Published in final edited form as:

IEEE Trans Haptics. 2008 ; 1(1): 19–26. doi:10.1109/ToH.2008.4.

Factors Influencing Haptic Perception of Complex Shapes

Jonathan M. Ehrich, Martha Flanders, and John F. Soechting

J.M. Ehrich is with the Graduate Program in Neurobiology and Behavior, University of Washington, Seattle, WA 98195. E-mail: jonathan.ehrich@gmail.com. M. Flanders and J.F. Soechting are with the Department of Neuroscience, University of Minnesota, Minneapolis, MN 55455. E-mail: flan001@umn.edu, soech001@umn.edu

Abstract

Exploration of an object by arm movement and somatosensation is a serial process that relies on memories and expectations. The present experiments tested the hypothesis that this process involves breaking the object into component shapes (primitives). This was tested by having human subjects explore shapes composed of semicircular arcs, as well as quarter circles or quarter ellipses. The subjects' perception was reported using a visual display. In the first experiment, in which a series of semicircular arcs was presented, with offsets that differed from trial to trial, performance was consistent with the perception of two (left and right) semicircles. In the second experiment, subjects often failed to detect the quarter circles or quarter ellipses and again behaved as if the object was composed of two (top and bottom) semicircles. The results suggest that the synthesis of haptically sensed shapes is biased toward simple geometric objects and that it can be strongly influenced by expectations.

Index Terms

Haptic sensing; haptic distortions; primitives; visual illusions

1 Introduction

Haptic exploration of an unfamiliar object is an intriguingly sequential process. Sensory information is acquired serially in time and is stored in working memory to result in a percept of the overall object. This process induces distortions. For example, when one explores a series of connected segments, the length of a segment previously encountered modifies the perceived length of later segments and their intersecting angles; but the reverse is not the case [1]. It has been proposed that such an effect of serial exploration may contribute to the radial-tangential illusion, as the perceived sizes of the radial and tangential segments are almost equal only when the radial segment is explored first [2].

One possible aspect of such a process may be that complex shapes are perceived as constituted of simpler shapes (geometric primitives) such as straight edges or elliptical arcs. An analogous hypothesis, known as recognition by components, has been explored in visual imagery [3], [4].

In fact, humans are capable of haptically determining the features of postulated primitives with a high degree of accuracy. Indeed, experiments have demonstrated that subjects can discriminate between angles differing by as little as 4 degrees using whole arm movements,

and they have similar accuracy in discriminating the length of line segments [2], [5], [6]. Subjects also demonstrate impressive accuracy when asked to make absolute judgments in such parameters as line orientation [6], curvature [7], or the eccentricity of a circle [7], [8].

The results of a recent experiment suggested that subjects do rely on the use of primitives when reconstructing complex shapes that they have previously explored. We examined subjects' ability to reproduce shapes consisting of two smaller circles merged with a large ellipse [9]. After they had explored the shape haptically, they were asked to reproduce it by drawing it. The drawings captured some features of the explored shape very well. Specifically, the segments of the drawing representing the ellipse and the two circles could be well fit with elliptical arcs. However, subjects reproduced alterations to the eccentricity of the ellipse with much lower fidelity than changes in the size of the circles, and the results suggested that the subjects perceived the base as much closer to circular than it actually was. The decrement in performance may have resulted from subjects selectively focusing attention on the region of higher spatial contrast where the smaller circles intersected with the base, since they spent less time exploring the large ellipse. Furthermore, subjects consistently drew a short segment connecting the smaller circles as though it were an extension of the base. Taken together, these results suggest that subjects perceived the contours presented as a union of geometric shapes and that they were biased towards remembering them as a circle.

In the present experiment, we have endeavored to further characterize the extent to which subjects' perception of haptically explored shapes is subject to a distortion that results from a reliance on primitives such as circular arcs and/or from a bias towards symmetry. Subjects were presented with a series of shapes composed of semicircles, quarter circles, and quarter ellipses that they explored haptically and then reproduced visually. Along with possible offsets at the proximal end or at the equator, these shapes also featured offsets at the distal end that were not directly explored. Our hypothesis was that an offset at the proximal end would bias subjects to more accurately detect a distal offset, whereas continuity at the proximal end should bias subjects to reporting no offset. Although we also uncovered an influence of overall expectations that differed from experiment to experiment, our results are generally consistent with this hypothesis.

