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Roughness perception in haptic virtual reality for sighted and blind people

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Abstract

Psychophysical functions for perceived roughness, relating ln (magnitude estimate of roughness) to ln (groove width), were obtained for blind and sighted participants in virtual reality using the PHANToM® force feedback device. The stimuli were sinusoidal surfaces with groove widths between .675mm and 2.700mm. Group functions showed a similar non-linearity to those obtained in physical reality using rigid probes (Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003; Lederman, Klatzky, Hamilton, & Ramsay, 1999). Individual functions gave a different picture. There were 13 out of 23 participants with wholly descending linear psychometric functions; 7 participants with quadratic functions similar to the group function; and 3 anomalous functions. Individual power law exponents showed no significant effects of visual status. All analyses gave a power law exponent close to -0.80. The implications for theories of roughness, methodologies of data analysis, and the design of haptic virtual reality interfaces are considered.

Roughness perception in haptic virtual reality for sighted and blind people

Roughness is one of the primary perceptual properties of objects. For example, Linus’ attachment to his soft security blanket may evoke empathy even in the most scientific of psychophysicists. Indeed, the physical properties that determine roughness have long been of psychophysical interest. Advances in technology have added to our knowledge in several ways. There is now a wider range of well-specified physical stimuli. Research is no longer limited to running fingers over sandpaper of different grain sizes. Nevertheless, the spacing and size of the texture elements on a surface remains the primary, if not the only, physical variables of interest. Consequently, determining the psychophysical function relating perceived roughness to inter-element spacing remains a major focus of research. Furthermore, it is now possible to produce virtual stimuli with properties that parallel those of the physical world. These developments provide the potential for tactile interfaces for everyone and particularly exciting opportunities to improve interfaces for blind and partially sighted people. The latter is a particularly important issue, as interfaces that replace visual information with auditory and haptic information are greatly needed by blind and partially sighted people (Petrie, O'Neill, & Colwell, 2002). Although the virtual reality devices have been developed primarily for such practical applications, they also provide potential for theoretical psychophysical investigations.

The main aim of this study is to take advantage of these advances to obtain psychophysical roughness functions in virtual reality using a force feedback device. These psychophysical functions have implications for whether a single or dual process underlies roughness perception. They also enable investigation of differences in virtual roughness perception between blind and sighted people, with implications for the extent to which visual experience influences touch perception. Psychophysical functions can also be used to address a range of applied issues. Differences according to visual status or type of probe have implications for the design of tactile interfaces to many applications. A further aim of this study is to address the methodological problems that arise from differing traditions for studying roughness perception. We believe this study is unique in providing both individual analyses, in the tradition of classical psychophysics (Stevens & Galanter, 1957), and group analyses using ANOVA techniques (Lederman & Taylor, 1972). Since the psychophysical functions may be non-linear the two methods can (and do) lead to different conclusions.

Pioneering work in the psychophysical tradition used magnitude estimation to obtain the Stevens power law exponent for roughness for individual participants. The first studies used sandpaper stimuli (Brown, 1960; Ekman, Hosman, & Lindstrom, 1965; Marks & Cain, 1972; Stevens & Galanter, 1957; Stevens & Harris, 1962; Stone, 1967), and found roughness increased with increasing granule size, i.e. with *inter-element spacing*, where each granule is an element. It should be noted that care is needed in interpreting the term '*inter-element spacing'*. For sandpaper, larger granule size always corresponds to greater separation between granules, meaning greater inter-element spacing. Similarly, for sinusoidal stimuli, such as those used here, a longer frequency corresponds to greater inter-element spacing. Other work has manipulated various combinations of groove width, ridge (also known as land) width, and pattern repetition width (equal to groove width plus ridge width), as is discussed below. For our sinusoidal stimuli, where there is obviously no sharp transition from ridge to groove, so the terms 'groove width' and 'inter-element spacing' are used interchangeably for the peak to peak separation that corresponds to the pattern repetition width (See Figure 2).

Other early work focused on the processes that underpin roughness discrimination rather than magnitude of perceived roughness. In1924 Katz suggested a two process model. The first process operates for fine-grained (small inter-element spacing) stimuli, and depends on the vibrations excited as a finger or probe is *moved* across a stimulus. A second process operates for coarse grained stimuli, depends only on the spatial geometry of the stimulus (Katz, 1924/1989). Direct evidence for a two process model comes from the work of Hollins and his colleagues, who found that movement, and hence vibration, is necessary for roughness discrimination for inter-elements spacing under .1 mm, whereas above that spacing, spatial information mediated by static touch is sufficient (Hollins & Risner, 2000). Roughness perception has been postulated to increase with inter-element spacing in the vibratory process and decrease in the spatial process. Many researchers have indeed found decreasing psychophysical functions for larger inter-element spacing (Bensmaia & Hollins, 2003; Blake, Hsiao, & Johnson, 1997; Hollins, Faldowski, Rao, & Young, 1993; Hollins & Risner, 2000; Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003; Yoshioka, Gibb, Dorsch, Hsiao, & Johnson, 2001). However, we found no studies that gave the exponent for the descending portion explicitly. The present study remedies this deficiency, as this is an important parameter for 'large' inter-element spacing, irrespective of the transition point from 'small' to 'large'. The occurrence of two psychophysical functions, one ascending and one descending, might be thought to imply two processes. However, elegant physiological modeling shows how an inverted U shaped function in evoked action potentials can be accounted for by neural codes based on firing-rate variation of both excitatory and inhibitory neurons (Yoshioka, Gibb, Dorsch, Hsiao, & Johnson, 2001). These researchers also show that psychophysical functions using human roughness judgments from bare finger exploration are extremely similar to those obtained from the evoked potentials of slowly adapting fibers (SA1) in the monkey cortex caused by moving a surface across the monkey's finger. The transition point to the deceasing function is about 3.2 mm inter-element spacing for both the narrower fingered monkey and the wider fingered human. This suggests that the density of sensor cells in the finger, rather than finger width is important.

