

Haptic curvature contrast in raised lines and solid shapes

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Abstract It is known that our senses are influenced by contrast effects and aftereffects. For haptic perception, the curvature aftereffect has been studied in depth but little is known about curvature contrast. In this study we let observers explore two shapes simultaneously. The shape felt by the index finger could either be flat or convexly curved. The curvature at the thumb was varied to quantify the curvature of a subjectively flat shape. We found that when the index finger was presented with a convex shape, a flat shape at the thumb was also perceived to be convex. The effect is rather strong, on average 20% of the contrasting curvature. The contrast effect was present for both raised line stimuli and solid shapes. Movement measurements revealed that the curvature of the path taken by the metacarpus (part of the hand that connects the fingers) was approximately the average of the path curvatures taken by the thumb and index finger. A failure to correct for the movement of the hand could explain the contrast effect.

Keywords Haptic perception · Curvature contrast · Illusion

Introduction

The human perceptual system is better at detecting differences than at estimating absolute values. For vision, this is illustrated by the vast amount of illusions that depend on the interaction of the surround with a target such as the Hering and Ebbinghaus illusions. Gibson (1933) showed that a straight line surrounded by curved lines is visually perceived as curved in the opposite direction. Because the surround (curved lines) and the target (straight line) are present simultaneously this was named “simultaneous contrast”. Gibson (1933) also showed that a similar bias was present when the contrast was successive, also known as the visual “curvature aftereffect”. During these visual experiments observers wore prism glasses that curved all vertical lines in the environment. Some observers noticed that the induced curvature seemed to affect their haptic perception of straightness. To investigate whether the same curvature aftereffect was present in the haptic modality, Gibson (1933) let observers haptically adapt to a convex stimulus and subsequently touch a straight stimulus. All observers reported that the straight stimulus felt concave. While successive curvature contrast was shown to be present in both modalities, simultaneous curvature contrast was only investigated for vision. The visual curvature contrast effect and aftereffect (e.g. Crassini and Over 1975), and the haptic curvature aftereffect (Vogels et al. 1996; Van der Horst et al. 2008a, b), have been investigated in depth, but no attention has been given to simultaneous contrast effects for the haptic modality. In the present study, we investigated the influence of a curved ‘surround’ on a straight target.

To understand whether visual illusions are modality specific, their haptic counterparts have been studied

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extensively. An early attempt was undertaken by Robertson (1902), who found that the Müller–Lyer illusion showed a similar bias in touch as in vision. She also found an illusion that seemed (at that time) exclusive for the haptic modality. When a shape consisting of a half-circle with both ends connected by a straight line (like the capital letter D) was explored with the whole hand, the straight line seemed to be curved outward. Although she did not systematically investigate and quantify the effect (the data consisted of sketches by the observers), she was the first to report an example of haptic curvature contrast. In the current study we wanted to systematically measure the effect but also extend it to stimuli that are more natural for the haptic modality. The material used in the study of Robertson (1902) and further studies on geometrical haptic illusions (e.g. Revesz 1934; Suzuki and Arashida 1992; Heller et al. 2002) consisted primarily of embossed lines, because in this way the layout of the haptic and visual stimuli is similar. However, in daily life the haptic channel is not often confronted with two-dimensional (2D) stimuli. It has been shown many times that identification of (raised) line drawings is dramatically more difficult with touch than with sight (e.g. Lederman et al. 1990; Wijntjes et al. 2008) whereas haptic identification of 3D objects seems to be effortless (Klatzky et al. 1985). Two-dimensional stimuli are thus more valid for vision than for touch. Therefore, the study of haptic illusions deserves extra attention on the aspect of stimulus dimensionality.

In the present study, we used both 2D and 3D stimuli to investigate the existence of haptic curvature contrast. Observers were instructed to explore two shapes, called ‘lateral’ and ‘test’ stimulus, with two fingers of the same hand simultaneously. The lateral stimulus was either straight (0 m^{-1}) or curved (4 m^{-1}), and served as the analogue of the surrounding curvature in visual experiments. The curvature of the test shape was varied using a 2AFC task to determine the point of subjective equality (PSE)—the curvature that was phenomenally flat. We used a hybrid form of the staircase method and the method of constant stimuli to measure the psychometric curve, as outlined below.

