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Haptic Synthesis of Shapes and Sequences

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Henriques, Denise Y. P., Martha Flanders, and John F. Soechting. Haptic synthesis of shapes and sequences. *J Neurophysiol* 91: 1808–1821, 2004. First published November 26, 2003; 10.1152/jn.00998.2003. Haptic perception of shape is based on kinesthetic and tactile information synthesized across space and time. We studied this process by having subjects move along the edges of multisided shapes and then remember and reproduce the shapes. With eyes closed, subjects moved a robot manipulandum whose force field was programmed to simulate a quadrilateral boundary in a horizontal plane. When subjects then reproduced the quadrilateral using the same manipulandum, with eyes still closed but now with the force field set to zero, they made consistent errors, overestimating the lengths of short segments and underestimating long ones, as well as overestimating acute angles and underestimating obtuse ones. Consequently their reproductions were more regular than the shapes they had experienced. When subjects felt the same quadrilaterals with the same manipulandum but drew them on a vertical screen with visual feedback, they made similar errors, indicating that their distortions reflected mainly perceptual rather than motor processes. In a third experiment, subjects explored the 3 sides of an open shape in a fixed order. The results revealed a temporal pattern of interactions, where the lengths and angles of previously explored segments influenced the drawing of later segments. In all tasks, our subjects were as accurate as subjects in earlier studies who haptically explored only single lines or angles, suggesting that the mental processes that synthesize haptic data from multiple segments into complete shapes do not introduce any net error.

INTRODUCTION

Haptic cues, derived by means of exploratory movements, can supply a great deal of information regarding the shapes of objects. These cues result from the integration of multiple signals, such as tactile, proprioceptive, and probably efference copy, across space and time. Unless an object is small enough that we can mold our hands around it, we cannot sense its shape from simultaneously available information. Instead, we scan its surface to collect a stream of haptic data, which are then combined to reconstruct the object's shape. The present study examines how well people can synthesize haptic information about a complex object based on the arm motions they have made in tracing its contours.

In most studies of haptic shape perception, subjects verbally estimate, or match, or discriminate between haptically sensed objects, or between haptically and visually sensed objects. These tasks usually test the subject's perception of just one aspect of object geometry, such as the length or the orientation of a line (e.g., Appelle and Gravetter 1985; Appelle et al. 1980; Armstrong and Marks 1999; Deregowski and Ellis 1972; Fasse et al. 2000; Gentaz et al. 2001; Hermens and Gielen 2003; Hogan et al. 1990; Kappers and Koenderink 1999; Klatzky and Lederman 2003; Newport et al. 2002). Thus it remains to be determined how the overall shape of an object, such as a quadrilateral, is synthesized from its basic elements: the length and orientation of individual segments and inner angles between segments.

Previous studies have shown that subjects systematically misestimate the length, inner angle, and orientation of felt edges (Appelle and Gravetter 1985; Armstrong and Marks 1999; Bingham et al. 2000; Gentaz et al. 2001; Kappers and Koenderink 1999; Lakatos and Marks 1998; Lederman et al. 1985, 1987; Newport et al. 2002). Furthermore, these distortions are not always geometrically consistent (Fasse et al. 2000; Klatzky 1999; Klatzky and Lederman 2003). For example, subjects moving in a horizontal plane tend to report that a given edge in a frontal plane is shorter than the same edge aligned with the sagittal plane (e.g., Fasse et al. 2000; Hogan et al. 1990). However, the same subjects do not, as a result, judge the hypotenuse of the resulting triangle to be tilted <45° relative to the sagittal plane. This finding shows that our perceptions of these spatial relations are not necessarily consistent.

The spatial relations of the segments of a quadrilateral are constrained by the laws of geometry, so that different aspects, such as segment lengths and angles, are interdependent. In the case of a closed quadrilateral, for instance, the length and orientation of one side are determined by the lengths and angles of the other 3 sides. It is possible that the aforementioned inconsistencies (e.g., Fasse et al. 2000) arise only when subjects are asked to judge just one aspect of object geometry at a time. How such incongruities are resolved in forming a percept of a closed object such as a quadrilateral is still an open question.

To address this issue, we asked subjects to trace the outline of quadrilaterals and then to reproduce the sensed shape from memory. We found that, in solving this task, subjects did not explore the sides of the quadrilateral in any fixed or consistent order. Thus to examine the effect of serial order on haptic sensation, in the last experiment we asked subjects to trace and reproduce the outlines of a series of 3 connected segments in a fixed serial order.

METHODS

Overview

We conducted 3 experiments. In the first experiment, subjects felt along the edges of various quadrilaterals with their eyes closed. They then reproduced the sensed shape by means of a freehand drawing, also with the eyes closed. If subjects performed this task perfectly, the

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arm movements for tracing and reproducing the shape would be identical.

To ascertain the extent to which performance was influenced by motor memory or by a cognitively formed percept of the object's shape, we conducted a second experiment. Subjects again traced an outline in the horizontal plane. They then reproduced the shape in the vertical plane. This way, the arm movements during contour tracing differed from those for drawing the reproduction.

In the first 2 experiments we placed no constraints on the manner in which subjects traced the shape. In contrast, the third experiment tested for serial effects, that is, how the length and orientation of one segment affected the perception of subsequent segments. Thus the subjects felt and reproduced a series of 3 segments in a fixed serial order.

Subjects

A total of 10 human subjects (6 males, 4 females, ages 16–59), with no history of sensory, perceptual, or motor disorders, participated in 3 different experiments. Three subjects, 2 of whom were left-handed, performed in all 3 experiments. The other 7 subjects were right-handed; 4 of them participated in 2 of the 3 experiments. Thus there were 6 subjects in each of the first 2 experiments and 8 in the last one. All subjects gave informed consent, and all procedures were approved by the Institutional Review Board of the University of Minnesota.

Apparatus

We tested how well subjects integrated haptic information about their hand path by measuring how accurately they could reproduce the felt shape of simulated objects. Using a 2-jointed robot arm (constrained to move in the horizontal plane) with a programmable force field (Interactive Motion Technologies), we simulated 3- or 4-sided shapes. Subjects sat facing the workspace and grasped the vertical handle of the robot arm with their dominant hand, so that their hand remained inside a restricted horizontal planar region, just above waist level. In the first 2 experiments, the 4 intersecting boundaries simulated a quadrilateral, whose sides ranged in length from 4 to 21 cm. At the boundary, subjects felt the resistance of the manipulandum as if they were hitting a straight wall. The resistance was generated by a force perpendicular to the edge and proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous damping of 5 N mm^{-1} s^{-1}. No force was exerted when subjects were inside the boundaries of the quadrilateral. Encoders on the shafts of the 2 torque motors measured position and velocity, which were sampled at 100 Hz. This information was used to generate the resistive forces.

