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Haptic roughness perception of linear gratings via bare finger or rigid probe

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Abstract. The magnitude of perceived roughness was haptically estimated as subjects freely explored linear gratings with either the bare finger or a rigid stylus-shaped probe. A considerably expanded range of ridge and groove width was investigated, relative to the extant literature. The four experiments collectively indicate that, for both finger and probe-end effectors, the variance in the estimates of perceived roughness was predominantly predicted by a single parameter: groove width. The functions relating perceived roughness to groove width increased over a narrow band relative to the full range of values, then flattened. These data have archival values for models of roughness perception involving both direct and indirect touch.

1 Introduction

Touch has been described as the "reality sense" (Lederman et al 1986). However, for much of the last century, touch remained an elusive subject of psychological study, because of the difficulty of producing well-controlled stimuli (ie objects and surfaces that vary systematically in shape, size, weight, temperature, texture, and compliance), and of controlling the manner in which subjects interact with the stimuli (ie exploration force, speed, and mode of exploration—active or passive; Lederman and Verry 1998). With recent technological innovations in stimulus production and presentation techniques, the sense of touch has begun to receive considerably more attention by researchers. Indeed, while touch research has traditionally been the domain of psychophysicists, the field has now experienced an influx of researchers from various other disciplines, ranging from cognitive neuroscience to computer science and engineering.

One line of research that particularly embodies this progression focuses on the haptic perception of surface roughness. The sensation of roughness is induced when the skin or a hand-held tool passes over a surface that is not uniformly smooth. Because stimulus parameters can be precisely controlled, it is amenable to study from various perspectives, including computational, neurological, and process modeling. Here, we provide a comprehensive data base pertaining to roughness perception of linear gratings by direct touch via the bare finger and by indirect touch via a hand-held rigid probe. Our data set is derived from the presentation of textured surfaces consisting of linear gratings, the geometric parameters of which are manipulated over a considerably expanded range relative to what is found in the existing literature, which we now review.

1.1 *Roughness perception*

Until very recently (Klatzky and Lederman 1999), almost all research on roughness perception used tactual exploration which involved the bare finger (ie direct touch). Early studies (Stevens and Harris 1962; Lederman 1978) employed sandpapers of varying grit

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value as stimuli. Lederman and Taylor (1972) assessed roughness perception using more precisely controlled stimuli: rectangular gratings varying along a single dimension made from engraved aluminum (eg figure 1). By varying the surface characteristics of these gratings (eg groove and ridge widths) Lederman and Taylor investigated the geometric determinants of the perceived roughness of 'macro-textures' (textures with spatial periods [1 interelement width + 1 element width] greater than ~200 μm) (Bensmaïa and Hollins 2003). They found that both groove width and ridge width affected perceived roughness, the former having considerably greater effect than the latter (Lederman and Taylor 1972; Taylor and Lederman 1975). Across the range of stimulus values examined, increasing groove width led to higher estimates of roughness, while increasing ridge width led to slightly lower estimates of roughness. Additional follow-up experiments established that neither vibration (Lederman et al 1982) nor spatial period (Lederman 1983) significantly influenced the perceived roughness of these stimuli. Thus, it appeared that for macro-textures the vibrations produced during skin–surface interactions did not play a prominent role in roughness perception.

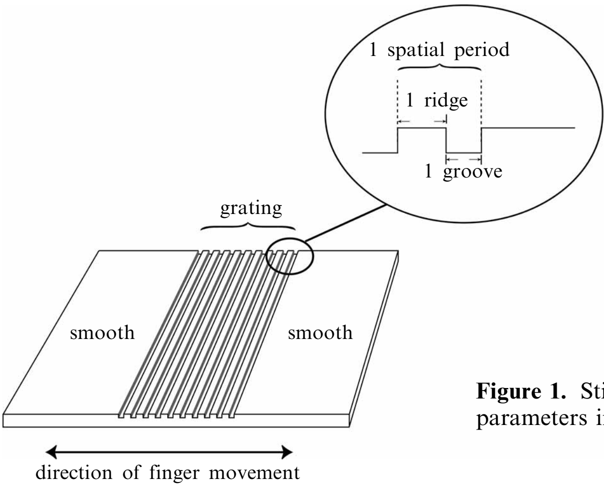

Figure 1. Stimulus grating with relevant physical parameters indicated.