2 Methods

2.1 Experimental Overview

We performed two experiments in which subjects, with eyes closed, haptically explored the contours of various shapes by grasping the handle of a manipulandum (Interactive Motion Technologies) whose movement was limited to the horizontal plane. Then, with eyes open, they attempted to reproduce the sensed shape by using a mouse to adjust the positions of several anchor points on a visual display mounted vertically above the manipulandum, slightly above eye level, 60 cm from the eyes. The contours of shapes were generated by simulating an elastic restoring force field whenever the handle penetrated the virtual contour [6], [7]. This restoring force was perpendicular to the contour, with a stiffness of 20 N/cm. Viscous damping was added ($0.05 \text{ N/cm} \cdot \text{s}^{-1}$) to this restoring force for stability. Encoders on the shafts of the two torque motors controlling the manipulandum measured position and velocity at 16 bit resolution and a sampling rate of 200 Hz. We also performed three control experiments focused on visual discrimination.

Eighteen subjects participated in the experiments, with the number of subjects participating in a given experiment ranging from 5 to 11. Eleven of the subjects participated in multiple experiments. All but one of the subjects in the haptic experiments used the right hand to explore the contours. All subjects in haptic experiments performed at least five practice trials before commencing the experiment. Most subjects completed the experiment in a single session, with

time to completion ranging from 2 to 4 hours and they were encouraged to take breaks as necessary, usually every half hour to an hour. Control experiments were either four or eight sessions of 3–10 minutes each. All subjects gave informed consent to procedures approved by the Institutional Review Board of the University of Minnesota.

2.2 Haptic Experiments

In both experiments, the shapes consisted of circular or elliptic arcs (Fig. 1), which could be either continuous or separated by an offset. In Experiment 1, the offset (“blade”) could be present at the proximal end (Fig. 1a), whereas in Experiment 2, this blade could be present symmetrically at the equator ($\pm x$ -axis, Fig. 1b). In both experiments, there was also a variable offset at the distal pole. Subjects were prevented from directly comparing the distal offsets by a barrier along the y -axis, 1 cm in thickness, and progressing from the interior of the shape beyond the distal pole (dashed rectangles in Fig. 1). Subjects were instructed not to cross the barrier, which was present in every trial; otherwise, they were allowed to explore the shape using any strategy they wished.

If subjects based their report only on the shape experienced on that trial, our hypothesis for Experiment 1 was that the absence of a blade at the proximal end would bias subjects toward not detecting an offset at the distal end, i.e., they would perceive the shape to be a circle. However, if they generalized a set of rules based on their experience on previous trials, they should readily detect the distal offset whether or not a blade was present. In Experiment 2, they should be biased to report the shape as consisting of a proximal and a distal semicircle.

In both experiments, one half of the shape was a semicircle with a constant radius, at a consistent location. The radius of the other side of the shape was adjusted to generate the desired offset along the y -axis. The contour of each shape was defined by the polar angle and the distance from the center, in steps of 0.01 radians. The edges resulting from intersections were smoothed by digital filtering.

Each trial began when the subjects closed their eyes and verbally signaled that they were ready to begin exploration. The manipulandum would then guide the hand to the center of the next shape before signaling that the contours were activated. Subjects were given unlimited time to explore each shape, but on the average, each trial took 80 seconds in exploration, as well as reproduction. In the reproduction mode, the subject with eyes open reproduced the sensed shape by using a mouse to move a series of anchor points on the monitor, connected by elliptic arcs or straight lines (Fig. 2). At the beginning of each trial, a distorted shape was presented. This was achieved by deviating each of the anchor points randomly (with a uniform distribution spanning ± 2 cm) relative to their location on a circle 15 cm in radius. The initial and the final positions of these anchor points were recorded as a set of Cartesian coordinates. For purposes of analysis, the reproduced shape was scaled to match the area of the one that was explored haptically.

Haptic Experiment 1—Five subjects performed in the first haptic experiment. The proximal blade, when present, was 3 cm in length, directed in or out (Fig. 1a). The distal end of the shape could have offsets that ranged from -4.5 cm to 4.5 cm in steps of 1.5 cm. The contours were generated from the union of two semicircles, the left semicircle having a radius of 15 cm, and the one on the right side having a radius ranging from 11.25 cm to 18.75 cm. The proximal blade and the distal offset size could vary independently from each other. As such, there were a total of 21 shapes. Each shape was presented four times, in random order, for a total of 84 trials.