In the second experiment, finger movement was recorded, with a spatial resolution of 0.3 mm, on a 21-in. touch-sensitive screen (Elo Entuitive 2125C Touchmonitor). The position of the finger was recorded at 50 Hz, using a custom-written program (LabVIEW, National Instruments). The entire finger path was displayed on the monitor until the subject ended the trial.

Experiment I: manipulandum reproductions of closed shapes

In the first experiment, 6 subjects were asked to close their eyes and trace, by moving a 2-joint robot manipulandum, the outline of one of 5 simulated quadrilaterals in the horizontal plane. After gripping and moving the manipulandum handle along the robotically generated boundaries of the quadrilateral, subjects then reproduced its outline, again moving the manipulandum, but now with the force field set to zero. In both parts of the experiment, tracing and reproduction, the manipulandum was constrained to move in the same horizontal plane.

Each quadrilateral was presented in 6 orientations: rotated 0, 60, 120, 180, 240, or 300° from its "home" orientation, for a total of 30 simulated objects. Figure 1 shows this home orientation for all 5 quadrilaterals (*left column*), plus the other 5 rotated forms for one quadrilateral (*right column*). The quadrilaterals' parameters were chosen to test subjects on a wide range of line lengths and angles. The perimeters of the 5 quadrilaterals ranged from 45 to 59 cm (see Fig. 5, *left*). Individual lines ranged in length from 4.3 to 21.2 cm, with an average length of 13.5 ± 5.2 cm (mean ± SD). Each quadrilateral fit within a workspace of about 30 × 30 cm and was centered at a point (the centerpoint) 30 cm in front of the subject in the midsagittal plane.

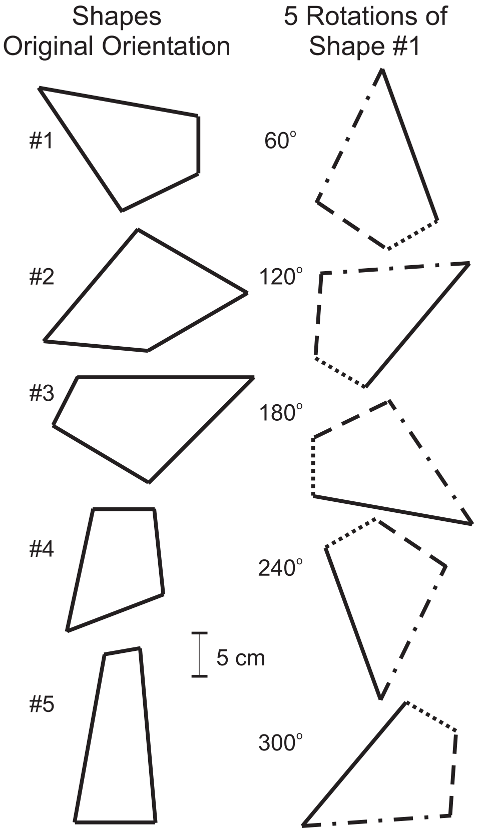

FIG. 1. Five quadrilaterals that subjects traced in Experiments I and II (*left column*). Five other rotated positions of one of the shapes (*right column*). For clarity, the individual segments of the shape are marked by different line styles. To produce these haptic boundaries, the robot exerted resistive forces perpendicular to the 4 sides.

The 30 objects were presented 5 times each in random order, for a total of 150 trials. Each trial began with the manipulandum moving the subject's hand to the centerpoint, where it stayed until the subject pressed a button with the other hand to initiate the trial. On this key press, the force field was set to zero as long as the subject remained within the contours of the quadrilateral, but the subject encountered a viscoelastic resisting force at the edges. With their eyes closed, subjects moved toward and then along the 4 boundaries to trace the contours of the simulated shape. Each subject traced these boundaries in the order he/she found most useful in ascertaining the contours. Typically, subjects moved the manipulandum at a comfortable speed of about one circuit round the perimeter every 2 s. Subjects felt along these simulated contours for as long as they needed and were free to use any strategy to determine the quadrilateral's shape.

Once subjects decided they had an adequate sense of the shape, they again pressed a button, at which point the robot guided the arm to the center of the polygon. After pressing the button again, subjects then reproduced the outline of the shape using the same robot manipulandum, but now with the force field turned off. They were asked to reproduce the entire shape at least once, but preferably twice with their eyes closed. Subjects for the most part drew the shape twice, but when a third drawing was performed it was also included in the data analysis. Because the experiment was mentally fatiguing, subjects typically completed the experiment in 3 to 5 separate sessions.

Experiment II: touch-screen reproductions of closed shapes

In the second experiment, we had 6 subjects trace the same 30 robot-simulated quadrilaterals, but reproduce them by drawing the sensed shape on a vertical touch screen with their eyes open and with on-line visual feedback. The touch-screen monitor was placed to the subjects' right at a close distance so that they needed only to rotate their trunk about 90° to face the monitor (45 cm away) and reproduce the traced quadrilateral. Subjects were asked to confine their drawings to a rectangular area (33 × 24 cm) on the screen. In the center of this area was a red dot that subjects had to touch (so that it disappeared) before beginning to draw the shape. They were told that the red dot corresponded to the center of the shape. As the finger moved along the screen, a persistent white line was generated to mark its path. After drawing the entire shape, subjects had the option to reject the drawing if it did not match their mental image of the quadrilateral; they could either redraw it again immediately or repeat the trial later. Drawing on the touch screen prevented the subjects from relying on remembered arm postures.

Of the 6 subjects who participated in Experiment II, 4 had also participated in the first experiment. Although the same 30 robot-simulated shapes were used in the 2 experiments, Experiment II was conducted 4 mo after Experiment I. Subjects were not given feedback regarding their performance in Experiment I nor were they exposed to the shapes (visually or haptically) outside of the experimental sessions, until after Experiment II was completed. Thus it is unlikely that the performance of the 4 subjects who took part in both experiments was influenced by their participation in Experiment I.