The study had two aims. The first aim was to test whether curvature contrast can be found for both 2D and 3D stimuli. The second aim was to measure discrimination performance for 2D and 3D stimuli. Curvature contrast would be shown by a shift of the PSE towards the curvature of the lateral shape; in other words, a straight test shape would feel oppositely curved with respect to the curved lateral shape. Differences in discrimination performance were quantified by comparing just noticeable differences (JNDs). The results could give insight in whether raised lines and solid shapes are differently processed.

Methods

Participants

Eight right-handed observers volunteered to participate in the first experiment. They were paid for their participation and were unaware of the purpose of the experiment.

Material

For the 2D stimuli, we used raised lines produced with Zychem swellpaper, which is often used for tactile pictures and maps for the blind. Raised line stimuli were printed on the paper, which was threaded through an infrared heater. The black lines of the print absorb the radiation and the microcapsules of alcohol embedded in the paper burst and make the black parts embossed. We printed 1 mm wide lines, which resulted in an embossed height of approximately 0.5 mm. To render the 2D stimuli we plotted circular arcs with the software package Mathematica. Each stimulus consisted of two lines: a lateral curvature that could either be straight ($C_r = 0 \text{ m}^{-1}$) or curved outwards ($C_r = 4 \text{ m}^{-1}$) and a set of test curvatures which varied in steps of 0.2 m^{-1} . The distance between the endpoints of a line was 20 cm, irrespective of the curvature. The distance between the end points of the lateral and test stimulus was 5 cm. The raised line stimuli were placed in a stainless steel holder that blocked lateral movement.

The 3D stimuli were made from PVC. The dimensions of these solid shapes were the same as for the raised lines except that the endpoint distance for the straight lateral test stimulus pair of the solid shapes was 8 cm instead of 5 cm. The solid shapes were 2 cm thick. These stimuli have been previously used and described by Pont et al. (1999). The solid shapes were placed in moulds made of cardboard in which they were fixated. Figure 1 shows the two kinds of stimuli and the two kinds of lateral shapes.

Procedure

Participants were seated on a chair and were visually shown example stimuli while the experimenter explained the task. A sheet was attached between the neck of the participant and two approximately 1 metre high poles that were standing on the table. The purpose of the sheet was to block vision of the stimuli. The participant could use a keyboard and computer screen to respond.

In all conditions, the participants had to explore both curves simultaneously (see Fig. 1). The exploration started on the left and comprised of two full cycle movements. The subjects were instructed to keep both index finger and thumb on the line or surface. The index finger was always touching the lateral stimulus, and the thumb the test

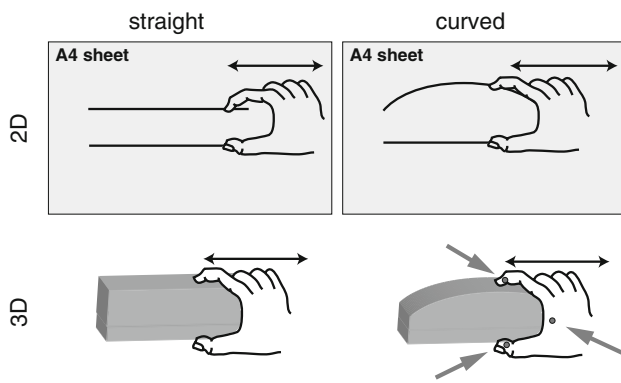


Fig. 1 A schema of the different stimulus materials and experimental conditions. Depicted are *top views*, stimuli were positioned on a table. The shape touched by the index finger is the lateral stimulus, which was either *straight* or *curved*. On the thumb a test stimulus was presented that varied in curvature. At the bottom right, *three grey arrows* indicate the placement of the three movement sensors that were used in all four conditions

stimulus. The task was to focus attention on the curvature they felt on their thumb and judge the sign of that curvature. To overcome possible confusion about the words normally used for the curvature sign, i.e. convex and concave, we graphically presented two choices on a monitor. After the exploration was finished, the choices appeared side by side on a screen. The left–right placements of the two choices were randomised. The participant had to respond by pressing the left or right arrow on a keyboard with his or her left hand. The key press was registered and a software program provided the experimenter with information about the next stimulus value to present. The software was written in Matlab, using the Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997).