Haptic Experiment 2—Eleven subjects participated in the second haptic experiment, three of whom had previously participated in the first experiment. In the second experiment, equally

sized blades at the equator were oriented along the x -axis, while the offset remained at the distal pole, oriented along the y -axis (Fig. 1b). The blades were 3 cm in length, and the offset ranged from -4.5 cm to $+4.5$ cm in steps of 1.5 cm. These shapes were generated from the union of a semicircle with a radius of 15 cm (in the proximal half), a quarter circle (distal left quadrant), and a quarter ellipse (distal right quadrant). The radius of the quarter circle ranged from 12 cm to 18 cm, corresponding to the “Blade In,” “No Blade,” and “Blade Out” positions (Fig. 1b). The x -axis of the quarter ellipse always matched the radius of the quarter circle on the left side, producing equal blades on the left and the right and the y -axis of the quarter-ellipse ranged from 7.5 cm to 22.5 cm. The blade and the offset size could vary independently from each other, generating a total of 21 shapes. Each shape was presented four times in random order, for a total of 84 trials.

2.3 Control Experiments

In the haptic experiments, subjects used a visual display to indicate the haptically sensed shape. Two control experiments were conducted to ascertain the accuracy with which subjects could visually detect the offset between two arcs separated by a gap and thus to determine whether or not the display induced visual illusions [10], [11]. Subjects were visually presented with a series of shapes formed by the combination of two semicircles with an elliptical gap. Using a two-alternative forced choice procedure and an adaptive staircase [7], [12], we asked subjects to report which side of the gap protruded more. In this procedure, subjects were initially presented with an offset that was discriminated readily, and this offset decreased on subsequent trials until subjects reversed their response.

The gap could appear at one of two positions, with its center corresponding to a polar angle of either 0 degree (Fig. 3) or 230 degrees. The surface of the shape opposite the gap would either be smoothly circular or feature a blade in either the “blade in” or “blade out” direction, as in Fig. 1a. The gap was perpendicular to the surface of each semicircle and its location and the blade direction could vary independently, leading to six possible shapes.

Subjects were presented with one shape (presence or absence of blade and gap location) for each session. In each trial, the subject was asked to report which side of the elliptic gap stuck out further. On the subsequent trial, the radius of the semicircle on one side of the gap would be adjusted, using a 2-AFC adaptive staircase algorithm [7], decreasing if the subject responded that the radius on that side was larger and increasing if the subject responded that it was smaller. Two such staircases, one with a variable radius on each side of the gap, were randomly interwoven for 30 trials each. Each began with a radius of 480 pixels (11.0 cm) on one side and a radius of 320 pixels (7.32 cm) on the other side with an initial step size of 20 pixels (0.457 cm). In the first experiment, subjects were presented with the shape’s outline drawn in black (Fig. 3), and in the second, the shape was a solid black. There were seven to nine subjects in each experiment.

3 Results

3.1 Haptic Experiments

In the haptic exploration phase, subjects typically moved along the perimeter of the contour several times, although they occasionally crossed the interior of the shape, as in the example shown in Fig. 4.

Consequently, the number of times different portions of the shape’s perimeter were explored was nonuniform. This is illustrated in Fig. 5 for one subject that participated in both experiments. We computed the number of times each segment of the perimeter was traversed, in bins of 1 degree, and averaged the results for all trials, sorted according to whether the

proximal blade was absent (Figs. 5a and 5c) or whether it was present (Figs. 5b and 5d). Results for Experiment 1 are shown in the top row, and the results for Experiment 2 are shown below. This subject explored the distal offset more often than she explored other portions of the contour, especially in Experiment 1. The results illustrated in Fig. 5 are representative of the results for all subjects. In Experiment 1, points close to the distal barrier (i.e., at ± 2 degrees from the midline) were explored 88 percent more often than other locations (ANOVA, $F_{8,72} = 6.35$, $p < 0.001$). Specifically, we compared the number of sweeps at each of nine points separated by 45 degrees along the contour, after first normalizing the values with respect to the average number of sweeps for that subject. (The values were normalized because the average number of sweeps varied largely from subject to subject, ranging from 2 to 10.) In Experiment 2, the two points bracketing the distal pole were explored 30 percent more often than were other locations, but this difference did not reach statistical significance.