Experiment III: manipulandum reproductions of serially connected segments

To examine how the sequence of haptic exploration influenced motor recall, we presented subjects in Experiment III with simpler, open shapes, that were formed out of 3 consecutive straight edges. Consequently, the end of the third boundary did not connect with the start of the first one (Fig. 2). Eight subjects traced what they knew would be an open contour, with eyes closed, and then reproduced its outline with the manipulandum. The serial order of the movement was strictly controlled. Subjects moved along the robot-simulated contours such that as they traced the second line, they pressed in the direction of their body.

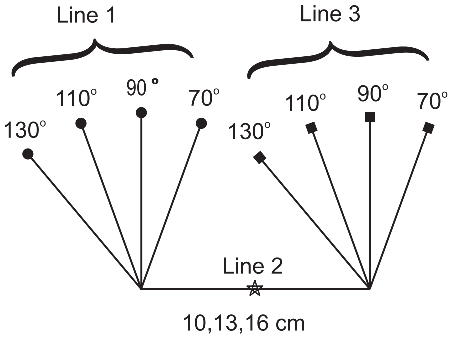

FIG. 2. Three-sided open shapes traced by subjects in Experiment III. On the *left* are the 4 orientations of the first segment (line 1), followed by the second segment (line 2) which varied only in length (10, 13, and 16 cm), and then by the 4 orientations of the third segment (line 3). Lines 1 and 3 were always 10 cm long. Circles and squares mark the start and endpoints for tracing the shapes. Right-handed subjects traced the shape in this left-to-right direction. For left-handed subjects, the shape was flipped so that they drew from right to left. All 48 shapes were centered so that the midpoint of the second segment was located at the star.

For these contours, the robot moved the subject's hand to the beginning point (circles in Fig. 2) of the first edge (line 1). Subjects then pressed a button to initiate the trial, and they traced the 3 straight edges as simulated by the manipulandum. A beep signaled to the subject when his/her hand neared the end of the traced contour (squares at line 3). After subjects completed the trace, they again hit the button, which turned off the force field. They then moved the robot handle to where they thought the 3-sided open shape began and drew the contour once, pressing a button at both the beginning and the end of this reproduction.

On each trial, we varied the orientation of the first and third lines and the length of the second line (Fig. 2). The first edge (line 1) and the third edge (line 3) were 10 cm in length and oriented either 70, 90, 110, or 130° relative to line 2, which was always oriented sideways. Line 2 varied in length between 10, 13, and 16 cm. Subjects traced and reproduced 48 (4 × 4 × 3) combinations of these 3-sided open shapes in random order 5 times each for a total of 240 trials.

In this experiment, lines 1 through 3 were traced and reproduced from left-to-right for right-handed subjects and from right-to-left for the 2 left-handed subjects. The shapes presented to the left-handers were mirrored reflections of the shapes felt and drawn by the right-handers. Shapes were positioned so that the midpoint of line 2 was always 25 cm in front and aligned with the subjects' midline. Because performance did not qualitatively vary with handedness, during the analysis we flipped the data about this midpoint for left-handed subjects, so that the traced and drawn lines were aligned with those of the right-handed subjects.

Each of the 3 experiments took about 3 h to complete, and was divided into several sessions across 1 or 2 days to prevent fatigue and boredom. Subjects generally took a minute to complete each trial in Experiment I, and slightly less for each trial in Experiment II. In Experiment III, subjects were restricted to tracing and reproducing the 3-sided shape only once, and trials generally lasted <30 s. Before each experiment, subjects practiced on 2 or 3 random trials to ensure that they understood the protocol. Subjects who were not familiar with robot-generated boundaries traced a 15-cm square with the manipulandum before they began the experiment.

Analysis

We measured errors in the location, length, and orientation of the lines, and the relative angles between the lines drawn by the subjects. Subjects drew the shapes using fairly straight lines: hand paths in Experiments I and III were only 1.4% (±1.2, SD) longer than a line directly connecting the start and endpoints of the trajectory; touch-screen hand paths in Experiment II were 2.7% (±2.0, SD) longer than straight lines. Consequently, we fitted each drawn segment with a straight line to obtain a measure of the reproduced line's orientation and length. We then compared the extent to which the orientation, length, and inner angles of these reproduced lines differed from those of the traced lines. We conducted additional statistical tests (between-subjects ANOVA and *t*-test) to check whether these systematic errors varied with the orientation, length, and inner angle of the traced lines of the simulated shapes.

To check whether the mode of reproduction, the shapes, and their rotations exerted any interactive effects on length errors, orientation errors, and inner angle errors, we conducted a 4-way ANOVA (including subjects as one of the independent factors) for each error type. We also computed correlations between errors made by individual subjects and the average errors for each of 3 experiments to determine the extent of intersubject variability (Table 1).

In Experiments I and II, after measuring inaccuracies in the location and the size of the reproduced shapes, we corrected for these errors by centering these drawings and by scaling each segment equally so that the length of its perimeter equaled that of the traced shape. After centering and scaling the reproductions, we decomposed the remaining error into 2 components: one that depended on the type of shape

TABLE 1. *Correlations between subject's errors and average errors in line length, line orientation, and inner angles for the three experiments*

Correlation	Subject	Line Length Errors	Line Orientation Errors	Inner Angle Errors
Experiment I: Manipulandum reproduction errors	R1	0.518	0.772	0.450
	R2	0.467	0.473	0.487
	R3	0.564	0.686	0.400
	R4	0.580	0.655	0.514
	L1	0.430	0.665	0.464
	L2	0.628	0.464	0.443
	Mean	0.531	0.619	0.460
Experiment II: Touch screen reproduction errors	R3	0.525	0.555	0.671
	R4	0.559	0.608	0.728
	R5	0.737	0.715	0.769
	R6	0.530	0.458	0.569
	L1	0.391	0.695	0.724
	L2	0.533	0.347	0.491
	Mean	0.546	0.563	0.659
Experiment III: Manipulandum reproduction errors	R1	0.560	0.341	
	R3	0.625	0.272	
	R5	0.821	0.368	
	R6	0.818	0.457	
	R7	0.794	0.568	
	R8	0.725	0.472	
	L1	0.865	0.592	
	L2	0.845	0.469	
	Mean	0.757	0.442	

Right-handed subjects are identified with R, and left-handed subjects with L.

and one that depended on the orientation of the shape. We computed the shape-dependent errors by calculating the average length of each segment and the average internal angle over all 6 rotations. We then computed the orientation-dependent errors by subtracting the shape-dependent error.

In Experiment III we measured the influence of the parameters of each sequentially traced segment on the errors in producing the prior and subsequent segments.