In Fig. 1, the experimental design is illustrated. The design with respect to stimulus materials was blocked while the curved and straight lateral conditions were mixed. The order of the blocks was counterbalanced among participants. Each block consisted of three separate sessions, the first two blocks consisted of psychophysical measurements and the last one consisted of movement measurements. In Fig. 2, the data collection procedure is illustrated. In the first session a 1-up-1-down staircase procedure was used to estimate the PSE. For each lateral condition (straight and curved) a staircase started at both $+1.4$ and -1.4 m^{-1} . Thus, four staircases, which were selected randomly per trial, were run simultaneously. Each staircase consisted of 20 trials. An example of staircase data for a curved lateral stimulus can be seen in Fig. 2a. The staircase data were transformed to psychometric data, which can be seen in Fig. 2b. In that figure the number of actual repetitions per test curvature is shown (light grey bars). The psychometric data were fitted to a cumulative Gaussian. From this fit the bias (PSE) and the 84%

thresholds (JND) were estimated. The bias is the estimated stimulus intensity that feels phenomenally flat. With the estimate of the PSE of each individual subject, a method of constant stimuli was designed around this point. The repetitions per test stimulus were chosen so that the total number of repetitions for the first and second session added up to 10. An example of additional trials is illustrated by the dark grey bars in Fig. 2b. The psychometric function was fitted to the data that were taken together from the first and second sessions, as illustrated in Fig. 2c. We defined a positive curvature to point in the direction of the lateral stimulus. This is important to remember because in the case of solid shapes, this means that a positive value is assigned to a concave curvature. The example shows that if a test stimulus has a curvature of approximately 0.88 m^{-1} (positive, so curved towards the lateral) it is perceived as straight. Equivalently, it means that a straight line feels curved away from the lateral stimulus.

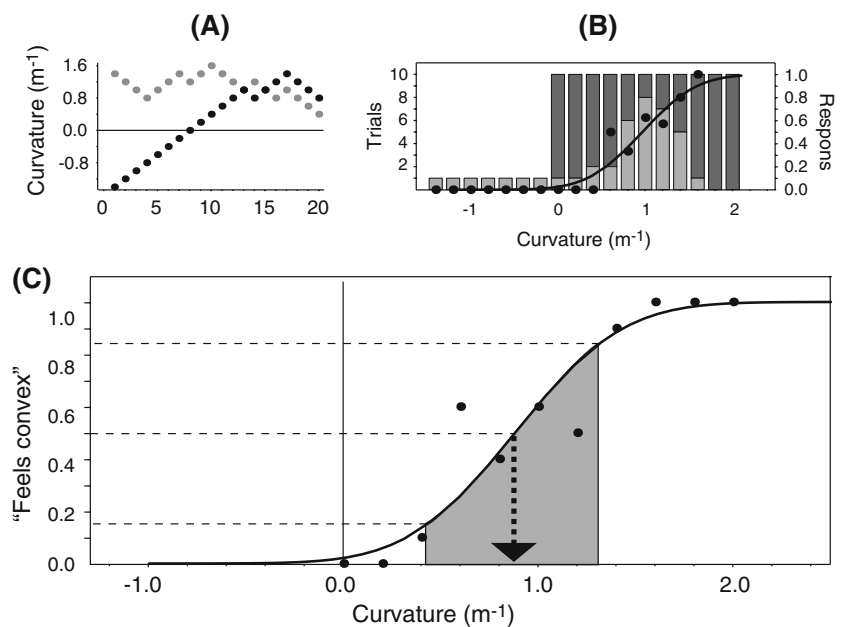
The third session of a block consisted of hand movement measurements using an Optotrak Certus system (NDI, Waterloo, ON, Canada). The reason for this measurement was to gain insight into how the index finger, thumb and metacarpus (the hand region connecting the fingers and thumb) move with respect to each other. We were interested in whether the position of the metacarpus followed an intermediate curved trajectory or that it followed the same curvature of the index finger or the thumb. To measure this, we placed three sensors on the hand: one on the index finger, one on the thumb and one on the metacarpus. We measured 20 trials, 10 per lateral stimulus, 2 repetitions for each of the 5 test stimuli which were distributed around zero in steps of 0.8 and 0.6 m^{-1} for the raised lines and solid shapes, respectively. We instructed the participants that it was a similar experiment and that they had to respond verbally because this measurement took place in a different location, where the setup used for sessions 1 and 2 was not available. We recorded the position of the sensors with a sample frequency of 100 Hz. The responses were not analysed further.