In the reproduction phase of the experiment, subjects used the computer mouse to adjust the locations of anchor points defining the visually presented contour. Fig. 6 presents the results from one representative trial in Experiment 2. Fig. 6a shows the explored shape, and Fig. 6b (dashed lines) shows the distorted shape, presented initially. The final shape, achieved after the subject had moved the anchor points, is indicated by the solid lines. Note that the subject did not adjust the locations of all seven anchor points; the distal one at the right and the one at the proximal pole remaining unchanged. This result was typical of the overall behavior. On the average, in Experiment 2, the two distal-most points were moved about 60 percent of the time, whereas the most proximal one was adjusted about 40 percent of the time. By contrast, the other points were adjusted on about 80 percent of the trials. In Experiment 1, the probability of moving each of the six anchor points (Fig. 2) was more evenly distributed, ranging from 0.7 to 0.8.

As we will show in the following, discontinuities (blades) at the proximal pole of the explored shape affected subjects' haptic sense of the offset at the distal pole. This bias was not introduced purely by the shape explored on that particular trial. Instead, it depended on the overall experimental context, i.e., on the types of shapes explored in prior trials.

In Experiment 1, where the proximal discontinuity was present on 2/3 of the trials (Fig. 1a), subjects were able to reproduce the offset's magnitude quite reliably (Fig. 7a). By contrast, in Experiment 2, where the discontinuities were at the equator (Fig. 1b), subjects were biased to report a continuous arc at the distal pole (Fig. 7b). Fig. 7 shows all of the results from one representative subject who participated in both experiments. In Experiment 1 (Fig. 7a), the slope of the regression of the reported offset on the actual offset was 0.895 ± 0.056 (SEM, $r^2 = 0.756$), and it was significantly smaller (0.223 ± 0.045 , $r^2 = 0.222$, and $p < 0.001$) in Experiment 2. For all subjects, the slope was 0.742 ± 0.029 ($r^2 = 0.603$) in Experiment 1, and it was substantially smaller (0.306 ± 0.014 , $r^2 = 0.349$) in Experiment 2. Both slopes were significantly different from 0, and the slope in Experiment 2 was significantly smaller than the slope in Experiment 1 ($p < 0.001$).

In neither experiment did the slope of the regression depend on the direction or the presence of the blade (Exp. 1 : $F_{12,399} = 1.2$, $p = 0.27$, Experiment 2 : $F_{12,897} = 0.31$, $p = 0.99$). However, as illustrated in Fig. 8a, in Experiment 1, the intercept of the regression did depend on the blade direction ($F_{2,399} = 15.13$, $p < 0.001$). When the proximal blade was directed outwards, the offset was shifted in the positive y direction by 1.2 cm compared to when it was directed inwards. This indicates a perceived expansion of the right semicircle in cases where the proximal blade was directed outwards (see, for example, Fig. 1a).

Occasionally, in Experiment 1, subjects produced large errors in the reported blade size, defined as trials in which subjects drew a blade of the wrong type such as drawing a blade directed

inwards when presented with a blade directed outwards. These errors correlated significantly with errors in reporting the offset at the top of the shape: subjects tended to reverse the direction of the offset as well (Fig. 8b). This result suggests the shape was remembered with respect to a cardinal anteroposterior (distalproximal, y) axis, since this error is consistent with a left-right reversal of the sensed shape, or a translation of the right half of the shape relative to the left half.

In Experiment 2, the decrease in the slope of the relation between the reported and the actual offset at the distal pole (Fig. 7b) could be due to two effects: 1) subjects detected an offset, but one of the much smaller size than in Experiment 1, and 2) the subjects' probability of detecting an offset was decreased substantially. The distribution of results from individual trials supports both interpretations (Fig. 9). Fig. 9a shows the distribution in reported offsets from all subjects when the actual offset was -4.5 cm. In Experiment 1, subjects reproduced the offset in a roughly unimodal fashion, centered around a peak of -3.0 cm (top panels). By contrast, in Experiment 2, there was a large peak at 0 cm, as well as another at -1.5 cm. When results from all seven offsets are combined (Fig. 9b), for Experiment 1, the distribution of reported offsets is essentially flat over the interval ± 3 cm, a result to be expected since the actual offsets were distributed with equal probability (14.3 percent). This was confirmed using the Kolmogorov-Smirnov test for a uniform distribution over the interval $[-4.0, 4.0]$ ($p = 0.077$). On the contrary, the results for Experiment 2 show a large peak at 0 cm, superimposed on a flat distribution over a shorter interval (± 2.5 cm). Using the K-S test, the hypothesis of a uniform distribution could be rejected ($p < 0.001$). If we define drawn shapes having offsets between -0.5 and 0.5 cm as trials in which no offset was perceived, in Experiment 1, 11.7 percent of the trials fell into this category (compared to an expected value of 14.3 percent). By contrast, in Experiment 2, almost half (47.4 percent) of the trials fell into this category (bottom panels).