RESULTS

Experiments I and II: drawing closed shapes

Subjects used various tracing strategies when following the contours of robot-simulated quadrilaterals in Experiments I and II. Subjects received no instructions other than to move along the contours. They usually traced the perimeter of the quadrilateral several times; some traced the outline following a clockwise (CW) path, whereas others proceeded in a counterclockwise (CCW) direction and some alternated between the 2. Most subjects moved the handle back and forth along one or 2 segments at a time, presumably to arrive at a better estimate of a line's length or the inner angle between 2 segments.

On any one trial, subjects usually reproduced the felt shape twice. For one orientation of shapes #2 (*top panel*) and #3 (*bottom panel*), Fig. 3 shows the first drawing of one subject for all 5 trials using the manipulandum (*left panels*) and the touch screen (*right panels*). The dashed lines indicate the veridical quadrilateral that the subjects had traced. Although the subject drew the shape using the manipulandum with his eyes closed, he came close to drawing a closed figure. Endpoints of manipulandum drawings tended, on average (across subjects), to miss joining up by only 3.8% of the total length of the perimeter. This subject's drawings were also mildly distorted in overall size and shape, and these distortions were consistent across trials. Likewise for all subjects, examining the effect of practice, we found that the errors did not change as the experiment progressed.

Like most of the subjects reproducing shapes with the manipulandum, this individual tended to draw the quadrilateral larger than the traced shape, especially along its width (sideways dimension). When the subject could see the outline as he drew it on the vertical touch screen, he also made errors in size and shape that were consistent across trials. Touch-screen drawings were smaller, and not so proportionally wide.

The distortions in the reproductions were consistent across subjects. The correlations of the errors made by each of the subjects with the overall average are reported in Table 1. All were positive and statistically significant, with a mean value of 0.572. Accordingly, in the following, we combined the results for all subjects in analyzing these errors, concentrating our analysis on the errors in reproducing the length and orientation of each of the line segments, and on the angles between adjacent segments.

LOCATION ERRORS. As illustrated by the results in Fig. 3, subjects did not always center their reproduction in the same location as the traced shape (open circles), which was constant for all shapes. Each individual subject had a consistent bias across shapes. This is shown in Fig. 4 by the ellipses (marking 95% confidence intervals) fitted to the centers of the reproduced shapes for each subject for both experiments. For manipulandum drawings, the right-handed subjects tended to draw the shape more to the left and away from themselves (front), whereas the 2 left-handed subjects (L1 and L2) drew them closer to the body. For drawings made on the touch screen, the origin of the plot represents the midpoint of the drawing area where subjects were asked to center their reproduced shapes. Given this visual cue, subjects were able to center their drawings more accurately. Handedness had no effect on the centering of these touch screen drawings, nor did it influence performance on other measured parameters for the 2 experiments.

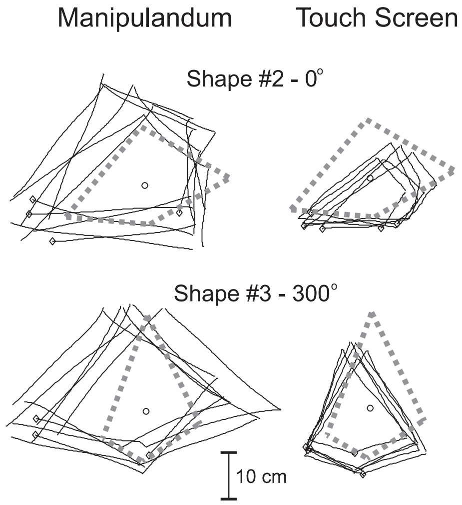

FIG. 3. Five drawings for 2 quadrilaterals made with the manipulandum (*left*) and on the touch screen (*right*) for Experiments I and II. Solid lines: reproduced hand paths for the first iteration from each of the 5 trials. Dashed lines: veridical shapes. A diamond marks the start of each trial. Circles mark the centroids of the veridical shapes.

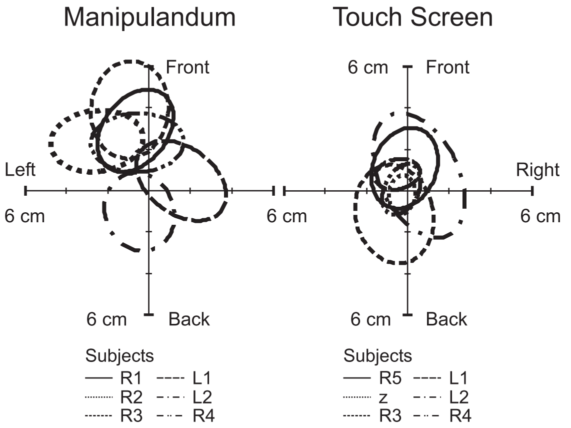

FIG. 4. Location of the centroids of all the shapes reproduced with a manipulandum (*left*) and on a touch screen (*right*) for each subject in Experiments I and II. These 95% confidence-interval ellipses were computed from the covariance matrices of the centroids. Origin of the plots indicates veridical centering.

SIZE ERRORS. Together with these location errors, subjects tended to make errors in the size of their reproductions. Like the individual in Fig. 3, when using the manipulandum subjects reproduced a contour about 15% larger than the quadrilateral's actual perimeter. When drawing the shape on the touch screen, they drew it about 45% smaller. The *middle* and *right panels* of Fig. 5 chart the average ratios between the perimeters of the reproduced and the traced quadrilaterals for each of the 5 shapes for the 2 experiments. Ratios over 1.0 indicate that the drawings were larger than the traces. Ratios varied slightly (by 10%), but significantly, with the 5 quadrilaterals. Larger ratios were found for shapes with smaller perimeters, such as shape #4. As a result, the drawn perimeters varied less than the actual ones (SD of 4.5 cm vs. SD of 5.7 cm), both with the manipulandum and on the touch screen.

Along with drawing the shapes too large with the manipulandum and too small on the touch screen, subjects also systematically misjudged the length of the individual lines that made up the quadrilateral. To separate errors in drawing the lengths of individual lines from those related to the entire shape, we expressed the length of each line as a fraction of the perimeter. For example, the lines that make up shape #1 (shown in Fig. 1) are 19.3, 6.6, 9.6, and 17.9 cm in length, with a perimeter of 53.4 cm. The lengths of these lines as a fraction of the perimeter are 0.36, 0.12, 0.18, and 0.34. Fractional lengths for the reproduced lines were computed similarly. The average of these unsigned length errors was 0.036 (±0.029, SD averaged across trials and subjects) for manipulandum drawings and 0.037 (±0.034, SD) for touch-screen drawings. Differences in errors for the mode of reproduction were small but significant (see the effect of Mode on length errors in Table 2*A*, $P < 0.05$).