Data analysis

We fitted the psychometric data using the maximum likelihood estimation model as described in Wichmann and Hill (2001a). A 2×2 repeated measures ANOVA was conducted on both the JNDs and PSEs. The factors were lateral stimulus (0 or 4 m^{-1}) and stimulus material (raised lines or solid shapes). The thresholds and biases were analysed separately (univariate analysis) since no correlation was found between them.

Aside from the group analysis we wanted to assess whether the contrast effect was present in the individual psychometric data of each participant. Therefore, we

Fig. 2 **a** Raw data of a 1-up-1-down staircase used to estimate the PSE. **b** The data of the two staircases converted to psychometric data. The *light grey bars* denote the repetitions from the staircase. The *dark grey bars* denote the number of repetitions used to measure the remaining trials in the second session. **c** From the final data, the point of subjective equality (*dashed arrow*) and the just noticeable difference (half of the width of the grey area) were extracted



needed a measure for the confidence interval of the contrast effect. To estimate the variability in the PSEs we used bootstrap simulations as described in Wichmann and Hill (2001b). We defined curvature contrast as the difference between the biases for straight and curved lateral shapes: $\mu_{\text{contrast}} = \mu_{\text{curved}} - \mu_{\text{straight}}$. From the bootstrap simulations 95% confidence intervals were calculated. The resulting confidence interval of the curvature contrast was then calculated from the two bootstrap variabilities: $\Delta\mu_{\text{contrast}}^2 = \Delta\mu_{\text{curved}}^2 + \Delta\mu_{\text{straight}}^2$. We calculated per subject whether the resulting 95% confidence interval enclosed zero, in which case the curvature contrast effect would not be present.

From the 3D Optotrak data we extracted the 2D data that lay in the table plane, where the x axis was defined as frontoparallel and y axis as midsagittal. These data were fitted to parabolas of the form $y = \frac{1}{2}c(x - a)^2 + b$, where a and b are translation parameters and, for small ranges, c is approximately equal to the curvature. Thus for each test curvature c_t and lateral curvature c_r we measured the movement curvatures of the thumb c_{th} , metacarpus c_{mc} and index finger c_{if} . We regressed a linear model through the data (test curvature vs. measured curvature): $c_{\text{measured}} = a_0 + a_1c_t$. We hypothesised that the thumb would follow the test stimulus, i.e. $a_1 = 1$ and $a_0 = 0$, for both conditions $c_r = \{0, 4\}$. For the index finger we hypothesised that its path would be independent of the test curvature ($a_1 = 0$) and would depend only on the lateral curvature, i.e. $c_{\text{if}} = c_r$. These predictions are trivial since they say that the fingers follow the stimulus geometry. The measurement of interest was the curvature of the metacarpus. If its parameters are similar to those of the index finger this means that the index finger does not move with

respect to the hand. The same holds for the thumb. We hypothesised that the parameters of the metacarpus would lie somewhere in between those of the index finger and thumb, meaning that the hand moves with an intermediate curvature and that both the index finger and the thumb move with respect to the hand.