In contrast, recent work by Bensmaïa, Hollins, and colleagues suggests that vibration does play a role in the perceived roughness of surface 'micro-textures' (textures with spatial periods < ~200 μm) (Hollins et al 1998; Bensmaïa and Hollins 2003, 2005; Bensmaïa et al 2005). The work has focused in particular on the role of the Pacinian corpuscles. Bensmaïa and Hollins (2005) found that texture discrimination performance was well accounted for by a vibratory model based on the responses of the Pacinian system, as were the percepts of surface roughness and stickiness.

In more recent years, technical and economic considerations have led roughness researchers to expand the stimulus domain to include raised-dot patterns, consisting of truncated cones or cylinders with various interelement spacings. These stimuli, typically created through photoengraving techniques (see eg Lederman et al 1986; Connor et al 1990; Meftah et al 2000), have furthered our understanding of the psychophysical and neural substrates involved in the perception of roughness via touch.

Work by Johnson and his associates with raised-dot stimuli (for a review, see Johnson and Hsiao 1994) has led to a model of roughness perception that Klatzky and Lederman (1999) have described as *spatial-intensive*. According to this model, a spatial map of the local skin-deformation pattern is passed up to area SI in the somatosensory cortex; this spatial representation is then passed to cortical area SII where it is integrated into a single intensity value. The neural model relates well to the psychophysical model developed by Taylor and Lederman (1975), which proposed that roughness is a power function of the total area of the skin that is instantaneously deformed through contact with the surface texture.

Another view has been proposed by Smith et al (2002), who observed that roughness estimates are strongly predicted by the rate of change in force in the scanning direction during a scan of a surface. These findings followed observations by Meftah et al (2000) that roughness estimates increased nearly linearly up to spatial periods of 8.5 mm—albeit with some flattening at the higher spatial periods (personal communication with Elaine Chapman 2005). These data conflict with those obtained by Connor et al (1990) and by Klatzky and Lederman (1999); both papers documented psychophysical functions with a clear downturn, peaking between 3 and 4 mm. Differences among these studies may be attributable to the raised 2-D dot-pattern stimuli. Those used by Meftah et al were non-rigid, and had deep grooves that prevented the finger from 'bottoming out', which likely changed the mechanics of the interaction between finger and surface relative to the rigid stimuli used by others.

1.2 *Remote texture perception*

A recent development in the field of haptic texture research has been the advent of teleoperation and virtual-environment applications. Early work in these domains focused on simulating visual and auditory environments; however, it has become increasingly salient that without touch information these environments are limited in their information content and perceived realism (Lederman and Pawluk 1992). Accordingly there has been growing interest in how to simulate tactile and haptic experiences. One model for the remote presentation of texture information (Lederman et al 2002) is the rigid probe (figure 2a). Exploration with a rigid probe renders spatial skin-deformation cues to the surface microstructure inaccessible, yet potentially useful vibratory cues remain available. By investigating the relationship between these vibratory cues and the perception of roughness, it may be possible to develop very simple vibration-based systems for virtual texture presentation (Klatzky and Lederman 2006; Lederman et al 2006).