Fractional length errors for the 20 different line lengths for both experiments are shown in Fig. 6. In both experiments, subjects, on average, tended to draw shorter lines too long and longer lines too short. The result is that subjects drew the quadrilateral so that its 4 lines were more nearly equal in length than was the case for the veridical figure. [Results of a 4-factor ANOVA, shown in Table 2*A*, indicate that length errors varied significantly with the line length ($P < 0.001$).] Subjects overestimated the lengths of shorter traced lines and underestimated longer ones a bit more for shapes reproduced with the manipulandum (Fig. 6*A*, slope = −0.17, $r^2 = 0.10$) than for those drawn on the touch screen (Fig. 6*B*, slope = −0.10, $r^2 = 0.03$). In keeping with this difference, the interaction effect of line length and reproduction mode was significant (Mode × Line length, $P < 0.05$, Table 2*A*) and the 95% confidence intervals for the 2 slopes did not overlap.

There were some subtleties to this tendency to extend short lines and contract long lines. A notable one, indicated by the arrows in Fig. 6 (relative length = 0.18), corresponds to the second smallest of the edges of shape #1 (see Fig. 1). In keeping with the overall trend, its length was overestimated less than the smallest line of the 4 and more than the 2 longer lines, although it was drawn shorter than predicted by the regression. The reason may be that subjects reconstructed the shape as more symmetric or regularly proportioned than it really was, and so misperceived pairs of lines of similar length as being even closer in size. For example, the ratio between the 2 longest lines of this traced shape was 1.077 and between the shortest 2, 1.452. Subjects drew these pairs of lines as even closer in length so that the ratios for lines reproduced with the manipulandum were only 1.036 for the longer pair and 1.225 for the shorter pair. These ratios were also slightly smaller when drawing on the touch screen: 1.072 and 1.277, respectively. When we calculated the mean ratios between longer paired segments and between shorter paired segments for all 5 quadrilaterals, they were significantly smaller than the actual ratios for traced lines both for the manipulandum reproductions [$t(9) = 2.96$, $P < 0.05$] and for touch-screen reproductions [$t(9) = 3.01$, $P < 0.05$].

Next, we determined whether the orientation of the traced line also influenced subjects' estimates of line length when drawing the shape. For example, did the subject draw lines longer when they were oriented mediolaterally compared with when they were oriented along a diagonal? First, we removed the shape-dependent errors, i.e., those that could be attributed to each line's length (as described in Fig. 6), by averaging line length error for the same segment of the quadrilateral across its 6 rotated forms. We then subtracted these average values from the length errors for each line orientation. These remaining length errors (averaged across trials and subjects) are plotted as a function of the orientation of the traced line in Fig. 7.

These orientation-dependent errors exhibit a clear trend, varying approximately sinusoidally. To characterize this trend

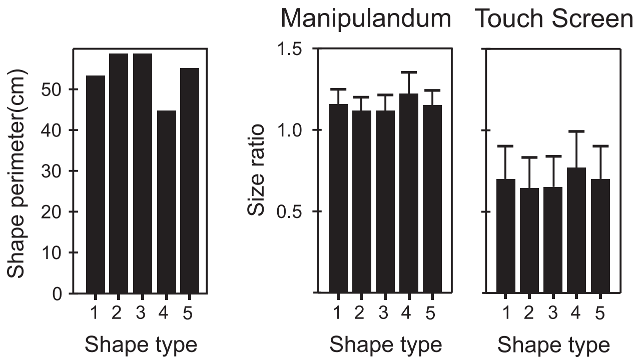

FIG. 5. Perimeters of the 5 traced shapes (*left panel*) and the ratios between drawn and traced perimeters for manipulandum reproductions (*middle*) and touch-screen reproductions (*right*). Error bars represent SE across all trials and subjects.

TABLE 2. *Statistical analysis for line-length errors, inner-angle errors, and line-orientation errors (shape-independent)*

Dependent Variable	Factor	*F*	*df*	*P*
A. *Line-length errors*	Reproduction Mode	3.956	1, 6,497	0.047
	Line length	11.434	7, 6,497	0.000
	Line orientation	5.321	40, 6,497	0.000
	Subjects (Ss)	0.907	7, 6,497	0.500
	Mode × Line length	2.871	4, 6,497	0.022
	Mode × Line orientation	4.793	37, 6,497	0.000
	Line length × Line orientation	2.236	11, 6,497	0.011
	Mode × Line length × Line orientation	3.720	8, 6,497	0.000
	Mode × Ss	0.679	3, 6,497	0.565
	Line length × Ss	3.170	29, 6,497	0.000
	Mode × Line length × Ss	3.027	12, 6,497	0.000
	Line orientation × Ss	2.058	260, 6,497	0.000
	Mode × Line orientation × Ss	1.666	111, 6,497	0.000
	Line length × Line orientation × Ss	1.696	56, 6,497	0.001
	Mode × Line length × Line orientation × Ss	1.290	24, 6,497	0.156
B. *Inner-angle errors*	Reproduction Mode	0.8572	1, 6,994	0.355
	Inner angle	50.946	19, 6,994	0.000
	Subjects (Ss)	0.089	7, 6,994	0.999
	Mode × Inner angle	4.1556	19, 6,994	0.000
	Mode × Ss	0.0813	3, 6,994	0.970
	Inner angle × Ss	3.5832	133, 6,994	0.000
	Mode × Inner angle × Ss	1.3795	57, 6,994	0.031
C. *Line-orientation errors (shape-independent)*	Reproduction Mode	0.0026	1, 6,497	0.960
	Line orientation	7.6351	40, 6,497	0.000
	Line length	1.6453	7, 6,497	0.118
	Subjects (Ss)	0.1043	7, 6,497	0.998
	Mode × Line orientation	2.6229	37, 6,497	0.000
	Mode × Line length	0.0503	4, 6,497	0.995
	Line orientation × Line length	2.2175	11, 6,497	0.011
	Mode × Line orientation × Line length	2.3696	8, 6,497	0.015
	Mode × Ss	0.0596	3, 6,497	0.981
	Line orientation × Ss	3.2157	260, 6,497	0.000
	Mode × Line orientation × Ss	1.8899	111, 6,497	0.000
	Line length × Ss	0.0331	29, 6,497	1.000
	Mode × Line length × Ss	0.0194	12, 6,497	1.000
	Line length × Line orientation × Ss	2.4619	56, 6,497	0.000
	Mode × Line orientation × Line length × Ss	1.0851	24, 6,497	0.351