Results

Response analysis

The average values (and standard errors) of the thresholds and biases for all conditions are plotted in Fig. 3. As can be seen, the discrimination thresholds (JNDs) for raised line stimuli are larger than for solid shapes. This is confirmed by the ANOVA, which showed a significant main effect of stimulus material ($F(1,7) = 10.9$, $P = 0.013$). There was no significant main effect of lateral stimulus ($F(1,7) = 0.8$, $P = 0.4$), but the interaction between stimulus material and lateral stimulus was significant ($F(1,7) = 8.8$, $P = 0.021$). This interaction reflects that for solid shapes the JND is more influenced by the lateral stimulus than for raised lines.

On the right-hand side of Fig. 3, the PSE—the parameter that indicates the existence of haptic curvature contrast—is plotted. The PSE is clearly affected by the lateral stimulus. In the curved lateral condition the test stimulus should be curved in the direction of the lateral to be perceived as straight. Equivalently and possibly more intuitive, if the test stimulus is straight it is perceived as being curved oppositely to the lateral curvature. The ANOVA confirmed that the main effect of lateral condition was

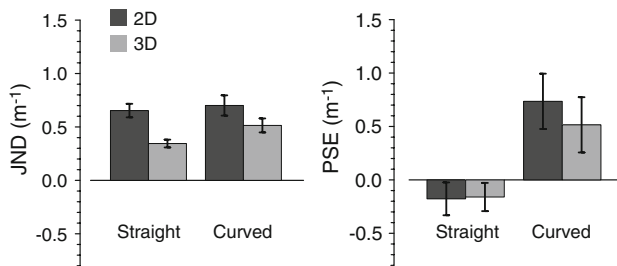


Fig. 3 Average data of the JND and PSE, averaged over subjects. *Straight* and *curved* bars refer to the lateral stimulus. *Error bars* denote standard errors

significant ($F(1,7) = 18.293$, $P = 0.004$). Furthermore, neither the factor stimulus material ($F(1,7) = 0.6$, $P = 0.470$) nor the interaction ($F(1,7) = 3.0$, $P = 0.128$) was significant. On average the contrast effect amounted to 20% of the value of the lateral stimulus curvature.

To assess the individual contrast effects we calculated the 95% confidence intervals of the difference between the biases for the straight and curved lateral. For seven out of eight subjects the individual data showed a significant curvature contrast effect. Furthermore, we compared the 16 biases from the raised lines condition with the 16 biases from the solid shape condition and found a high correlation ($r = 0.82$, $P < 0.0001$).

Movement analysis

From the movement data we calculated the curvature of the paths taken by the thumb, metacarpus and index finger. An example of the raw movement data and the fitted parabolas is presented in Fig. 4a. To assess the goodness of fit, we calculated the coefficients of determination (R^2). All values were above 0.998. Ideally, the curvature of the thumb path would be identical to the curvature of the test shape and the index finger path would be identical to the curvature of the lateral shape. The curvature data are plotted in Fig. 4b.

The figure shows that the index finger (black line) follows the lateral curvature since it is constant at either 0 or 4 m^{-1} . The thumb (light grey) follows the test curvature as can be seen by the linear increase with respect to the test curvature. The important finding is that the metacarpus (dark grey) follows an intermediate curvature. The regression coefficients and standard errors are presented in Table 1. The bold typeface indicates the mean curvature of the metacarpus for the curved lateral condition.

Discussion

Our study complements the findings of Gibson (1933): visual and haptic perception are subject to both successive