Klatzky and Lederman and their co-workers also investigated the transition point from ascending to descending functions, using rigid probes as well as bare fingers (Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003; Lederman, Klatzky, Hamilton, & Ramsay, 1999). They show that the transition point is lower for narrower than wider probes, and that the function with a wide probe is very similar to the function with a bare finger. Their model postulates that the transition or 'drop' point occurs at the inter-element spacing where the probe can fully penetrate the groove. To the extent that the width of a rigid probe parallels the sensor separation in a finger, the neural code model might also predict that transition point is lower for narrower probes. The original two process theories, based on discrimination data suggest a fixed transition point, irrespective of probe characteristics, around 1mm (Hollins & Risner, 2000; Katz, 1924/1989). Psychophysical judgments, by contrast, show a higher transition point, 3.2mm for the bare finger (Hollins, Seeger, Pelli, &

Taylor, 2004) or 5mm (Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003). These values are nevertheless less than a human finger width, about 9mm. Klatzky and Lederman and their co-workers explain this by deformation of the finger, plus speed of movement across the surface. Researchers who model neural firing rate suggest that it is the density of receptors, also in combination with speed of motion, which is critical. However, there are as yet no data that can distinguish these two kinds of model. The PHANToM® force feedback device has a virtual contact area on infinitively small proportions, equivalent to a probe of zero width. The theoretical prediction of models that rely only on the geometry of probe and surfaces is that the psychophysical function with the PHANToM will be entirely descending. Theoretical models that include finger deformation or density of sensors do not make this prediction, as participants may grip probes differently for different inter-element spacings or probes and so cause changes in finger deformation or sensor contact.

The transition point from an ascending to a descending psychophysical function is thus a key property for roughness perception. It is undoubtedly affected by speed of movement, force exerted, friction and whether the movement is active or passive, as well as the geometry of the surface and the probe. However, this study focuses only on the geometry of the probe (by using both a stylus and thimble probe with the PHANToM), and the visual status of the participants (blind or sighted). The results may be compared with those obtained in physical reality with rigid probes (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003).

Determining the transition point presents methodological problems that may not have been fully appreciated in earlier work. All the studies cited above that show a descending portion of the psychophysical function are based group analyses of data. For each value on the x-axis; the average of all participant judgments was obtained, and used as the value on the y-axis. The x-axis values were usually some form of inter-element spacing (groove width or ridge width or pattern repetition width). In some cases log(y) was plotted against log(x) rather than y against x. However, in all cases the data points were averaged over participants *before* obtaining the psychophysical functions. The parameters of the psychophysical function, i.e. the transition point, curvature and depth for quadratic functions or the slope and intercept for linear functions were obtained only *after* this averaging process. This method of analysis is different from the original psychophysical work which obtained individual functions for each participant (Stevens & Galanter, 1957; Stevens & Harris, 1962; Stone, 1967) and then gave the power law exponent as the average of the slopes obtained from the individual psychophysical functions. One advantage of the original method is that it generates the range of exponents across participants, and so gives a picture of individual diversity. Of course, if the functions are linear this makes no difference to the obtained mean power law exponent (as was the case for the narrow range of inter-element spacing in these early studies). An even more crucial advantage of the individual analysis method occurs when the individual psychophysical functions are non-linear. In that case, the average of the parameters of the individual function is *not* necessarily the same as the parameters obtained from the group function. Thus the transition point for the group function may be substantially different from the average of the transition points of the individuals. Furthermore, a minority of participants with non-linear individual functions may cause the group function to be non-linear. This is misleading, as one might conclude that the function is non-linear for every individual, when in fact it is linear for the majority of participants. Similar dangers of improper averaging have been noted for decision bound models of categorization (Maddox, 1999) and the problem is probably quite widespread in psychology. Thus, comparing whether the two methods of analysis lead to similar conclusions about roughness perception is an important aim of this study.

New technologies provide the ability to produce an ever-growing range of virtual textures and virtual haptic interfaces (Basdogan & Srinivasan; Choi & Tan, 2004; Drewing, Ernst, Lederman, & Klatzky, 2004; Ellis, Ganeshan, & Lederman, 1994; Hardwick, Furner, & Rush, 1998; Hollins & Risner, 2000; Hollins, Seeger, Pelli, & Taylor, 2004; Jansson, 1998, 2002; Jansson & Billberger, 1999; Kitada, Hashimoto, Kochiyama, Kito, Okada, Matsumura, Lederman, & Sadato, 2005; Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003; Lederman, Klatzky, Hamilton, & Ramsay, 1999; McGee, Gray, & Brewster, 2001; Moore, Broekhoven, Lederman, & Ulug, 1991; Oakley, Adams, Brewster, & Gray, 2002; Otaduy, Jain, Sud , & Lin, 2004; Reed, Lederman, &

Klatzky, 1990; Sjöström, 2000; Smith, Chapman, Deslandes, Langlais, & Thibodeau, 2001; Srinivasan, Basdogan, & Ho, 1999; Verrillo, Bolanowski, & McGlone, 1999). Currently the most common type of haptic device in perception experiments is the force feedback device, for example, the PHANToM, manufactured by SensAble Technologies Ltd (SensAble, 2006)[1]. Figure 1 shows the PHANToM and a similar earlier device, the IE 3000. Such devices work by representing to the user the force at a single point in space. By varying the direction and magnitude of the forces exerted, a force feedback device can create a virtual object of any shape and can simulate a range of object attributes such as hardness and roughness. Such devices can only directly supply kinesthetic information to their users in terms of the force transmitted through the probe used, typically a stylus or a thimble. This may be contrasted with physical reality, where cutaneous information is also available. So any comparison with physical reality must be with studies that use a rigid probe (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003).

Insert Figure 1 about here

There have been several studies using force feedback devices to study roughness perception in virtual reality. Jansson (1998) found that the perceived roughness of virtual textures that simulated sandpaper increased as a function of increasing inter-element spacing, just as with physical reality. Colwell, Petrie, Kornbrot, Hardwick, & Furner (1998) used sinusoidal groove patterns and found that perceived roughness in virtual reality decreased with increasing inter-element spacing for most participants. A study comparing the PHANToM with the IE 3000 showed slightly superior performance for the PHANToM (Weisenberger, Krier, & Rinker, 2000). Studies using the PHANToM and regularly spaced elements all found roughness decreasing with inter-element spacing (Drewing, Ernst, Lederman, & Klatzky, 2004; McGee, Gray, & Brewster, 2001; Wall & Harwin, 2001). The current study uses sinusoidal stimuli, because of the possibility that tactile space may, like visual space, be successfully modeled as a Fourier decomposition of spatial frequencies. Sinusoidal stimuli are difficult to produce in physical reality, providing a further reason for investigating such stimuli in virtual reality.

