-element spacings. The medium speed produces significantly greater unpleasantness than the slow speed for all inter-element spacings except 1.5 and 2.0 mm (ps < 0.05), which both show similar trends (ps < 0.09).

Roughness. A two-factor repeated-measures ANOVA [(8 levels of inter-element spacing) $\times$ (3 levels of speed)] was performed on the $\log_{10}$ magnitude estimates for perceived roughness. The main effect of inter-element spacing is highly significant ($F_{1.9,\,21.4} = 114.8$, $p < 0.001$, $\eta_p^2 = 0.91$). As shown in figure 2d, linear trends account for most of the variance on log–log scales, with R^2 values for the slow, medium, and fast speeds all above 0.90 (table 1).

The main effect of speed is also strongly significant ($F_{1.6,\,17.6} = 97.4$, $p < 0.001$, $\eta_p^2 = 0.90$); mean estimates of roughness increase monotonically with increasing speed. The interaction term is not statistically significant ($p = 0.07$). A-posteriori paired comparisons (with Bonferroni correction) among the three mean estimates averaged over inter-element spacings for each speed revealed that the fast motion produces significantly greater roughness estimates than either of the other two speeds (ps < 0.001); moreover, the medium speed produces significantly greater roughness estimates than the slow speed ($p < 0.001$).

3.2.2 *Psychophysical functions: unpleasantness versus roughness as a function of inter-element spacing.* The psychophysical functions for unpleasantness and roughness are highly similar: the magnitude estimates of both percepts monotonically increase with inter-element spacing, the rate of growth declining at the upper end. Figures 3d–3f show the linear functions fitted to the magnitude estimates of perceived unpleasantness as a function of those corresponding to perceived roughness. The Pearson's correlation coefficient between unpleasantness and roughness scores on the forearm is > 0.98, regardless of speed level. The mean slope value of the linear functions across the three speeds was 0.99, suggesting that the effect of inter-element spacing is almost identical for the two percepts. A statistical test in the next section confirms that the slope values of the inter-element spacing functions for unpleasantness and roughness are not statistically different.

3.2.3 *The effect of inter-element spacing on perceived unpleasantness and perceived roughness at two body loci.* For both experiments 1 and 2, we compared the slopes of the linear functions fitted to the $\log_{10}$ magnitude-estimate scores for each percept as a function of inter-element spacing.(3) Table 1 shows parameters and goodness of fit for the linear functions fitted to the data. For roughness perception, the slope value for the fingers (experiment 1) was consistently greater than for the forearm (experiment 2), while such a clear difference in pattern at the two body loci was not obtained with perceived unpleasantness.

To further statistically compare the relative size of the effects of inter-element spacing on both percepts at the two body loci, we calculated a first-order approximation of the magnitude of the effect of inter-element spacing for each percept as follows. Initially, for each inter-element spacing, the magnitude estimates of the percept (unpleasantness;

roughness) were averaged across all speed levels for each participant.[4] Next, again for each participant, we determined the slopes of the linear functions that best fitted the $\log_{10}$ mean magnitude estimates (unpleasantness; roughness) as a function of inter-element spacing ($\log_{10}$ spacing). The linear functions fit the unpleasantness and roughness conditions reasonably well: mean R^2 values were 0.95 (± 0.01) for unpleasantness and 0.96 (± 0.01) for roughness in experiment 1, and 0.91 (± 0.03) for unpleasantness and 0.92 (± 0.01) for roughness in experiment 2. Finally, we averaged the slopes of the participants for each body locus in each percept. We interpret the mean slopes of the linear function as indicating, to a first approximation, the increment in the effect of inter-element spacing for forearm versus fingers.

In order to compare slope patterns between the two percepts on fingers versus forearm, we then conducted a two-factor between-subject ANOVA [(2 percepts) × (2 body loci)] on the mean inter-element spacing–slope values. However, this analysis revealed neither significant main effect nor interaction ($ps > 0.1$). As a supplemental analysis, we further compared the slope value of each percept between the two body loci. An independent t test on the slope value for perceived roughness showed that the finger slope tended to be significantly greater than that for the forearm ($t_{22} = 1.8$, $p = 0.09$). On the other hand, the same test on the unpleasantness slopes revealed no such trend ($p = 0.7$).

3.2.4 *Speed effects on perceived unpleasantness and perceived roughness at two body loci.* For both body loci, increasing the speed of relative motion tends to monotonically increase magnitude estimates of unpleasantness and roughness across all inter-element spacings. However, as can be seen in figure 2, the effect of speed on perceived unpleasantness is notably greater than on perceived roughness.