Signed length and orientation errors were analyzed using a 4-way ANOVA as a function of the Reproduction Mode (or Mode), the length of the line (Line length), the orientation of the line (Line orientation) and Subjects (Ss). Signed inner angle errors were analyzed using a 3-way ANOVA as a function of the Mode, the inner angle between lines, and subjects.

more precisely, we fitted a sinusoid (solid line) to the data, and computed its phase and amplitude. The effect of line orientation on errors in the length of the drawn line differed for the 2 experiments (Table 2*A*: Mode × Line orientation; $P < 0.001$). When subjects reproduced the shape with the manipulandum (Fig. 7*A*), they drew lines oriented mediolaterally (peak at −14.0°, ↔) longer and lines oriented nearly parallel to the sagittal plane (minimum at 76.0°, ≻—≺) shorter. The opposite was true for touch-screen drawings (Fig. 7*B*, peak at −69.7° and minimum at 20.4°). Thus the 2 experiments gave results that were almost 180° out of phase with each other. This bias to draw quadrilaterals wider (along the sideways dimension) than the veridical when using the manipulandum was apparent in the example illustrated in Fig. 3 (*left*).

INNER-ANGLE ERROR. Subjects also systematically erred when reproducing the angles between the intersecting lines. Their errors varied with the inner angle of the traced lines (Table 2*B*, $P < 0.001$). Figure 8 shows that for both manipulandum (*A*) and touch-screen (*B*) drawings, subjects on average overestimated the inner angles of the quadrilateral when the angles were acute, but underestimated them when they were >100°. The pattern of errors was similar for both means of reproduction. Signed errors in estimating inner angles using the manipulandum and those with the touch screen were not significantly different ($P > 0.05$). However, unsigned errors in estimating inner angles using the manipulandum (grand unsigned mean = 11.51 ± 9.21°, SD averaged across trials and subjects) were significantly smaller than those when using the touch screen [grand unsigned mean = 13.45 ± 11.62°; $t(3{,}577) = -7.99$, $P < 0.001$; 3-way ANOVA for unsigned errors, $F(1{,}6{,}994) = 19.04$, $P < 0.001$].

LINE-ORIENTATION ERRORS. The magnitude of the errors in reproducing the orientation of individual segments also differed in the 2 experiments [$t(3{,}579) = -14.20$, $P < 0.001$; 3-way ANOVA for unsigned errors, $F(1{,}6652) = 44.09$, $P < 0.001$]. Averaged unsigned error was 8.47° (±7.21, SD averaged across trials and subjects) for manipulandum drawings and 11.29° (±10.01, SD) for the touch-screen drawings.

Errors in drawing the orientation of individual segments depended on the orientation of the traced line. To quantify this effect, we first subtracted shape-dependent errors in line orientation, that is, the mean orientation error for the same segment for all 6 rotated forms, for each subject. The convention for defining orientation *error* is indicated by the diagrams to the *left* of the plots in Fig. 9, *A* and *B*. When subjects reproduced the shapes using the manipulandum, orientation errors

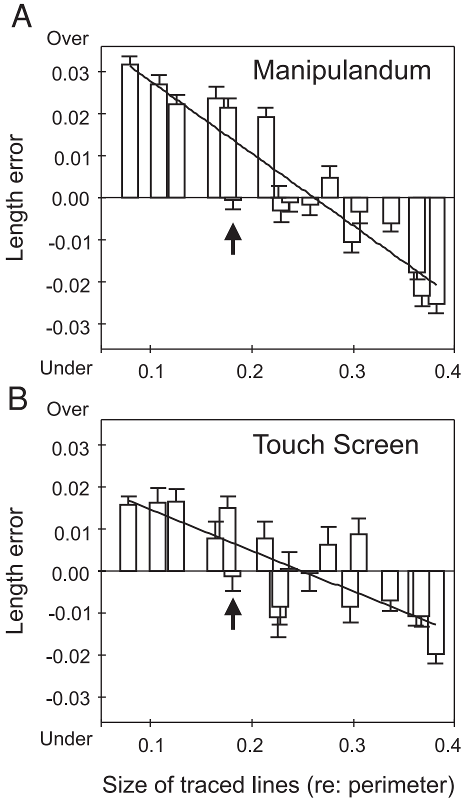

FIG. 6. Mean fractional length errors as a function of the fractional length of the traced line segments for manipulandum reproductions (*A*) and touch-screen reproductions (*B*). Errors, on the ordinate, are expressed as fractions of the perimeter of the drawn shape; lengths of the traced lines, on the abscissa, are expressed as fractions of the real perimeter of the explored shape. Solid lines are regression fits to the data. Error bars denote the SE.

were largest in the CCW direction for traced lines oriented between −60 and −80°. Small CW errors were found for lines oriented about −10 and about +60° from the mediolateral direction.

For drawings produced on the touch screen, the pattern of line-orientation errors (Fig. 9*B*) showed similarities and differences with those generated when subjects used the manipulandum (see Mode × Line orientation, Table 2*C*: $P < 0.001$). The largest CCW errors were produced when subjects drew lines whose simulated orientation was +25 to +30°, whereas the largest CW errors were produced for simulated lines oriented at −30°. To compare the patterns of errors as a function of the orientation of the traced line, we fitted a smoothing function to the errors, as shown by the solid curves. The dashed curves reproduce the smoothing function from the other drawing tool. The relative maxima and minima of the 2 curves roughly coincide, but there are consistent differences in the magnitude of the errors. For traced lines with positive orientation, lines reproduced using the manipulandum had a CW bias compared with those drawn on the touch screen. A CCW bias was observed for traced lines with a negative orientation. Thus irrespective of the orientation of the traced line, the lines drawn using the manipulandum were oriented closer to the mediolateral direction compared with those drawn on the touch screen. This is consistent with the length errors illustrated in Fig. 7. Although length errors varied systematically with the orientation of the line, the converse was not the case: inaccuracies in drawing line orientation did not vary with the length of that line for either reproduction task (see Line length in Table 2*C*: $P > 0.05$).