The results of the analysis presented in Fig. 10 confirm the conclusion that the threshold for detecting an offset at the distal pole was elevated in Experiment 2. In this analysis, we computed the probability that the subject would report (by means of the drawing) that the right side of the gap was higher than the left side, as a function of the actual offset of the shape. We fitted the pooled data from all subjects with the logistic distribution function (Matlab), and we defined the threshold for detection to be $1/2$ the difference threshold, the difference between the offsets at which subjects responded with a probability of 25 percent and 75 percent. The difference thresholds for Experiment 1 (1.35) and 2 (3.6) were significantly different; with 95 percent confidence intervals of $[0.94, 1.96]$ and $[2.96, 4.67]$, respectively. In both experiments, the bias was less than 1 cm (-0.5 cm in Exp. 1 and 0.8 cm in Experiment 2).

In contrast to the offset at the distal pole, subjects were able to reproduce the other features of the shapes with equal fidelity or better fidelity in Experiment 2 compared to Experiment 1. For example, in Experiment 1, the slope between the actual and the reproduced blade size was 0.621 ($r^2 = 0.654$). In Experiment 2, subjects actually performed better, with a slope of 0.720 ($r^2 = 0.769$). An ANOVA on the size of the drawn blade (factors: experiment and blade size) gave a significant interaction ($F_{2,1332} = 7.5$, $p < 0.001$) but no main effect of experiment ($p = 0.12$). Other parameters (such as the radii of the right side of the shape in Experiment 1 and the radii of the distal half of the shape in Experiment 2) were also well reproduced, with slopes greater than 0.6 (compared to a slope of 0.31 for the distal offset in Experiment 2), the coefficients of determination exceeding 0.5 . Thus, the decrement in the performance in the second experiment with respect to the first was restricted to discriminating the presence of an offset at the distal pole.

3.2 Control Experiments

In the haptic experiments, subjects had to adjust the shape of the visual display to match the perceived shape, and in the analysis, we assumed that the visually generated shape was a

veridical match to the one that was perceived, i.e., that no visual illusions were present [10], [13], [14]. We also assumed that inaccuracies in judging offsets visually were minimal. The control experiments, in which we asked subjects to visually discriminate the offsets of arcs separated by a gap (Fig. 3) tested these assumptions.

Overall, subjects demonstrated a remarkably high visual accuracy, often discriminating the two points composing the offset within a single pixel (0.02 cm). Furthermore, the presence of a discontinuity (blade) did not introduce any bias into the subjects' responses in either of the two control experiments. Subjects in the first control experiment (in which the shape was presented in the outline) consistently demonstrated a bias (representing the 50 percent point of the psychometric function) of less than a single pixel (0.02 cm) and difference thresholds (see Fig. 10 for a definition) within 1–2 pixels (0.02–0.05 cm). One of the worst performances from this experiment is shown in Fig. 11, from a shape featuring the offset at the 230 degrees position and no blade. Overall, there was no effect of the position of the offset location (0 degree or 230 degrees), nor did the presence or direction of the blade affect the performance ($p > 0.05$).

The second control experiment (in which the contour was filled) gave similar results, the bias being less than a single pixel for all shapes. However, subjects were somewhat less accurate when the offset was presented at 230 degrees than when it was at 0 degree, the 95 percent confidence intervals of the difference thresholds in the latter case being 0.5–1.2 pixels and those for the 230 degrees position, spanning 2.3–8.1 pixels.