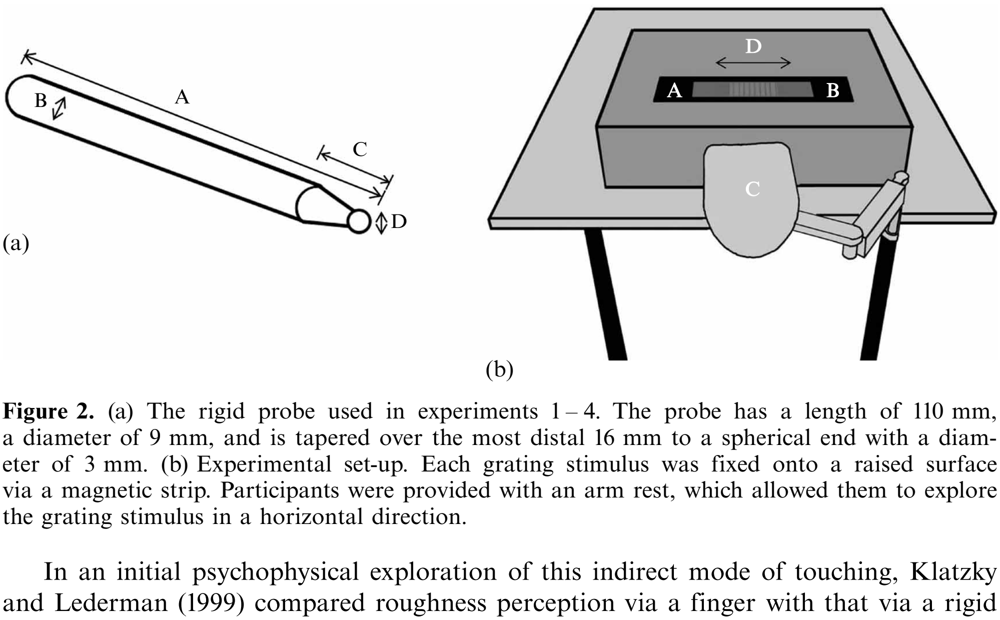

Figure 2. (a) The rigid probe used in experiments 1 – 4. The probe has a length of 110 mm, a diameter of 9 mm, and is tapered over the most distal 16 mm to a spherical end with a diameter of 3 mm. (b) Experimental set-up. Each grating stimulus was fixed onto a raised surface via a magnetic strip. Participants were provided with an arm rest, which allowed them to explore the grating stimulus in a horizontal direction.

In an initial psychophysical exploration of this indirect mode of touching, Klatzky and Lederman (1999) compared roughness perception via a finger with that via a rigid probe and found several important results. As with the finger, perceived roughness via a probe varied strongly with changes in interelement spacing. Furthermore, both modes of exploration produced psychophysical roughness data that were best fit by quadratic functions. However, the interelement spacing value at which these quadratic functions reached their peak was systematically different. It appeared that the size of the contact surface (whether finger or probe tip) strongly influenced the location of this peak (Klatzky et al 2003).

On the basis of these findings, Klatzky et al (2003) developed a model of roughness perception via a probe that considers the effects of probe size, surface geometry, and manual exploration factors (eg speed, force). Their model predicts that roughness perception via a probe will increase across larger interelement spacings until the point is reached where the probe tip can make contact with the uniform base between the surface elements. Beyond this 'drop point', the nature of the contact mechanics changes such that further increases in interelement spacing lead to the perception of decreasing roughness. Klatzky et al emphasized that, when exploring such surfaces with a rigid probe, the downturn in the perceived roughness function does not reflect a continuous psychophysical process, but instead a qualitative change in processing at the interelement spacing value that corresponds to the drop point.

In the present study we used newly produced linear grating surfaces to investigate roughness perception as a function of ridge width and groove width, with each manipulated over a considerably wider range than typically examined in the past (0.125 mm – 8.5 mm, as opposed to 0.125 mm – 1.00 mm). We chose grating stimuli because this allows us to extend early work of Lederman and Taylor (1972), who documented significant effects of groove and ridge width on roughness perception. It also allows us to compare roughness perception with the bare finger versus a rigid probe with a different type of stimulus than the raised-dot surfaces used in the previous work of Klatzky and Lederman (1999) and Klatzky et al (2003). The interactions between a rigid probe and a grating are likely to be quite different mechanically from those of the probe with raised-dot elements, especially as the groove widths become large. When a surface of raised dots is explored with a probe, as the spacing between elements becomes larger than the probe tip, there will be a drop point, where the probe tends to rise around the elements along the lower substrate and when it does strike one, to detour around the element, as opposed to up and over it. In contrast, a grating had ridges that span the direction orthogonal to probe movement, thereby creating a series of inevitable obstacles that will eventually be struck, regardless of groove width. As groove width increases, then, there is no discontinuity between riding above the raised elements and riding below them; there are only increasingly longer periods without a mechanical perturbation. A question of particular interest, then, is whether the function relating perceived roughness to interelement spacing (here, groove width) of gratings will show a downturn, as is characteristic of raised-dot surfaces when the probe is near the drop point.