As described above, we found consistent errors in reproducing the length and orientation of the edges of traced quadrilaterals. Nevertheless, subjects were remarkably good at synthesizing the overall shape of the polygon. This was already apparent in the examples shown in Fig. 3. The conclusion is reinforced by the results shown in Fig. 10, which plots the drawings (solid outline), averaged across trials and subjects, produced on the manipulandum (*left panels*) and the touch screen (*right panels*) for the 6 rotated forms of shape #3. Before averaging, the drawings were adjusted for location (centered) and size (so that the perimeter of each drawing equaled the perimeter of the simulated shape). Traced quadrilaterals are shown by the dashed outline and stars marks the centroids of the traced and reproduced drawings. At the corners of each shape are 68% confidence-interval ellipses fitted to each line endpoint across all subjects. Sizes of these ellipses tended to differ for the 2 modes of shape reproduction. The axes of these ellipses (both major and minor, for each of the 4 corners of the 30 shapes, averaged across subjects) were significantly larger for touch-screen reproductions than for those on the manipulandum [$t(238) = -6.45$ and $t(238) = -7.83$, $P < 0.001$], although the orientations of the ellipses were not significantly different [$t(238) = -1.33$, $P > 0.05$]. This sug-

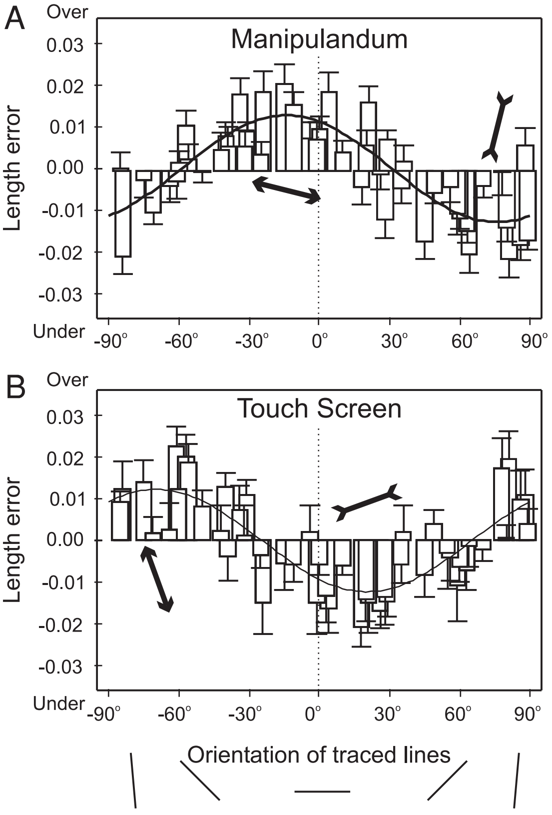

FIG. 7. Mean fractional length errors as a function of the orientation of the traced line segments for manipulandum reproductions (*A*) and touch-screen reproductions (*B*). Line segments at the bottom of the figure depict the orientations of the traced lines plotted along the abscissa. Solid lines are sinusoidal fits to the data. Outward-arrowed lines (↔) indicate the orientation whose line length was most overestimated, and inward-arrowed lines (>—<) indicate the same for most underestimated line length. Error bars as in Fig. 5.

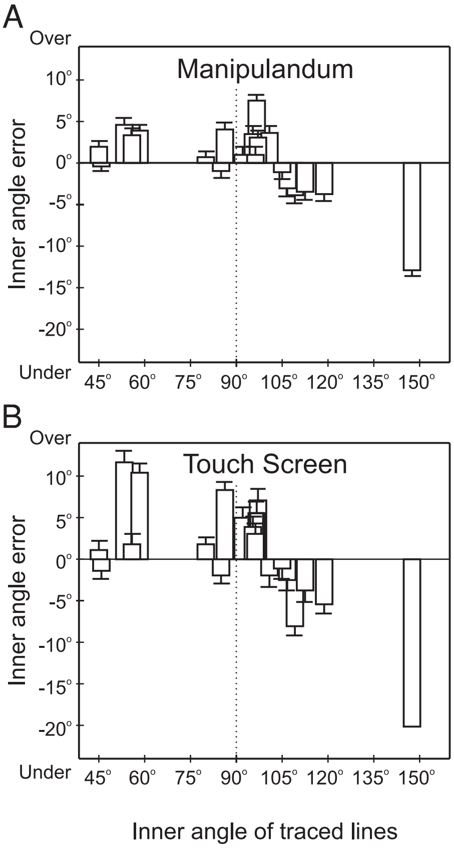

FIG. 8. Average errors in estimating inner angles between line segments plotted as a function of the inner angles between traced segments for manipulandum reproductions (*A*) and touch-screen reproductions (*B*). Vertical dashed lines indicate the 90° angles. Error bars denote the SE.

gests that subjects were less precise when drawing shapes on a touch screen despite having visual feedback.

In Fig. 10, we can see some of the results described above. For one, the shortest line for this shape tended to be drawn slightly longer, whereas the longest line tended to be drawn shorter, for both modes of reproduction. Recall from Fig. 7 that length also varied with line orientation. That is, when subjects drew the shape with the manipulandum they tended to stretch lines oriented sideways, but they did the reverse when they reproduced the outline on the touch screen. In Fig. 10, drawings generated with the manipulandum were wider but those drawn on the touch screen were narrower than the traced figure (see particularly for rotated forms 120 and 300°). The more complex pattern of orientation error is harder to see in Fig. 10. However, many of the acute inner angles were drawn larger, whereas the obtuse angles were drawn smaller.

In summary, subjects were relatively accurate at reproducing haptically sensed quadrilaterals both with the manipulandum and on the touch screen, although the magnitude of the various errors tended to be larger for touch-screen drawings. The pattern of errors in estimating line length and the inner angle between lines was similar for the 2 methods of reproduction. Subjects overestimated the inner angles of quadrilaterals when the angles were acute, but underestimated them when they were obtuse. They also tended to overestimate the length of traced lines when they were short. Subjects tended to distort aspects of the spatial shape in opposite ways for the 2 methods of reproduction.

The accuracy in reconstructing shape from haptic information may be partially ascribed to the geometric constraints provided by a closed shape. We tested the extent to which subjects relied on this redundant input when integrating shape information by removing the fourth line segment from haptically sensed shapes in Experiment III.

Experiment III: serial effects in haptic sensation

In Experiment III subjects traced the contours of an open 3-sided polygon and reproduced its shape using the manipulandum. As illustrated in Fig. 2, the orientation of lines 1 and 3 varied, but not their length. In contrast, the orientation of the second segment remained constant but its length varied. Right-handed subjects always traced the figure from left to right, and left-handed subjects traced it from right to left. Thus this experiment was designed to determine the extent to which serial order of the motion influenced the haptic perception of the length and orientation of each of the lines.