Force feedback devices may have probes of different widths corresponding to the rigid links in physical reality. The PHANToM, as used in the present study, has a wide thimble probe and a narrow stylus probe. When these probes are handled freely, not connected to any computer, they may be experienced by (and seen by sighted) participants as different (see Figure 1). However, both probes, as used in our research, simulate interactions at a single point. Nevertheless, because participants know the probes are different, they may generate differences in one or more parameters relating to an individual's interaction with a virtual texture. There may also be differences between the perceptions generated by different force feedback devices due to the algorithms they use or their physical properties. To this end the stimuli and methodology that Colwell et al (1998) used with the IE 3000 are replicated here to allow precise comparisons.

The effect of visual status on the perception of roughness with the PHANToM was investigated for both theoretical and practical reasons. Theoretically, it might be hypothesized that blind participants would have more sensitive roughness perception than sighted participants, because they make greater use of the haptic sense. Conversely, it might be hypothesized that sighted participants would be more sensitive as they also have visual information to supplement their haptic perception. Differences in sensitivity might then lead to differences in psychophysical function. A finding of no effect of visual status would support the autonomy of the haptic sense. On a practical level, there is potential for haptic devices to enhance access to computer-based information, particularly for blind people. In order to ensure accessibility it is essential that designers know of any relevant differences between blind and sighted people.

In summary, the present study investigates the effect of visual status and probe type in virtual reality on the form of the psychophysical function relating ln (magnitude estimate of roughness) to ln (inter-element spacing).

Method

Participants

There were 23 participants, 13 sighted and 10 blind. The sighted participants comprised 6 males and 7 females, with ages ranging from 19 to 36 years, all of whom were university students, with no reported sensory or motor impairments. The blind participants comprised 8 males and 2 females, with ages ranging from 19 to 54 years. All these participants had no useful vision, but reported having no other sensory or motor impairments. Of these, 5 were blind from birth or early blind (before 2 years of age), and the remaining 5 lost their sight between the ages of 8 and 42 (late blind) (see Table 1 for details). All were volunteers recruited from a panel of blind and partially sighted individuals who participated in research at the Sensory Disabilities Research Unit at the University of Hertfordshire.

Apparatus

The PHANToM 1.0 device was controlled by a Pentium II 400 MHz computer with 64MB RAM running Windows NT. A set of Sanyo PH 200N headphones played white noise to the participants for the duration of the experiment. The intensity of the white noise was adjusted so that no participant could detect any auditory cues from the PHANToM.

Stimuli

The stimuli consisted of the same 10 sinusoidal virtual textures used by Colwell et al (1998), developed with the same haptic rendering software (Hardwick, Furner, & Rush, 1998). The algorithm is sufficiently robust that speed of motion of probe does not change the presented texture and so could not affect the results. Using a coordinate system with x horizontal to the right, y horizontal away from the user, and z vertical, the textured surface is in the x-y plane[2]. The sinusoidal ridges and troughs are in the z-direction and run parallel to the y-axis. Figure 2 illustrates the parameters of the sinusoidal waveform. The amplitude of the sinusoidal grooves was constant across the virtual textures at .1125mm in the z direction. The sinusoidal grooves ranged between .675mm and 2.700mm in 10 equal increments of .225mm. The groove width for these stimuli thus represents inter-element spacing. The groove width of 1.575mm was used as the standard texture for the magnitude estimation comparisons. The textured space runs from x = -20mm to x = +20mm. There are smooth portions of -15mm at each edge, i.e. from x = -35mm to x = -20mm at the left edge and from x = +20mm to x = +35mm at the right edge. The extent of the grooves is effectively infinite in the y-direction. The participant was seated square on to the desk that held the PHANToM and the seat was adjusted so that the bottom of the texture, corresponding to z = -. 0563 mm appeared to be on the desk. Participants were not given any visual representations of the virtual textures.

Insert Figure 2 about here

Design

The task was magnitude estimation of roughness, where participants gave a number expressing the ratio of the perceived roughness of a stimulus presented by the PHANToM relative to a modulus number that the participant had chosen to assign to the standard stimulus. Magnitude estimation of roughness was the dependent variable. All participants examined 6 runs of the 10 virtual textures with varying groove widths, and with two different probes (stylus or thimble), making 12 runs in all. Visual Status with two levels, blind and sighted, was investigated as a between group factor. There were then three repeated measures factors: Probe with two levels, stylus and thimble; Groove Width with 10 levels; and Run Number with six levels. Each participant made 120 judgments (10 textures x 6 runs x two probes). A run comprised one presentation of each of the 10 groove widths, with a single probe, in random order. Participants performed six runs with one probe followed by six runs with the other probe, with the order of the probe counterbalanced between participants.

Procedure

Sighted participants were blindfolded for the duration of the experiment to prevent them picking up any cues as to the dimensions of the virtual textures by visually monitoring the movement of their hand. Each participant then donned the headphones and was seated in front of a desk holding the PHANToM. The seat was adjusted so that the textured surface appeared to be lying on the desk. Participants were informed that the white noise was necessary to drown cues from the motor. They were then instructed to feel the virtual texture by sweeping the stylus or thimble probe across each virtual texture once from left to right starting in the flat portion 15mm to the left of the beginning of the texture. They were encouraged to use the same force and speed for each sweep, although this was not controlled.

They were then presented with the standard stimulus and instructed to give that roughness a number of their own choice, the modulus. The magnitude estimation procedure was explained and they were instructed to give each subsequent stimulus a number representing the ratio of the roughness of that stimulus to the standard. Examples were given relative to the participant's own chosen modulus. So if a participant chose 20 as the modulus, then they would be told "if the stimulus appears twice as rough as the standard, call it 40, if it appears half as rough, call it 10". This procedure allows participants to choose their own range of numbers, but aims to ensure that judgments are ratios. Participants then completed the 12 runs in counterbalanced order. There was a short break between runs.