We statistically compared the relative size of the speed effects on perceived unpleasantness versus roughness by employing the same approach as section 3.2.3; we calculated a first-order approximation of the magnitude of the speed effect for each percept. First, for each speed level, the magnitude estimates of the percept (unpleasantness; roughness) were averaged across all inter-element spacing levels for each participant.[4] Subsequently, for each participant, we specified the slopes of the linear functions that best fitted the $\log_{10}$ mean magnitude estimates (unpleasantness; roughness) as a function of speed ($\log_{10}$ speed). Mean R^2 values were 0.87 (± 0.07) for unpleasantness and 0.78 (± 0.10) for roughness in experiment 1; 0.96 (± 0.02) for unpleasantness and 0.97 (± 0.01) for roughness in experiment 2. Finally, for each body locus, the means of the unpleasantness and roughness slopes were separately calculated across participants.

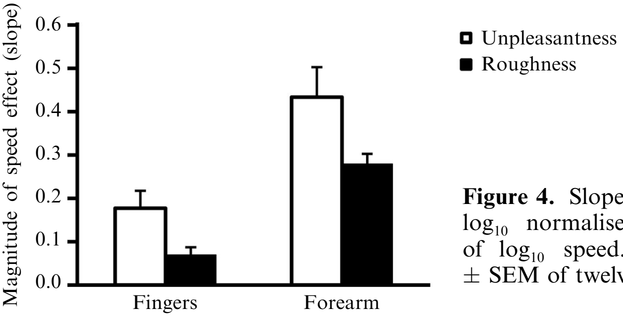

Figure 4. Slope value of linear function fitted to $\log_{10}$ normalised magnitude scores as a function of $\log_{10}$ speed. Each data point indicates mean ± SEM of twelve participants.

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[4] This procedure can be justified because the interaction between speed and inter-element spacing was not statistically significant for the fingers; although the speed × inter-element spacing interaction term was significant for the forearm, its effect size ($\eta_{\mathrm{p}}^2 = 0.28$) was notably smaller than those for either main effect (inter-element spacing: $\eta_{\mathrm{p}}^2 = 0.89$; speed: $\eta_{\mathrm{p}}^2 = 0.77$).

Figure 4 shows the mean slopes for unpleasantness versus roughness on the fingers and forearm. In order to compare slope patterns between the two percepts on the fingers versus the forearm, we conducted a two-factor between-subject ANOVA [(2 percepts) × (2 body loci)] on the mean speed – slope values. This analysis revealed a significant main effect of percept ($F_{1,44} = 9.4$, $p < 0.01$, $\eta_p^2 = 0.18$); speed effects were larger for unpleasantness than for roughness judgments. The main effect of body locus was also highly significant ($F_{1,44} = 29.9$, $p < 0.001$, $\eta_p^2 = 0.40$); speed effects were greater on the forearm than on the fingers. The two-way interaction, however, was non-significant ($p = 0.59$).(5)

4 General discussion

The current psychophysical study examined numerical estimates of unpleasantness produced when rigid 2-D raised-dot textured surfaces that varied in inter-element spacing were moved at three different speeds across two stationary body sites (fingers, forearm). Corresponding judgments of surface roughness were also obtained for purposes of psychophysical comparison.

4.1 *The psychophysics of perceived unpleasantness relative to perceived roughness*

4.1.1 *Inter-element spacing.* In the present study, the tactile psychophysical functions for nonpainful unpleasantness and roughness as a function of the inter-element spacing of 2-D raised-dot patterns were highly similar, and well described by power functions. These data confirm and extend the results of previous studies with abrasive surfaces (Ekman et al 1965; Verrillo et al 1999) by demonstrating that inter-element spacing on rigid, well-controlled textured surfaces is a critical determinant of the perception of nonpainful unpleasantness, and by statistically quantifying close relationships with corresponding roughness percepts on both the fingers (experiment 1) and the forearm (experiment 2).

The effect of inter-element spacing on perceived roughness of 1-D (linear gratings) and 2-D raised-dot surfaces has been well explained by spatial/intensive models based on skin mechanics by Taylor and Lederman and on neural coding by Johnson and his colleagues, respectively. More specifically, Taylor and Lederman (1975) proposed that the perceived roughness of coarse linear gratings is related to the total area of skin instantaneously indented from a baseline resting position during quasistatic contact with linear gratings that spatially vary in inter-element spacing. Johnson and his colleagues subsequently proposed that a spatial intensive code is used to neurally encode the roughness magnitude of 2-D raised-dot patterns; spatial variation of the surface pattern is computed by SA-I afferents and then coded as intensity in the brain (eg Connor et al 1990; Connor and Johnson 1992; Hsiao et al 1993; Blake et al 1997). As the inter-element spacing between surface texture elements increases, the skin becomes more indented from the baseline resting position by the sharp edges of the texture elements, thus potentially increasing the possibility of damage to the skin. Although further research is clearly necessary, we suggest that such spatial/intensive models may account for the magnitude of nonpainful unpleasantness, as well as roughness perceived via touch.