2 Experiment 1: Groove widths of 0.125 mm – 1.00 mm

This experiment replicated the range of stimulus parameter values used in the early work with gratings (Lederman and Taylor 1972; Lederman 1974; Taylor and Lederman 1975). It also extended this work by including a comparison of roughness perception with the bare finger with that obtained now when using a rigid probe. With the latter's single point of contact, it serves as a simple model for haptic interfaces that likewise deliver only point contact.

2.1 *Method*

2.1.1 *Participants.* A total of twenty-four experimentally naive participants (thirteen females, five males; mean age = 19.1 years, SD = 3.5 years) from a first-year introductory psychology class participated for course credit. They were restricted to those who were right-handed (self-defined) and who had no known sensory or motor impairments in their hands.

2.1.2 *Materials.* A set of 24 photoengraved linear, rectangular polymer gratings with metal bases (manufactured by North American Graphics Co.) was used (figure 1). The dimensions of the gratings varied in terms of groove width (0.125 mm to 1.00 mm, in increments of 0.125 mm) and ridge width (0.25 mm, 0.5 mm, and 1.5 mm), with the two factors completely crossed. Since ridge-width effects have been previously shown to be quite small, relative to groove-width effects, in order to keep the number of stimuli presented to a manageable number, we tested fewer ridge-width than groove-width values in all four experiments. The surfaces were 177 mm long and 44 mm wide. The grating spanned the middle 75 mm of the surface, with 51 mm of smooth surface at either end. The height of the ridges and smooth ends was 0.46 mm.

A rigid, pencil-like Delrin probe was used by half of the subjects (figure 2a). This probe was 110 mm in length and 9 mm in diameter and tapered over the most distal 15 mm to a spherical end with a diameter of 3 mm. All participants wore a blindfold and active noise cancellation headphones (Sennheiser NoiseGard HMEC 300) through which pink noise was played to mask any ambient or exploration-related sounds. Each surface was presented to the participant on a magnetic strip that fixed the surface in place during exploration. An armrest was provided for the participant's comfort which allowed free movement in the horizontal plane, but was fixed in the vertical plane. The experimental setup is depicted in figure 2b.

2.2 *Procedure and experimental design*

Participants were randomly assigned to the finger or probe condition. Both groups used the same general procedure except that the finger group used the right middle finger to explore the surfaces, while the probe group used a probe held in their right hand. The experiment consisted of 96 trials, broken into 4 blocks of 24 trials (1 trial per grating). The first block served as a practice block, and was followed by 3 experimental blocks or repetitions per grating. The entire set of gratings was presented randomly within each block.

The participant's task on each trial was to explore the stimulus surface in a lateral back-and-forth manner along a frontoparallel axis, making sure to touch the smooth ends on each pass, and to judge how rough it felt. To make this judgment, subjects were taught to use the absolute magnitude estimation procedure (Zwislocki and Goodman 1980). They were instructed to provide a positive number (decimal fraction, or whole number, excluding zero) that best represented how rough the surface felt. Neither speed nor force was controlled in these experiments; if asked how to explore, the experimenter instructed the participant to use a comfortable speed and force. Although not recorded, participants typically took 2 – 3 s.

2.3 *Results and discussion*

In order to achieve a stable roughness estimate for each grating, the data for all experiments presented here were treated as follows. First, an average estimate was determined across the repetitions. Each participant's data were then normalized in order to control for differences in numerical scale used by different participants. This normalization procedure was performed by dividing each data point by the participant's mean and then multiplying by the grand mean for the group (finger or probe). Finally, a logarithmic transformation was performed on the normalized data in order to map onto traditional $\log_{10} - \log_{10}$ scales.