Results

The raw dependent variable for all analyses is ln (ME). Magnitude estimate, ME, is the ratio of the number given by the participant divided by the modulus number the participant had given to the standard stimulus (i.e. judgments were normalized).

Group Psychophysical Functions

Magnitude estimation functions for blind and sighted participants with stylus and thimble probes are shown in Figure 3. In the ANOVA tradition all observations for a given value of visual status, probe and groove width are first logged and then averaged The slope of the four functions shown in Figure 3 are given as the power law exponent for each of the four possible combinations of visual status and probe. Only participants with all individual psychophysical functions having significant negative exponents are included in the group analyses reported here. Two participants were excluded: Participant Blind8 with significant positive exponents for stylus and thimble (Table 1, Figure 4); and participant Sighted12 with completely flat functions for both probes (Table 1, Figure 5). However, analyses including all participants gave similar findings, but with reduced power because of the wider range of individual differences. Best fitting linear functions are superimposed for the four functions. It *appears* that the linear function for the blind participants with a stylus has a shallower slope, and so a smaller power law exponent, than the other three functions. The interactions in the ANCOVA described below shows that this difference in slope is statistically significant. A post hoc comparison of the slope of blind stylus condition compared with the other three conditions was also significant. Figure 3 also suggests systematic non-linearity.

Insert Figure 3 about here

In order to test whether the differences in slopes apparent in Figure 3 are statistically significant an ANCOVA was conducted. The dependent variable was mean (over participants) ln (ME). Visual status was a between group factor, and probe was a within group factor. Ln (groove width) was entered as a metric, but independent, covariate in the analysis. This method ensures that the true magnitude of the ln (groove width) is taken into account. No (incorrect) assumption as to equal spacing of ln (groove width) is made, as would be the case if ln (groove width) was entered as a within group factor and a trend analysis conducted. There is no implication that ln (groove width) is a covariate in the sense of being a correlational variable, which the analysis aims to control for statistically, because of lack of experimental control. Ln (groove width) was manipulated experimentally and hence is an independent metric variable. In such an analysis, significant differences in slope are indicated by significant interactions between factor variables and the ln (groove width) covariate. The ANCOVA gave a significant main effect for visual status, F (1, 32) = 55.4, $p < .0005$, partial $\eta^2 = .63$, and ln (groove width), F (1, 32) = 740.8 $p < .0005$, partial $\eta^2 = .96$. The main effect of visual status has, of course, no effect on the power law exponent. There are also significant interaction effects of ln (groove width) by visual status, F (1, 32) = 5.7, $p = .023$, partial $\eta^2 = .15$ and ln (groove width) by visual status by probe F (1, 32) = 4.6, $p = .040$, partial $\eta^2 = .13$. These interactions correspond to the function for blind participants with a stylus having a significantly shallower slope than the other three functions, as shown in Figure 3.

In order to test for quadratic effects in the functions in Figure 3, a similar ANCOVA that also includes a quadratic term of $[\ln(\text{groove width})]^2$ was conducted. Type I sums of squares were used so that a significant quadratic term is calculated over and above any linear effect. The quadratic term was statistically significant at the 95% confidence level, F(1,28) = 7.1, $p = .013$. The quadratic function gave a peak at a groove width of 1.25 mm, 95% with confidence limits 1.12, 1.39. Although the quadratic term is significant at the 95% confidence level, it only increases the adjusted r^2 for the full model from 0.954 to .977. At a more stringent confidence level of 99%, neither the slope differences nor the quadratic terms are statistically significant.

These group analyses taking means across participants are included for purposes of comparison with other studies. In fact, a more informative and appropriate ANCOVA analysis would include participant as a random effect, with probe nested under participant. Such an ANCOVA analysis including only a linear term for ln (groove width) gives a significant effect *only* for ln (groove width), F(1,410) = 260.6, $p < .0001$. That is the shallower slope for the blind stylus condition is no longer statistically significantly different from the slopes for the other three functions. The mean exponent is 0.80. The confidence limits are 0.70 to 0.90 for the analysis including participants, tighter than the limits of 0.65 to 0.95 for the analysis not including participants. The parallel ANCOVA including a quadratic term, still gives a significant quadratic effect, F(1,406) = 5.6, $p = .019$. The quadratic term makes a minimal improvement in adjusted r^2, from .433 to .443. (The adjusted r^2 is much smaller, as there is now substantial between participant variance that has not been glossed over).

In summary, the mean power law exponent is -.80 with 95% confidence levels 0.70 to 0.90. Group analyses of the functions in Figure 3 show a slightly lower slope for the blind stylus function. However, the effect size, eta-squared, is small, in the order of 0.15, relative to the effect size for ln (groove width), 0.96, and is only significant at the 95%, not the 99% level. This effect disappears when participant is included as a random effect. Quadratic effects, although present, are small and not significant at the 99% level of significance. A deeper look at psychophysical functions requires analysis at the individual level.

Individual Psychophysical Functions: General

Individual psychophysical functions were obtained for all participants for thimble and stylus separately. These functions of mean (over six replications) ln (ME) as a function of ln(groove width) are shown in Figures 4 and 5. For each participant an ANCOVA was conducted, including all possible interactions, with ln (magnitude estimate) as the dependent variable; probe as a repeated measures factor with levels stylus and thimble; and ln (groove width) and ln (groove width) squared (quadratic term) as metric covariates. The main effects of probe, indicating overall different means for stylus and thimble were *not* statistically significant for 12 participants (5 blind, 7 sighted). That is all participants in Figure 4 had no significant difference in the height of the stylus and thimble functions. These participants showed very similar functions for the thimble and stylus, as shown in Figure 4. The other 11 participants with a significant effect of probe are shown in Figure 5. There were 3 blind and 3 sighted participants' functions with stylus significantly greater than thimble; and 2 blind and 3 sighted participants' functions with thimble significantly greater than stylus.