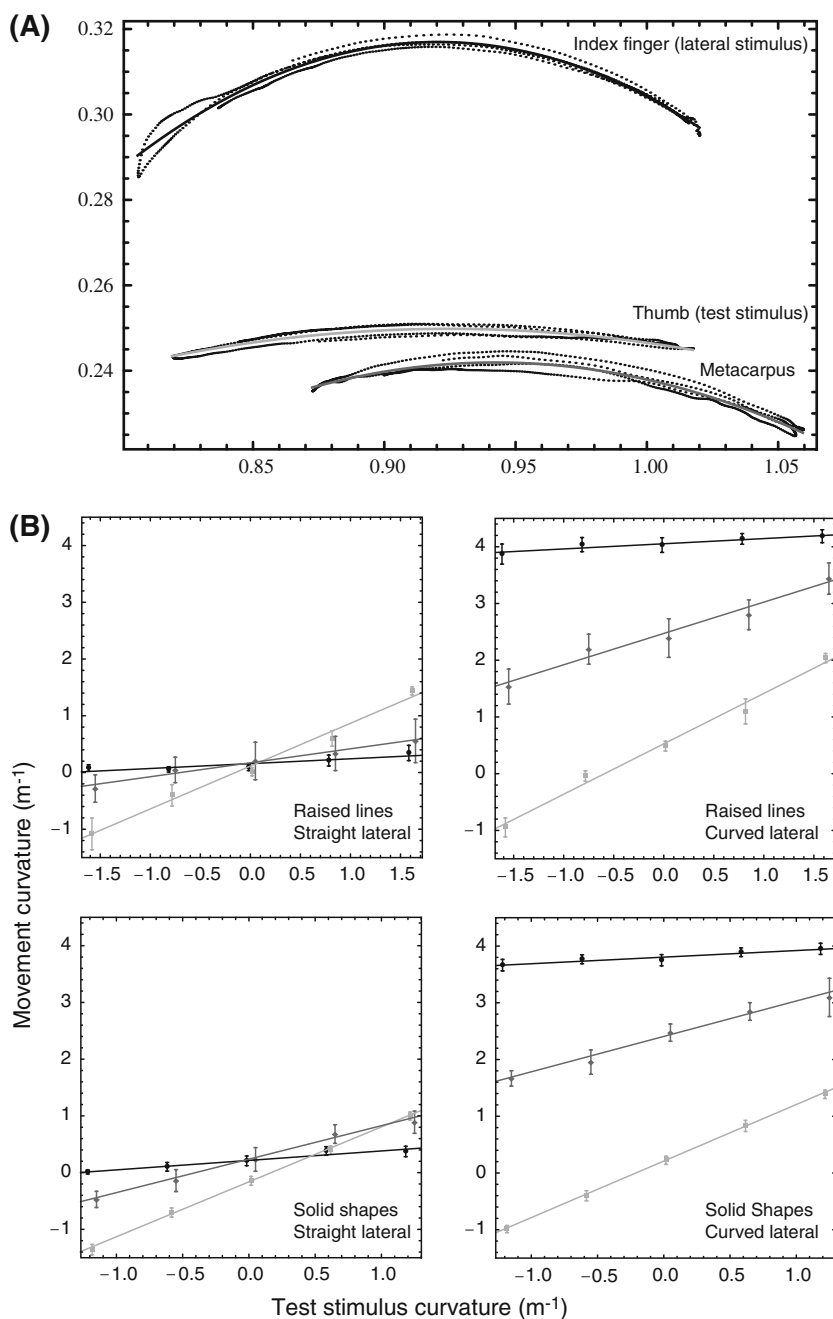
and simultaneous curvature contrast effects. Our experiments show that the contrast effect is clearly present in both 2D and 3D shapes and does not depend on a particular way of exploration. The contrast effect amounted to 20% of the lateral curvature. These relative magnitudes are equal to or larger than the relative magnitudes found for successive contrast. Vogels et al. (1996) measured the static curvature aftereffect using hand-sized, spherically curved surfaces and found that the subjective straightness was biased by about 20% of the adaptation curvature. Van der Horst et al. (2008b) studied the dynamic aftereffect and used exactly the same stimuli as we did. The aftereffect they found was about 7% of the adaptation curvature, a substantially smaller effect than the simultaneous contrast effect. Before discussing possible explanations of the haptic curvature contrast we will first discuss the different thresholds for the two materials we found.