Initial data analysis revealed consistently abnormal roughness estimated for the 0.375 mm and 0.825 mm groove-width stimuli in the 1.5 mm ridge-width set. Visual inspection of these stimuli confirmed that they appeared to have significant manufacturing defects.

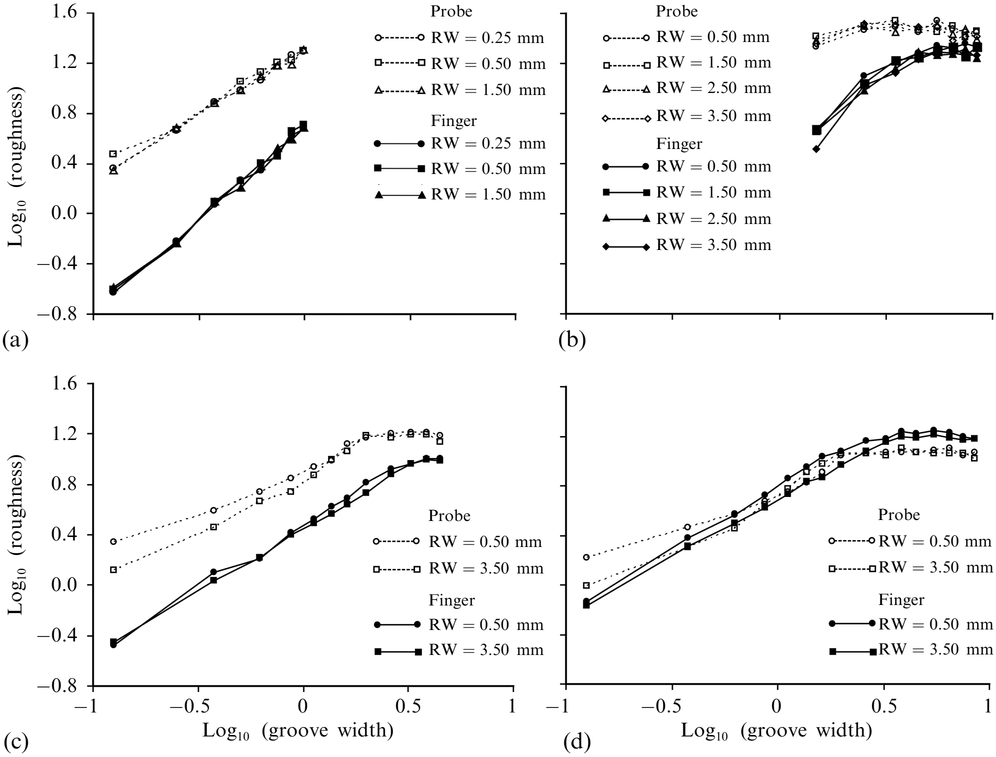

Figure 3. Perceived roughness magnitude as a function of groove and ridge width (RW) for experiment 1 (a), experiment 2 (b), experiment 3 (c), and experiment 4 (d). The scales used for the x and y axes are the same across experiments to permit direct comparison. Probe conditions: open point symbols; dashed line symbols. Finger conditions: filled point symbols; solid line symbols.

Therefore, the roughness values for these surfaces were replaced by the average of their groove-width counterparts in the 0.25 mm and 0.5 mm ridge-width sets. Figure 3 shows the data for all four experiments reported here, in the form of functions relating $\log_{10}$ normalized roughness magnitude to $\log_{10}$ groove-width in the stimuli.

As the normalization process maps all subjects within a group to a common mean, it does not afford direct comparisons between bare-finger and probe groups. Hence, in this and subsequent studies, each end-effector condition was analyzed separately with a 2-factor repeated-measures ANOVA on factors groove width (8 levels) and ridge width (3 levels). The Greenhouse – Geisser correction was applied for degrees of freedom in this and all experiments. For the finger, this analysis revealed only a main effect of groove width ($F_{1.65,\,18.12} = 80.72$, $p < 0.001$, $\eta^2 = 0.89$). The ANOVA for the probe group likewise found only a main effect of groove width ($F_{1.75,\,19.19} = 67.08$, $p < 0.001$, $\eta^2 = 0.81$).