Insert Figures 4 and 5 about here

Individual Psychophysical Functions: Power Law Exponents

Stevens' power law exponents were obtained for all participants as the slope of the linear regression of ln (magnitude estimate) on ln (groove width), separately for the stylus and thimble conditions. The obtained exponents are shown in Table 1 together with their associated adjusted r^2 and the visual impairment type of the blind participants. There were 21 out of 23 participants (9 out of 10 blind, 12 out of 13 sighted) with significant negative exponents. Blind8, who was early blind (Figure 4), had highly significant, and near identical positive exponents for both stylus and thimble. Sighted12 (Figure 5) showed no effect of groove width but estimates with the stylus were substantially greater in roughness than those with the thimble. The 7 participants with significantly different exponents with the two probes are indicated in bold in Table 1. Of these participants, 4 had more negative exponents for thimble than stylus (Blind1, 4, 10 and Sighted13); and 3 had more negative exponents for stylus than thimble (Blind6, Sighted3 and 8).

Insert Table 1 about here

In order to investigate the effects of visual status (between groups) and probe (within group) on the psychophysical function, an ANOVA was conducted with Stevens' power law exponent as the dependent variable. The two participants who did not have a significant negative exponent were excluded. The mean Stevens' power law exponent was -.81, with 95% confidence limits -.69, -.93. There were no statistically significant effects: for visual status, F (1, 19) = .93, p = .347; or for probe with a multivariate F (1, 19) =1.17, p = .293; or for the interaction between probe and visual status, F (1.19) = 2.21, p = .154.

The power law exponents obtained with the PHANToM were compared with those found with the IE 3000 (Colwell, Petrie, Kornbrot, Hardwick, & Furner, 1998), as shown in Table 2. For the IE 3000 9 out of 22 participants gave significant negative exponents, compared with 21 out of 23 for the PHANToM. A test of this comparison gave a significant difference, $\chi^2 = 12.9$, p =.0004.

Insert Table 2 about here

Individual Psychophysical Functions: Transitions from ascending to descending

The form of the psychophysical functions was examined using the coefficients in the quadratic ANCOVA conducted for each participant. As only one participant (Sighted9) had a significant interaction between probe and $[\ln(\text{groove width})]^2$, simpler individual ANCOVAs were conducted with just ln (groove width) and $[\ln(\text{groove width})]^2$ as explanatory variables (i.e. excluding probe). The rightmost columns of Table 1 give the linear and quadratic coefficients and peak groove width for these regressions, with significant quadratic terms indicated in bold (Peak groove width = - quadratic coefficent/2linear coefficient).

There were 13 participants out of 23with a wholly descending psychometric function, indicated by a significant linear trend with negative slope and no significant quadratic trend. The mean exponent for these participants alone was -.79 (confidence limits: -.62, -,95). There were 7 participants (Blind5, 6, 9 and Sighted1, 2, 3, 6) showing a rising psychometric function for lower groove widths and a descending function for higher groove widths. The transition points as measured by peak groove width ranged from .78mm to 1.82 mm. There were 3 participants with ‘anomalous’ results: Blind8 had a wholly ascending function; Sighted12 had a flat function with no significant linear or quadratic trend; Sighted 10 had a noisy function with only the quadratic term significant, although the simple linear analysis did give a significant negative exponent.

Discussion

Power Law Exponents from Psychophysical Functions

The power law exponent was close to a value of -.80 whatever analysis method was used. Group ANOVA, including participants, gave exponent of -.80 (confidence limits: -.70, -.90) (excluding 2 anomalous participants); means of individual exponents from linear analyses for these same participants was -.81 (-.68, -.92); while mean individual exponents for the 13 participants with wholly negative functions was -.79 (-.62, -.95). Thus one can conclude that for ‘large’ inter-element spacing, the Stevens power law exponent for roughness is about -0.80 in both virtual and physical reality. The functions obtained by Johnson and his co-workers (Connor, Hsiao, Phillips, & Johnson, 1990; Johnson & Hsiao, 1992; Yoshioka, Gibb, Dorsch, Hsiao, & Johnson, 2001) and of Klatzky and Lederman’s group (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003) would be consistent with an exponent of -.80, although they do not explicitly give an exponent. It is interesting that the exponent for small inter-element spacing is close to +.80 (Hollins, Seeger, Pelli, & Taylor, 2004; Stevens & Galanter, 1957; Stevens & Harris, 1962; Stone, 1967).

Form of the Psychophysical Function

Conclusions about the form of the psychophysical function depend on the method of analysis. However, as noted above all analyses give descending functions for large inter-element spacing. This supports either the neural coding model or a separate spatially-based process for larger inter-element separations. These are difficult to distinguish experimentally, although the single process is more parsimonious and has physiological support (Yoshioka, Gibb, Dorsch, Hsiao, & Johnson, 2001).

Analyses based on group data are best fit by a quadratic psychophysical function with a peak at an inter-element spacing of 1.25 mm. The value of 1.25 mm was obtained when combining data over group and probe, as these factors had low effect sizes and were not significant at the 99% confidence level. This does not support the prediction that the zero contact point of the PHANToM will lead to a wholly descending psychophysical function. It suggests that the transition point is not completely determined by the width of the probe relative to groove width. The functions in Figure 3 are in fact very similar to those obtained for a 2 mm probe in physical reality (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003). Thus the group data provide no reason to suppose any differences between virtual and physical reality with a narrow rigid probe, even though the virtual probe has effectively zero width.

The individual analyses tell a different story. The psychophysical functions in Figures 4 and 5 graphically demonstrate the range of roughness perception patterns across different individuals. At the individual level, 13 participants (more than half the sample) had linear psychophysical functions for the complete range of stimuli from .675m to 2.700 mm. For all these participants the transition from an increasing to a decreasing psychophysical function must be substantially below the peak of 1.25 mm, found for our group quadratic function, and of most of the group functions obtained by previous researchers (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003). Unfortunately, the reliability of the PHANToM for groove widths lower than .675 mm was low, so we could not test behavior at lower grooved widths. There were 7 participants with significant quadratic trends with peaks at groove widths within the stimulus range (minimum 0.75mm, maximum 2.69mm). These 7 do show behavior that is broadly consistent with the group data. Finally there were three ‘anomalous’ participants. This wide range of individual functions may also occur in physical reality with a rigid probe. For example, previous researchers (Klatzky & Lederman, 1999; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003) report rejecting some participants because of anomalous judgments.