Literature about the spatial acuity with which raised line stimuli are perceived is rather sparse and none of the existing studies addresses curvature discrimination. On the other hand, solid shapes have been used extensively for haptic curvature perception. It has been shown that the effective cue for solid shape curvature discrimination is the change of the local surface orientation (Pont et al. 1999; Wijntjes et al. 2009). The local orientation of a raised line is sensorially rather different from a local surface orientation. The difference we found between the thresholds for solid shapes and raised lines could indicate that the orientation of a surface is more accurately perceived than the orientation of line.

The interaction between stimulus material and lateral stimulus indicates that a solid shape is better discriminated when a straight lateral stimulus is present than a raised line. One could expect that, in contrast with a curved lateral stimulus, a straight lateral stimulus may serve as an informative reference shape. Since this is true for both materials a main effect of lateral stimulus should be observed, which is not the case. The reason that only discrimination of the solid shape profits from the straight lateral stimulus may again be attributable to the different sensorial inputs. Observers may be better in perceiving whether two opposed surfaces are parallel than whether two raised lines are parallel.

Although the threshold analysis showed differences between the perception of the two types of material, they both induce the haptic curvature contrast effect. The biases between the materials correlate strongly, which indicates that a similar mechanism underlies the contrast effect. Also the movement data are similar: the metacarpus follows an intermediate curved path for both materials. The different threshold values indicate that curvature is differently processed for raised lines and solid shapes and therefore the curvature representations may be different.

Fig. 4 a Example movement data. **b** Movement curvature plotted against the test stimulus curvature. The *black triangles* denote the index finger exploring the lateral stimulus, the *grey diamonds* denote the metacarpus movement, and the *light grey squares* denote the movement of the thumb along the test stimulus



The explanation should not depend on these different representations but should be based on mechanisms that are common to both types of stimuli. We hypothesise that the origin of the curvature contrast effect can be attributed to the intermediate path of the metacarpus. From a reference frame located at the hand, convex lateral and straight test stimuli explored together appear both convex. To correct for this and to encode the real curvature of the test stimulus, the path of the hand needs to be taken into account. It has been shown (Wijntjes et al. 2009) that curvature discrimination based on purely kinaesthetic input is about 2 m^{-1} , which is near the curvature of the metacarpus path.

This implies that the movement that needs to be taken into account is subliminal. A failure to correct for the hand movement may thus be responsible for the contrast effect reported in this paper.

As noted in the introduction, many haptic illusions have been investigated with raised lines, inspired by their visual counterparts (e.g. Suzuki and Arashida 1992). The research presented here followed that tradition but extended it to 3D stimuli. Research on raised line illusions can be interesting to reveal the role of visualisation, amodal processing or specific tactile mechanisms. Haptic illusions of 3D shape reveal which mechanisms

Table 1 Linear fit parameters of the curvature from different parts of the hand (and standard errors)

	c_r	Index finger	Thumb	Metacarpus
a_0	0	0.16 (0.02)	0.11 (0.04)	0.17 (0.07)
a_1	0	0.09 (0.02)	0.75 (0.04)	0.25 (0.06)
a_0	4	4.05 (0.03)	0.53 (0.03)	2.47 (0.07)
a_1	4	0.09 (0.03)	0.89 (0.03)	0.55 (0.06)
a_0	0	0.22 (0.02)	−0.16 (0.02)	0.24 (0.04)
a_1	0	0.17 (0.02)	0.97 (0.02)	0.59 (0.05)
a_0	4	3.80 (0.02)	0.21 (0.02)	2.41 (0.05)
a_1	4	0.12 (0.02)	1.00 (0.02)	0.62 (0.06)

The offset is denoted by a_0 and the slope by a_1 . Above data for the raised line stimuli. Below data for the solid shape stimuli. The offset (i.e. mean) curvature for the metacarpus in the curved lateral condition is indicated by the bold typeface, and reveals that the hand follows an intermediate path

underlie haptic perception of shape, such as force (Robles-De-La-Torre and Hayward 2001) and local orientation (Dostmohamed and Hayward 2005). The research presented here makes a connection between these two types of haptic illusions by reporting an illusion that holds for both raised lines and 3D shapes.

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