Inspection of the functions relating the logarithm of roughness magnitude to the logarithm of groove width (figure 3a) shows a strong linear trend and provides no evidence of a downturn. Table 1 shows the results of least-squares linear and quadratic functions for the data obtained in each experiment, pooled across ridge widths. The linear functions produced R^2 values greater than 0.99 for both finger and probe conditions. The data can therefore be summarized by saying that for both exploratory conditions, perceived roughness essentially increased linearly with groove width and was unaffected by ridge width.

Table 1. Parameters and goodness of fit of linear and quadratic functions fit to the data of each experiment for each end-effector, pooled over ridge width.

Experiment	End-effector	Linear functions fit			Quadratic functions fit			
		slope	intercept	R^2	quadratic	linear	intercept	R^2
1	probe	1.01	1.30	0.999	−0.02	0.99	1.30	0.999
	finger	1.45	0.69	0.997	0.12	1.56	0.70	0.998
2	probe	0.03	1.44	0.030	−0.69	0.81	1.26	0.866
	finger	0.84	0.62	0.835	−1.67	2.72	0.20	0.999
3	probe	0.68	0.86	0.953	−0.14	0.65	0.89	0.963
	finger	0.97	0.45	0.993	−0.09	0.96	0.47	0.995
4	probe	0.55	0.70	0.882	−0.25	0.60	0.77	0.944
	finger	0.74	0.70	0.925	−0.32	0.80	0.78	0.983

3 Experiment 2: Groove widths of 1.5 mm – 8.5 mm

In experiment 2 we extended our investigation by employing a set of gratings well beyond the 0.125 mm – 1.00 mm range for groove and ridge widths used originally by Lederman and Taylor (1972) and Lederman (1974), and more similar to recent research with 2-D raised-dot surfaces (eg Connor et al 1990; Connor and Johnson 1992; Klatzky and Lederman 1999; Meftah et al 2000; Klatzky et al 2003). Given the differences between gratings and raised-dot elements that were described previously, we did not predict a quadratic trend indicative of a physical drop point in the stimuli. However, it is possible that, subjectively, groove widths beyond a particular value may not be discriminated or that the percept may change to one of smoothness, in which case the function relating roughness to groove width could flatten or even turn down at these higher spacing values.

3.1 *Method*

3.1.1 *Participants.* A total of twenty-four experimentally naive participants (nineteen females, five males; mean age = 20.0 years, SD = 6.4 years) were recruited from the same undergraduate population and with the use of the same criteria as in experiment 1.

3.1.2 *Materials and procedure.* The stimuli were 32 gratings that varied in groove width (1.5 mm to 8.5 mm, in increments of 1.0 mm) and ridge width (0.5 mm to 3.5 mm in increments of 1.0 mm), with the two factors completely crossed. The procedure was the same as in experiment 1, except that owing to the additional time required to test 32 gratings, the 96 trials were broken into 1 practice block and only 2 (3 in experiment 1) experimental blocks.

3.2 *Results and discussion*

The magnitude-estimation functions are shown in figure 3b. The ANOVA on ridge width and groove width for the probe group revealed no significant main effects or interactions. The same analysis for the bare-finger group revealed significant main effects of groove width ($F_{1.56,\,17.11} = 35.84$, $p < 0.001$, $\eta^2 = 0.70$), ridge width ($F_{2.38,\,26.18} = 8.65$, $p = 0.001$, $\eta^2 = 0.01$), and of the interaction ($F_{6.35,\,69.88} = 2.26$, $p = 0.044$, $\eta^2 = 0.01$). As evidenced by the effect of sizes as measured by η^2, groove width accounted for much more of the variance in roughness estimates (70%) than the main effect of ridge width (1%) or the ridge width × groove width interaction (1%). Therefore, further analyses focus solely on the effect of groove width.

As supported by the ANOVA analysis, figure 3b clearly indicates that the magnitude-estimation functions for the probe group were essentially invariant across groove width.

This suggests that roughness at these large groove widths was unaffected by the differences in distance and time between perturbations of the probe tip. The function for the finger group, however, increased and then tended to flatten, producing a quadratic trend.