A substantial minority of participants do have quadratic functions with transition points similar to those in physical reality, even with a zero width probe. Consequently a probe narrower than the groove width is not sufficient to ensure a wholly descending psychophysical function for all people. This implies that geometry alone cannot account for roughness perception. Using the zero contact width probe provides evidence for factors other than geometry that could not be obtained from physical reality experiments. Nevertheless, the majority of participants show wholly negative functions. So for some people, the transition to a negative function might indeed be wholly determined by whether the probe can penetrate the groove. The diversity of individual roughness perception using rigid probes is itself an important finding.

Methodological Issues

This study provides a clear illustration of the dangers of ignoring individual analyses. The group analyses suggest a quadratic psychometric function with peak groove width of 1.25 mm. Nevertheless more than half the participants had wholly descending linear psychometric function.

Haptic Perception by Blind and Sighted People

There were no significant differences between blind and sighted participants. A wide range of behaviors was apparent for both blind and sighted participants. In particular, both the blind and the sighted groups had some people with a pattern showing quadratic effects, and others not. Both groups had some participants showing a main effect of probe (Figure 5), others not (Figure 4). Finally, both groups had some people showing differences in exponents for stylus and thimble, others not.

Devices and Probes

There were no consistent differences between the psychometric functions for the stylus and thimble probes, although a few participants did have statistically significant different functions. Our results are similar to those obtained by Colwell et al (1998) with the IE 3000 device, using an identical procedure. Hence the findings are likely to be generalizable to other 3-D force feedback devices. More of the participants showed significant effects of groove width with the PHANToM, implying greater reliability.

The Potential for Virtual Haptic Reality

The finding that most people, both blind and sighted, can reliably discriminate virtual textures in terms of roughness using force feedback devices augurs well for their potential. Such devices might be used to substitute for the symbolic use of color or shading in virtual interfaces for blind people or to enhance such interfaces for sighted people. The first caveat is that some minority of people would not be able to use such devices effectively. The second caveat is that there are likely to be individual preferences for different force feedback probes, just as there are for different pointing devices such as mouse, tracker ball or joystick.

Summary

The psychometric function for roughness in virtual reality for large inter-element spacing is a power law with exponent -.80. This is consistent with other studies in both physical and virtual reality.

The form of the psychometric function with zero contact point device had both ascending and descending portions for a substantial minority (7 out of 23) of participants. This implies that penetration of the groove width is not sufficient for a descending psychometric function.

Individual psychometric functions showed considerable diversity. The majority (13 out of 23) participants had functions that were wholly linear descending, In spite of this diversity, there was no effect of either visual status or probe. This diversity has implications for virtual reality applications.

Conclusions based on individual analyses are not the same as those based on grouped analyses. In our view, this implies that individual analyses should always be conducted, and should precede any group analyses.

At a theoretical level, any satisfactory account of the mechanisms underlying haptic perception must account for these functions, as well as those already obtained in virtual and physical reality with stimuli of quite diverse geometric forms. Even in physical reality much remains to be learnt about the form and determinants of the psychophysical function.

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Notes

[1] A full listing of available force feedback devices can be found at the haptics community website ("Haptics Community ", 2004)

[2] There are at least 4 de facto standard Cartesian co-ordinate systems in engineering. The convention used in the present software and by Sensable internally in Ghost, is the commonest ‘mathematical’ notation. It has a two dimensional representation in the horizontal plane, as when writing on paper(x right, y away from observer). This may be contrasted with some screen software where the two dimensional representation is of a vertical screen (x right, y vertical). There are also different conventions about whether away from the observer is positive or negative.

Table 1

Individual Power Law Exponents from Linear Regressions and Associated Levels of Significance and Adjusted r^2 as a function of Visual Status and Probe

ID	Type[a]	Figure	Linear Regression Exponent[b]			Linear Adjusted r^2		Quadratic Regression[d]		
			stylus	thimble	Mean[c]	stylus	thimble	linear coefficient	quadratic coefficient	peak groove width mm
						Blind participants				
Blind3	B	Fig 4	-.47	-.70	-.58	.731	.877	-.59	.01	.99
Blind5	L	Fig 4	-.88	-.85	-.86	.918	.860	-.62	**-.37**	**1.35**
Blind8	E	Fig 4	.60	.61	.60	.826	.928	.75	-.22	.86
Blind9	L	Fig 4	-.74	-.77	-.75	.763	.889	-.43	**-.51**	**1.82**
Blind10	L	Fig 4	-.55	-.89	**-.72**	.770	.925	-.72	-.01	1.00
Blind1	B	Fig 5	-.89	-1.46	**-1.17**	.793	.896	-1.20	.03	.99
Blind2	B	Fig 5	-.53	-.60	-.57	.937	.907	-.60	.05	.96
Blind4	L	Fig 5	-.29	-1.49	**-.89**	.507	.903	-.65	-.36	1.32
Blind6	B	Fig 5	-.46	-.16	**-.31**	.747	.144	-.50	**.30**	**.75**
Blind7	B	Fig 5	-.75	-.61	-.68	.820	.788	-.43	-.38	1.56
						Sighted participants				
Sighted1		Fig 4	-.86	-.85	-.86	.662	.637	-.45	**-.63**	**2.01**
Sighted3		Fig 4	-.97	-.47	**-.72**	.766	.582	-.32	**-.63**	**2.69**
Sighted4		Fig 4	-1.48	-1.35	-1.42	.922	.870	-1.01	-.62	1.36
Sighted7		Fig 4	-.87	-.60	-.74	.860	.890	-.66	-.12	1.10
Sighted8		Fig 4	-.85	-.24	**-.54**	.780	.143	-.23	-.47	2.75
Sighted9		Fig 4	-.81	-1.18	-.99	.642	.768	-.86	*-.21*	*1.13*
Sighted11		Fig 4	-.49	-.38	-.44	.442	.339	-.62	.28	.80
Sighted2		Fig 5	-1.57	-1.55	-1.56	.960	.953	-1.25	**-.48**	**1.21**
Sighted5		Fig 5	-.73	-.89	-.81	.737	.911	-.60	-.33	1.31
Sighted6		Fig 5	-1.08	-1.54	-1.31	.715	.912	-.74	**-.87**	**1.80**
Sighted10		Fig 5	-.59	-.56	-.58	.593	.565	-.07	**-.78**	**348.24**
Sighted12		Fig 5	*-.05*	*.13*	*.04*	-.058	-.043	-.06	.16	.27
Sighted13		Fig 5	-.30	-.59	**-.45**	.919	.972	-.39	-.08	1.11

Note a. Status: B = blind form birth, E =early, blind before 2 years, L = late, blind after 2 years

Note b. Italic indicates that there was no significant effect of ln (groove width)

Note c. Bold indicates that exponents for thimble and stylus were significantly different

Note d. Bold indicates that quadratic term in the ANCOVA was significant for both probes. Italic indicates that the quadratic term in the ANCOVA was significant for only one probe.