4 Summary and Conclusions

The experiments described here were designed to test the hypothesis that subjects perceive complex shapes that they have explored haptically as being constituted of simpler elements (primitives) such as circles or elliptical arcs. Such a representation would also lead to a bias towards a perception of shapes exhibiting an axis of symmetry. To test this hypothesis, we used shapes in which one half was semicircular, while the other half could have a discontinuity that subjects were prevented from exploring directly by the presence of a barrier. In Experiment 1 (Fig. 1a), we hypothesized that subjects would be less likely to detect a discontinuity at the distal pole if the proximal pole were continuous, i.e., that they would be biased to perceive a circular shape. In the strong form of the hypothesis, this bias should depend only on the shape explored on that particular trial. However, it is also possible that subjects generalize a set of rules based on their experiences on previous trials. If so, the presence or absence of a blade on a particular trial should not bias their perception of the distal offset.

The results of Experiment 1 were not in accord with the strong form of the hypothesis, since the presence or absence of the proximal discontinuity (blade) did not affect their ability to detect the discontinuity at the distal pole. However, in Experiment 2, where the proximal half of the shape was always a semicircle (Fig. 1b), subjects were significantly impaired in detecting the distal discontinuity (Fig. 7). They did not merely underestimate its size, rather, in a large number of trials, they failed to detect it (Figs. 9 and 10). Thus, in Experiment 2, subjects were biased to perceive the shape as being composed of two circular or elliptical arcs, one constituting the proximal semicircle and other constituting the distal half.

The results of both experiments suggest that the biases reflect not only the experience on the present trial but also the experience of previous trials. Specifically, a blade was present in the first experiment in 2/3 of the trials and presumably subjects generalized their experience on successive trials to expect shapes composed of two arcs joined at the proximal and distal ends by (potential) discontinuities. Since we presented the shapes in a randomized order and since there was considerable variability in the subjects' responses on individual trials, we cannot characterize the time course over which such expectations evolved.

Importantly, subjects were equally accurate in discriminating all other aspects of the shapes (such as the presence and direction of the blades) in both experiments, with levels of performance comparable to those found previously when we asked subjects to synthesize complex shapes explored haptically [1], [9]. This indicates that the present results cannot be attributed to inhomogeneities in the subject pool or to the possibility that subjects were less attentive in the second experiment. Furthermore, the control experiments demonstrated that subjects could visually discriminate discontinuities without a bias and with much higher acuity than was found in the haptic experiments. Thus, our results are not contaminated by any visual illusions in the reproduction phase of the experiment.

In summary, our results suggest that the perception of haptically sensed shapes is biased to a representation of simple geometric objects and towards shapes exhibiting symmetry. They also suggest that perception can be influenced strongly by expectations.

Acknowledgements

This work was supported by NIH Grant NS-15018. Martha Flanders was partially supported by an IPA grant from the US National Science Foundation.

Biographies

Jonathan M. Ehrich received the BS degree from the University of Minnesota in 2006. He is currently in the graduate program in neurobiology and behavior of the University of Washington.

Martha Flanders received the BS and PhD degrees from the Michigan State University in 1980 and 1984. She is currently a professor in the Department of Neuroscience, University of Minnesota.

John F. Soechting received the BS degree from Lehigh University in 1965 and the PhD degree from Cornell University in 1969. He is currently a professor in the Department of Neuroscience, University of Minnesota.

References

1. Henriques DY, Flanders M, Soechting JF. Haptic Synthesis of Shapes and Sequences. *J Neurophysiology* 2004;91:1808–1821.
2. McFarland J, Soechting JF. Factors Influencing the Radial-Tangential Illusion in Haptic Perception. *Experimental Brain Research* 2007;178:216–227.
3. Biederman I. Recognition-by-Components: A Theory of Human Image Understanding. *Psychological Rev* 1987;94:115–147.
4. Riesenhuber M, Poggio T. Models of Object Recognition. *Nature Neuroscience* 2000;3:1199–1204.
5. Voisin J, Benoit G, Chapman CE. Haptic Discrimination of Object Shape in Humans: Two-Dimensional Angle Discrimination. *Experimental Brain Research* 2002;145:239–250.
6. Fasse ED, Hogan N, Kay BA, Mussa-Ivaldi FA. Haptic Interaction with Virtual Objects. *Biological Cybernetics* 2000;82:69–83. [PubMed: 10650909]
7. Henriques DY, Soechting JF. Bias and Sensitivity in the Haptic Perception of Geometry. *Experimental Brain Research* 2003;150:95–108.
8. Soechting JF, Poizner H. The Use of Motion Cues in the Haptic Sense of Circularity. *Experimental Brain Research* 2005;165:413–421.
9. Soechting JF, Song W, Flanders M. Haptic Feature Extraction. *Cerebral Cortex* 2006;16:1168–1180. [PubMed: 16221922]
10. Gentaz E, Hatwell Y. Geometrical Haptic Illusions: The Role of Exploration in the Müller-Lyer, Vertical-Horizontal, and Delboeuf Illusions. *Psychonomic Bull Rev* 2004;11:31–40.