Since the probe group failed to show a significant effect of either stimulus factor and ridge width had little effect in this or the previous study, experiments 3 and 4 used a broad range of groove widths across which roughness judgments could be evaluated within a single set of observations.

4 Experiment 3: Groove width 0.125 mm – 4.5 mm

In experiment 3, we used grating stimuli with groove widths that varied between 0.125 mm and 4.5 mm. Thus the lowest value was equal to the minimum value in experiment 1, and the highest exceeded the probe diameter but did not reach the maximum groove width in experiment 2 (8.5 mm). As ridge width previously had little effect, only two values were compared.

4.1 *Method*

4.1.1 *Participants.* A total of twenty-four experimentally naive participants (seventeen females, seven males, mean age = 21.2 years, SD = 2.5 years) were recruited from the same undergraduate population with the same criteria as in experiment 1.

4.1.2 *Materials and procedure.* A set of 24 gratings was used. There were 12 values of groove width (0.125, 0.375, 0.625, 0.875, 1.125, 1.375, 1.625, 2, 2.625, 3.25, 3.875, 4.5 mm) and two of ridge width (0.5 mm, 3.5 mm), with the two factors completely crossed. The procedure was the same as in experiment 1.

4.2 *Results and discussion*

The magnitude-estimation functions appear in figure 3c. The ANOVA for the probe group revealed significant main effects of groove width ($F_{1.47,\,16.18} = 71.38$, $p < 0.001$, $\eta^2 = 0.82$), and ridge width ($F_{1,\,11} = 12.75$, $p = 0.004$, $\eta^2 = 0.01$), and a significant interaction between the two factors ($F_{3.60,\,39.65} = 4.28$, $p = 0.007$, $\eta^2 = 0.01$). The ANOVA on the bare-finger data revealed significant main effects of groove width ($F_{1.52,\,16.67} = 72.13$, $p < 0.001$, $\eta^2 = 0.85$), and ridge width ($F_{1,\,11} = 7.79$, $p = 0.018$, $\eta^2 < 0.01$), but the interaction term was non-significant. As before, inspection of effect sizes reveals that for both groups, groove width accounts for the vast majority of variance in roughness estimates. Therefore, we again focus on the effects of groove width. Figure 3c shows increasing functions across this broader stimulus range, in both cases appearing to flatten at the higher values of groove width. As the flattening appears just at the end of the stimulus range, linear trends account for most of the variance for both probe and finger (see table 1).

5 Experiment 4: Groove width 0.125 mm – 8.5 mm

To broaden the range still further at the high groove-width end, in experiment 4 we used values of groove width from 0.125 mm to 8.50 mm, along with two levels of ridge width.

5.1 *Method*

5.1.1 *Participants.* A total of twenty-four experimentally naive participants (sixteen females, eight males, mean age = 23.1 years, SD = 4.4 years) were recruited from the same undergraduate population and with the same criteria as in experiment 1.

5.1.2 *Materials and procedure.* A set of 32 gratings was used with 16 values of groove width (0.125, 0.375, 0.625, 0.875, 1.125, 1.375, 1.625, 2, 2.625, 3.25, 3.875, 4.5, 5.5, 6.5, 7.5, 8.5 mm) and two of ridge width (0.5 mm, 3.5 mm), with the two factors completely crossed. The procedure was the same as in experiment 1.

5.2 *Results and discussion*

The magnitude-estimation functions appear in figure 3d. The ANOVA for the probe condition revealed a main effect of groove width ($F_{1.61, 17.74} = 101.40$, $p < 0.001$, $\eta^2 = 0.86$), no main effect of ridge width, and a significant interaction between groove width and ridge width ($F_{4.91, 54.01} = 8.08$, $p < 0.001$, $\eta^2 = 0.02$). The ANOVA for the finger condition revealed main effects of groove width ($F_{2.10, 23.15} = 91.15$, $p < 0.001$, $\eta^2 = 0.86$) and ridge width ($F_{1, 11} = 18.26$, $p = 0.001$, $\eta^2 = 0.01$), and no interaction. Again, the effects of ridge width were small. The functions relating perceived roughness magnitude to groove width in experiment 4 were quite similar in form to those in experiment 3, but with the inclusion of larger values of groove width, the flattened portion was extended over more stimulus values. Although there is a hint of a downturn in the functions in the figure, the quadratic trend was not strong.