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(5) We also performed the same analysis on data that were averaged arithmetically (ie analysis without logarithmic transformation). This second analysis revealed the same statistical results as the original. More specifically, mean R^2 values were 0.91 (±0.07) for unpleasantness and 0.73 (±0.10) for roughness in experiment 1; 0.94 (±0.02) for unpleasantness and 0.89 (±0.03) for roughness in experiment 2. The two-factor ANOVA [(2 percepts) × (2 body loci)] on the mean slope values revealed significant main effects of percept ($F_{1,44} = 6.8$, $p < 0.05$, $\eta_p^2 = 0.13$) and body locus ($F_{1,44} = 35.0$, $p < 0.001$, $\eta_p^2 = 0.44$). The interaction term, however, was nonsignificant ($p = 0.17$).

4.1.2 *Speed of relative motion.* Although unpleasantness and roughness perception similarly increase monotonically as a function of increasing speed of relative motion between skin and surface, the magnitude of the effect is notably larger for unpleasantness than for roughness, regardless of body site. Conversely, the speed effects are larger on the forearm than on the fingers, regardless of percept.

Such speed effects suggest that temporal factors may further contribute to the perception of unpleasantness, as well as roughness (for the latter, see also Cascio and Sathian 2001). One possibility pertaining to skin mechanics derives from the fact that when a rigid surface moves laterally across the skin, the skin may sequentially catch on the leading edges of surface elements, especially if those edges are sharp (for further consideration of how this factor may influence perceived roughness of rigid 2-D raised-dot patterns when a rigid probe is used, see Klatzky et al 2003). Thus, the tangential force on the skin may oscillate, alternately increasing at places where the skin snags and decreasing as it subsequently rides over the edge and along the flat top of each element. Smith et al (2002) have previously demonstrated that the rate of change in the tangential force (quantified as root mean square) increases with greater inter-element spacing of 2-D dot patterns, and that it can account for over 70% of the perceived roughness magnitude on the middle fingertip. As the speed of lateral motion is increased, the elements on a surface will snag the skin more strongly, increasing the amplitude of oscillating changes in tangential force and, thus, in the rate of change. It is not unreasonable to speculate that such variation in tangential force may be perceived as unpleasant because it signals potential damage to the skin. Based on this temporal cue, the perceived magnitude of unpleasantness (as well as roughness) may grow with increasing speed of relative motion because of an increase in the rate of variation of tangential force.

In the current study, the effect of speed of relative motion on perceived unpleasantness, an affective tactile dimension, was considerably larger than that for perceived roughness, a discriminative tactile dimension. Unpleasantness and roughness may be viewed as lying at opposite ends of an internal-subjective/external-objective continuum of human contact experience, with unpleasantness close to the internal-subjective pole (Craig 2002) and roughness close to the external-objective pole.

Physical roughness is an enduring feature of external surfaces and objects. It is therefore important that corresponding roughness percepts remain relatively invariant, regardless of how the skin contacts the surface. This has been confirmed by Lederman (1983) and Meftah et al (2000) with respect to fluctuations in speed of relative motion between skin and surface. More generally speaking, objects and their enduring physical properties (eg roughness and size) must be accurately perceived, discriminated, and recognised. Perceptual constancies therefore serve critically important functions. For the perceiver, they help to produce relatively veridical perceptions. For the actor, perceptual constancies would help achieve relatively stable hand/object interactions within external space.

Extending this argument, we now propose that veridical perception should be less critical for assessing unpleasantness, compared to roughness. Unlike discriminative touch, which may benefit from the stabilising influence of perceptual constancies during the assessment and manipulation of external objects, affective touch is presumably subject to fewer such demands inasmuch as the emotional components relate to a person's subjective, internal percepts. Unpleasantness need only reflect the observer's highly changeable internal sensations, with relatively little consequence on the external world. According to this perspective, the effect of speed of motion should influence perceived unpleasantness more than perceived roughness, indicating relatively lower perceptual constancy for the former than the latter.

Epstein's percept – percept theory (1973, 1982) proposes that perceivers trade off their peripheral sensory representation of a target property (eg retinal size) against some other intermediate percept (eg perceived distance) to achieve a final relatively veridical percept (eg perceived size). This cognitive approach may be applied in the current experiment with respect to tactile roughness constancy. Since humans can estimate the magnitude of the scanning speed of 2-D raised-dot patterns reasonably accurately (Dépeault et al 2008), perceivers may use perceived speed as an intermediate percept to produce relatively stable roughness perception. Such speculation is also consistent with a neural perspective on roughness perception. Meftah et al (2000) have made the following suggestion: "Based on the results of neurophysiological recordings in SI cortex, ... an invariant central representation of surface roughness could be extracted from the ambiguous peripheral signals that covary with roughness and the stimulating conditions (eg speed) by means of a simple subtraction process" (page 351).