11. Henriques DY, Flanders M. Distortions in the Visual Perception of Shape. *Experimental Brain Research* 2005;160:384–393.
12. Treutwein B. Adaptive Psychophysical Procedures. *Vision Research* 1996;35:2503–2522. [PubMed: 8594817]
13. Suzuki K, Arashida R. Geometrical Haptic Illusions Revisited: Haptic Illusions Compared with Visual Illusions. *Perception and Psychophysics* 1992;52:329–335. [PubMed: 1408643]
14. Spivey-Knowlton MJ, Bridgeman B. Spatial Context Affects the Poggendorff Illusion. *Perception and Psychophysics* 1993;53:467–474. [PubMed: 8332415]

Fig. 1. Characteristics of haptically explored shapes in (a) Experiment 1 and (b) Experiment 2. A discontinuity was present in 2/3 of the trials in each experiment. In Experiment 1, the discontinuity (blade) was at the proximal pole, whereas in Experiment 2, discontinuities were present along the equator. In both experiments, there was also an offset at the distal pole (ranging over ± 4.5 cm) that subjects were prevented from exploring directly by the presence of a barrier, which was present in all instances but is shown for clarity only in the top row.

Fig. 2.

Characteristics of the visual display subjects used to report the sensed shape in Experiment 1. Subjects could adjust the location of anchor points, denoted by arrows. In Experiment 2, there was only one anchor point at the proximal pole, but there were two anchor points at each end of the equator. These could be adjusted in x and in y .

Fig. 3.

Visual shapes presented in control experiments. Subjects reported which side of the elliptical indentation protruded more. In all experiments, a discontinuity (indicated by dashed lines) could be present opposite to the elliptical indentation.

Fig. 4.

Exploratory movements for one trial in Experiment 2. Note that the subject generally followed the contour of the object without crossing the barrier at the distal pole.

Fig. 5.

The thickness of the shaded area denotes the number of times each portion of the shape's perimeter was explored in (a) Experiment 1 and in (b) Experiment 2. Results are presented separately for trials in which no blade was present (right column) and when there was a blade (left column). The reference shape (inner trace) is drawn for only one condition (zero offset at the distal pole and blade out), but the data include all of the results from one subject.

Fig. 6. Reproduction phase for one trial in Experiment 2. (a) shows the shape that was explored. (b) shows the distorted visual shape presented initially to the subject (dashed lines). The shape as drawn by the subject is shown by the solid lines in (b).

Fig. 7. Variations in the reported offset at the distal pole as a function of the offset of the explored shape. Results are from the same subject in both experiments. The straight lines represent the results of a linear regression on the data. Note the markedly shallower slope and the greater variability in Experiment 2.

(a)

(b)

Fig. 8.

(a) Effect of blade direction on the reported offset in Experiment 1. The values denote the average ($\pm$ SD) intercept of the regression of the reported offset on the actual offset using data from all subjects. (b) Inverse relationship between the errors in reported offset and reported blade size in trials where subjects reversed the direction of the blade in Experiment 1.

Fig. 9. Probability distributions of the reported offsets at the distal pole (a) when the actual offset was -4.5 cm and (b) for all offsets. Data are for all subjects and Experiment 1 (top panels) and Experiment 2 (bottom panels).

Fig. 10.

Increase in the threshold of detection of offset in (b) Experiment 2 compared to (a) Experiment 1. The solid curve is the best fitting logistic function, and the dashed traces denote the 95 percent confidence limits on the slope of the logistic function.

Fig. 11.

Results from one series in a forced-choice discrimination task in the control experiment. The subject had to report which side of the elliptical indentation protruded more. There were two staircases, one ascending from a negative offset and the other descending from a positive offset. The two staircases were interleaved randomly.