6 General discussion

The present study extends earlier psychophysical data regarding the haptic roughness perception of macro-textures—specifically, rigid linear rectangular gratings—to include a considerably wider range of groove-width and ridge-width values. In addition to exploration with the bare finger, the data base includes comparable data obtained with a rigid probe. As in earlier studies, variations in groove width far outweigh variations in ridge width for both end-effector conditions. As it was not obvious, and even unlikely, that regular, linear rectangular gratings would replicate the same psychophysical functions with bare finger and probe as the 2-D raised-dot surfaces, we did not predict a downturn in these experiments with increasing groove width. Notably in these data, the functions relating the logarithm of roughness magnitude to the logarithm of groove width for both finger and probe flattened at higher values of groove width. In so doing, they deviate from functions with a clear downturn observed when the bare finger (Connor et al 1990) and the probe (Klatzky and Lederman 1999; Klatzky et al 2003) were used to explore displays of raised elements. They also diverge from the more strongly linear functions obtained by Meftah et al (2000) when the bare finger was used to explore regular matrices of compliant, raised 2-D dot patterns. However, as we noted earlier, the Meftah et al data do show some flattening at high values of groove width.

In section 1, we pointed out that exploring regularly spaced (ie unjittered) linear gratings forces the end effector (finger or probe) to contact all or most elements as the user moves it across the smooth substrate. As groove width increases, there will tend to be a point where the effector bottoms out before encountering the leading edge of the next rigid element. At this point, the regularity of the impact forces may become more salient than the interval between impacts, which depends on groove width. The resulting impression of a series of regular impacts may contribute to the relative flattening of the roughness function over the wider groove widths observed in this study.

To explore this speculation a little further, we haptically examined a previously untested set of rigid *unjittered* 2-D raised-dot surfaces that progressively increased in interelement spacing across separate plates. Informally, we noted that when the relatively wide, compliant bare finger was used, perceived roughness initially increased with interelement spacing and then levelled off, as with the present results. Surfaces appeared to remain about equally rough despite variations in spacing, seemingly as a result of the particular salience of the skin regularly catching on the leading edges of the raised elements. With the narrower and more rigid probe, encounters with the raised elements became variable as spacing increased, despite the geometric regularity. Correspondingly, we noted an actual downturn in perceived roughness with increased spacing, followed by a flattening.

The roughness values chosen by participants in the probe group were smaller in range, and with the exception of experiment 4, generally larger in magnitude than those used by the bare-finger group. We interpret such results as reflecting diminished sensitivity to changes in stimulus surface, a finding consistent with the data from both Klatzky and Lederman (1999) and Klatzky et al (2003) comparing probe and finger results.

Finally, the results of this study highlight the fact that the physical range of groove widths over which people can monotonically and unambiguously discriminate the gratings in terms of perceived roughness with either the bare finger or a rigid probe is substantially narrower than one might have anticipated. Extending the range of groove widths at the higher end failed to widen the range over which perceived roughness increased. The empirical peak values for experiments 2, 3, and 4, as indicated by the point of maximum perceived roughness in figure 3, were respectively 3.500, 3.875, and 3.875 mm for the probe (mean = 3.34 mm, as compared to 3 mm for the probe diameter), and 6.500, 3.875, and 5.500 mm for the bare finger (mean = 5.29 mm, compared to 9 mm for the contact width of the finger as estimated by Klatzky and Lederman 1999).

In conclusion, the current set of comprehensive results offers a valuable data set to those interested in modeling texture perception with a probe and/or in rendering synthetic textures for virtual environments. Our previous work on roughness perception with rigid probes has been simulated, for example, by Otaduy and Lin (2004), Meyer-Spradow (2005), and Unger (in preparation).

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