Table 2

The incidence of significant negative, non-significant and positive exponents for sighted and blind participants for the IE3000 as reported in Colwell et al. (1998) and for the PHANToM

Visual Status	# significant negative exponents	# non significant exponents	# significant positive exponents
		IE3000	
Blind	4	1	4
Sighted	5	6	2
All IE 3000	9	7	6
		PHANToM	
Blind	9	0	1
Sighted	12	1	0
All PHANToM	21	1	1

Figure Captions

Figure 1. Force feedback devices. Top panel: PHANToM with thimble probe; middle panel: PHANToM with stylus probe; bottom panel: IE 3000.

Figure 2. Parameters of the sinusoidal waveform.

Figure 3. Group psychophysical functions for blind and sighted participants with stylus and thimble probes. (Participants with psychophysical functions that did not have significant negative exponents excluded).

Figure 4. Fitted magnitude estimation functions for participants with highly similar thimble and stylus functions. Open triangles: stylus; filled circles: thimble.

Figure 5. Fitted magnitude estimation functions for participants with less similar thimble and stylus functions. Open triangles: stylus; filled circles: thimble.

Figure 1. Force feedback devices. Top panel: PHANToM with thimble probe; middle panel: PHANToM with stylus probe; bottom panel: IE 3000.

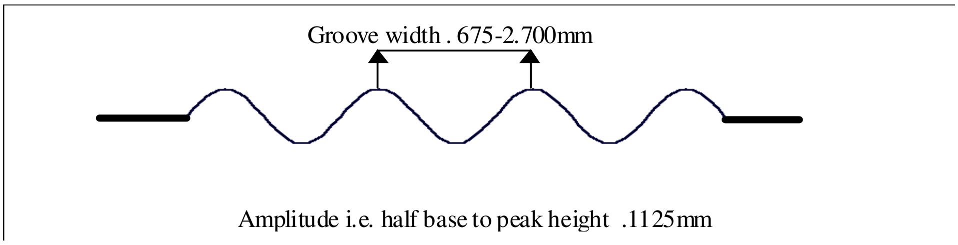

Figure 2. Parameters of the sinusoidal waveform.

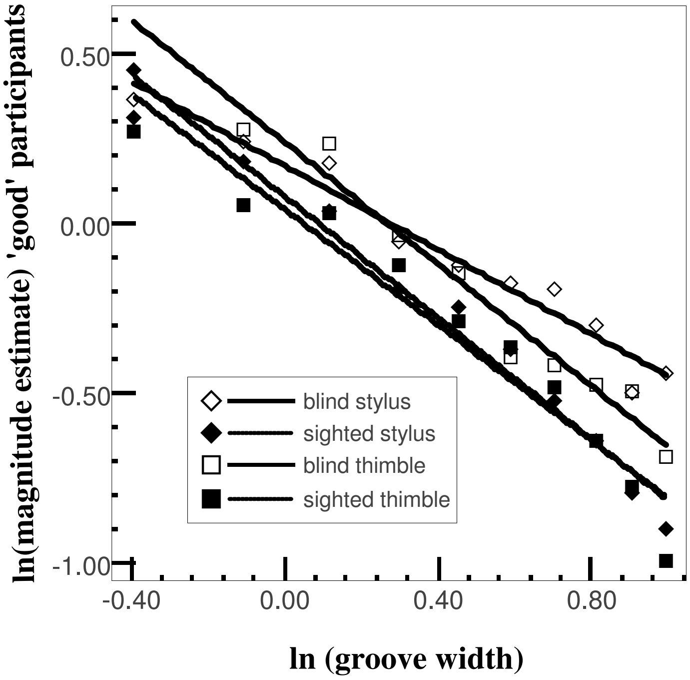

Figure 3. Group psychophysical functions for blind and sighted participants with stylus and thimble probes. (Participants with psychophysical functions that did not have significant negative exponents excluded).