4.1.3 *Body locus: fingers versus forearm.* The current psychophysical data for roughness judgments confirm Stevens's (1990) earlier finding that the slopes of the linear psychophysical functions for perceived roughness as a function of inter-element spacing are shallower for the forearm than for the fingers (table 1). Unlike Stevens (1990), we conducted additional analyses to statistically evaluate the effect of body locus. However, these statistical tests, which involved using the slopes of the linear function fitted to the data from each participant, yielded only a trend in the direction of Stevens's finding. Thus, further research is necessary in the future to statistically confirm the effect of body locus on perceived roughness.

The present study reveals that perceived unpleasantness via the forearm is more dependent on speed than corresponding perceptions via the finger (section 3.2.4, figure 2). This empirical finding suggests in turn that participants maintain greater unpleasantness constancy via the fingers than the forearm despite fluctuations in speed of relative motion. Our study expands on Löken et al's (2009) earlier results concerning the effects of speed on the perceived pleasantness of compliant surfaces (eg textiles, brush) on hairy (cf glabrous) body sites by confirming that speed also affects the perceived unpleasantness of rigid surfaces more on the forearm than on the fingers.

There are several possible explanations that alone or in some combination may account for why the speed effect was stronger on the forearm than the fingers. The first involves a difference in perceptual learning. Because individuals functionally use their hands considerably more often than other skin areas during everyday life, they may have learned to attend in a more discriminating manner to stimulation on the hand (relative to the forearm) as a result of greater practice (eg Harris et al 2001). The second and third reasons focus upon known differences between hairy and glabrous skin in terms of mechanoreceptor populations and skin structure/mechanics, respectively. With respect to receptor populations, only hairy skin (eg forearm) contains unmyelinated mechanoreceptors that vigorously respond to the slow, light stroke of a brush (CT afferents—Vallbo et al 1999; Löken et al 2009). It is possible, therefore, that C-tactile afferents, which respond most vigorously at the slow speed, augment the effect of speed on the forearm relative to the fingertips. Finally, with regard to skin structure and mechanics, we note that the rigid textured surfaces used in the current experiment consisted of truncated cones raised above a smooth base. The sharp edges of those texture elements will catch, deform, and drag the skin more than soft, compliant textiles and brushes, and such mechanical effects may vary with body site. The outermost layer of the epidermis is the stratum corneum, which consists of hard keratin that maintains homeostasis within the skin. The stratum corneum is substantially thicker on the hand than on the forearm, presumably serving to prevent the hand from being injured during frequent object contact during tactual perception and manipulation (Ya-Xian et al 1999; Fruhstorfer et al 2000; Egawa et al 2007). Because the skin on the forearm is more compliant than on the fingers, it may snag more on the leading edges of the raised elements than on the fingers. In accord with our argument in section 4.1.2, the rate of change in the tangential force on the forearm may fluctuate more with changes in speed than on the fingers. In keeping with perceived unpleasantness, it is also possible that such neural and anatomical differences between hand and forearm skin (eg presence/absence of CT afferents; thickness of stratum corneum) may additionally account for why speed influenced roughness perception via the fingers less than via the forearm.

4.2 *Implications for future application*

People frequently contact, explore, grasp, transport, and manipulate objects with their hands. It would seem self-evident that designing surfaces that reduce the experience of unpleasantness during contact would render users more comfortable when it is necessary to functionally interact with such objects. Moreover, surfaces that feel unpleasant to the touch can be designed to warn of impending danger. For instance, infants could be discouraged from playing with hazardous objects (eg a bottle of pills) by rendering initial contact with them unpleasant. Door surfaces coated with a material that is unpleasant to the touch can rapidly indicate to blind individuals that they are about to enter a hazardous location.

More generally speaking, the development of a comprehensive psychophysical model of the tactile perception of nonpainful unpleasantness may prove valuable to the field of tactile-product design and marketing. The current results make it possible to judiciously select an appropriate range of inter-element spacings that would effectively reduce the level of unpleasantness experienced when contacting rigid textured surfaces. Designers must also consider how observers typically contact rigid surfaces (eg applied force, speed, and mode of touch, ie active versus passive) during the assessment of surface unpleasantness; for example, the speed of relative motion between skin and surface has been shown to alter considerably the magnitude of unpleasantness experienced. Results from the present study constitute initial steps toward the construction of a psychophysical model of the perception of nonpainful unpleasantness via contact with rigid textured surfaces.

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