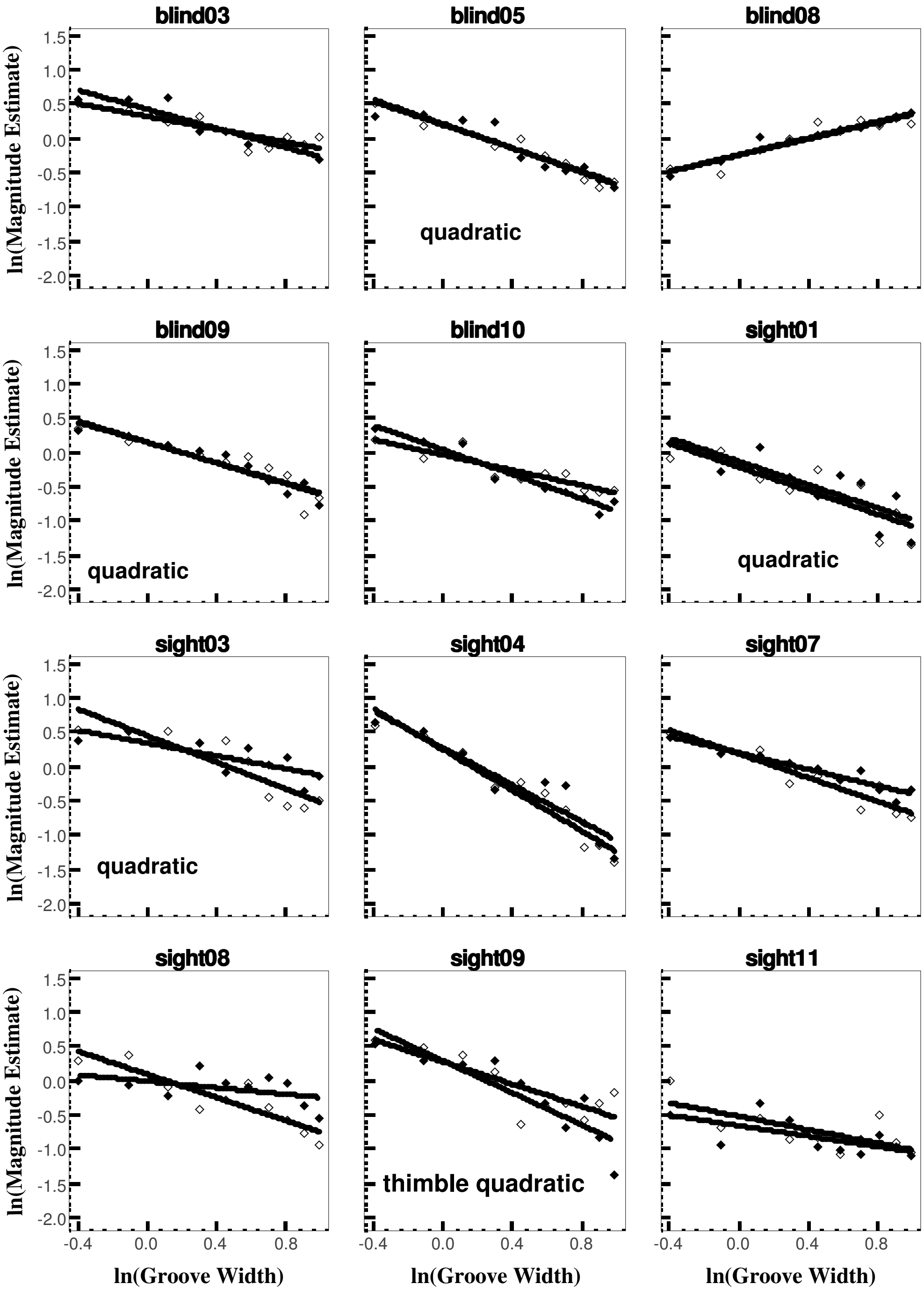

Figure 4. Magnitude estimation functions for participants with highly similar thimble and stylus functions. Open triangles: stylus; filled circles: thimble.

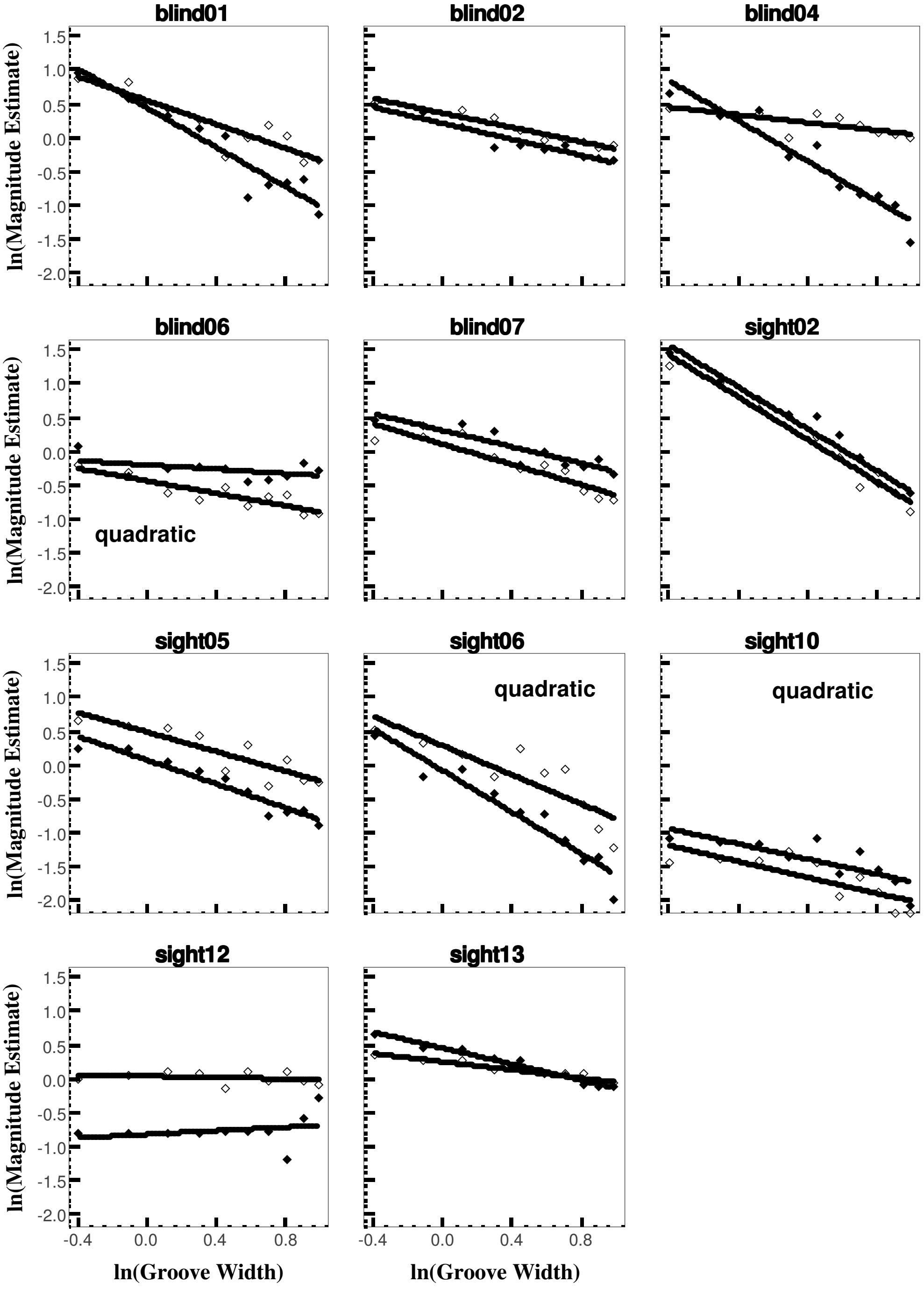

Figure 5. Magnitude estimation functions for participants with less similar thimble and stylus functions. Open triangles: stylus; filled circles: thimble.