Serial ordering did affect the errors in the lengths of the reproduced lines (Fig. 11). The length of the first line tended to be reproduced accurately, whereas the lengths of the second and third segments tended to be overestimated. These errors

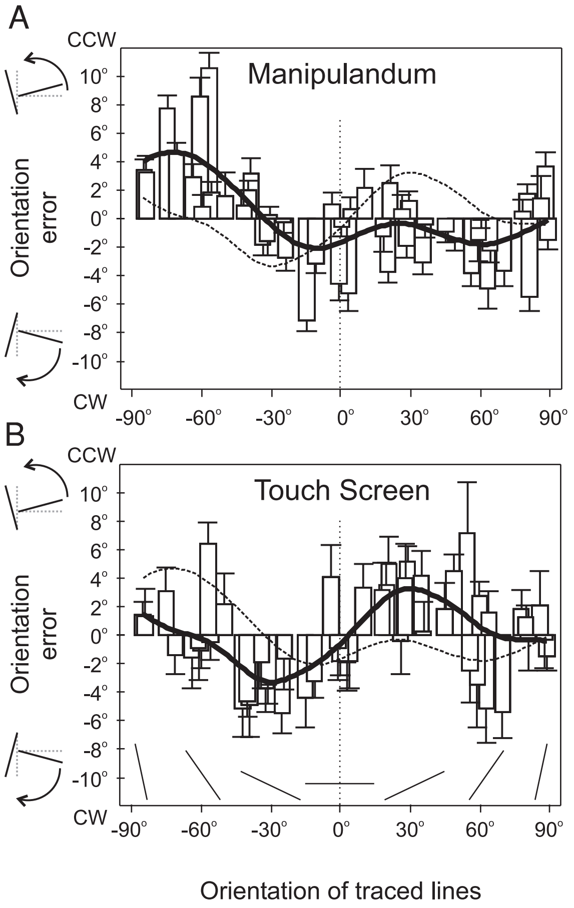

FIG. 9. Average orientation errors as a function of the orientations of the traced line segments for manipulandum reproductions (*A*) and touch-screen reproductions (*B*). Cartoons to the *left* of the ordinates indicate the directions of CCW and CW errors. In each panel, the solid curve is a smoothing fit to the data, whereas the dashed curve is the smoothing fit from the other panel, superimposed for comparison. Vertical dashed lines mark the 0° orientations. Error bars denote the SE.

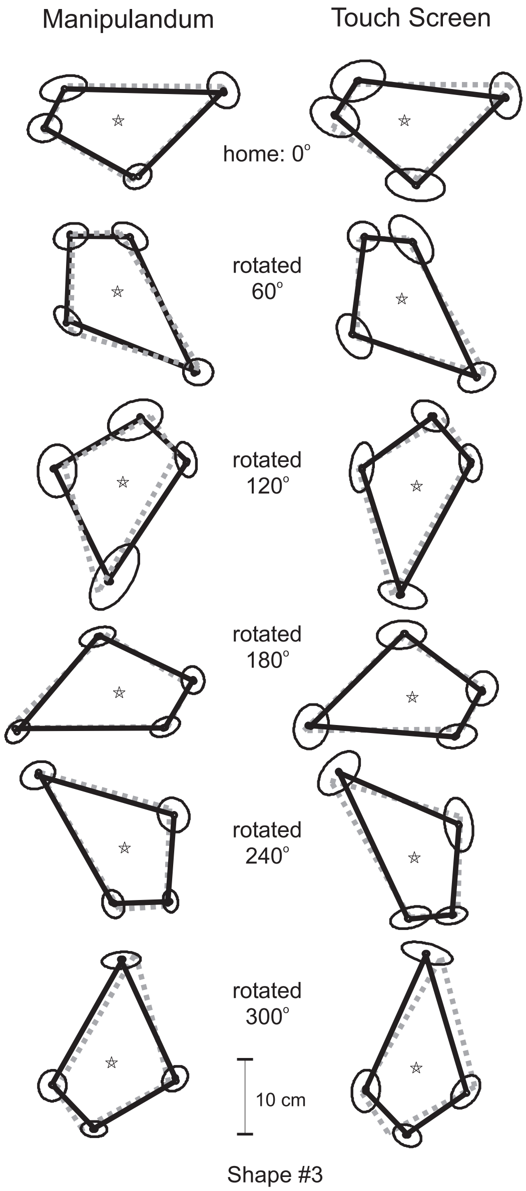

FIG. 10. Drawings made with the manipulandum (*A*) and on the touch screen (*B*), centered and scaled to match the traced quadrilaterals. Solid contours are the reproductions, averaged across trials and subjects, whereas dashed contours are the veridical shapes for all 6 rotated forms of shape #3. Ellipses represent 68% confidence intervals for segment endpoints. Stars mark the centers of these traced and reproduced shapes.

depended on the length of the second segment. For the second segment, the error was inversely related to the length of line 2; subjects overestimated the 10-cm line more than they did the 16-cm one [$F(2,1,861) = 73.69$, $P < 0.001$], analogous to results obtained in the first 2 experiments (Fig. 6). The length of the second segment also influenced the perceived length of the third (although its actual length never varied); subjects overestimated the length of line 3 more when line 2 was longer [$F(2,1,861) = 5.80$, $P < 0.01$].

The orientation of the traced lines also influenced subjects' haptic perception of line length. In Fig. 12*A*, we plot length errors for each of the 3 lines, as a function of the orientation of line 1, with different symbols indicating the corresponding orientation of line 3. Figure 12*B* shows the same errors but with orientation of line 3 plotted on the abscissa and the symbols marking orientation of line 1. Length errors for line 1 depended only on its own orientation [$F(3,1,861) = 10.52$, $P <$ 0.001], whereas errors for line 3 varied significantly with the orientation of both lines 1 and 3 [$F(3,1,861) = 8.28$, $P < 0.001$ and $F(3,1,861) = 4.36$, $P < 0.01$]. Length errors for line 2 also varied with the orientations of both outer lines [$F(3,1,861) =$ 36.55, $P < 0.001$ and $F(3,1,861) = 15.51$, $P < 0.001$]. These errors are also depicted by the grayscale grid in Fig. 12*C*. Subjects overestimated the line's length the most (darkest grid) when the flanking lines were tilted inward, and the least (lightest grid) when they were tilted outward.

Orientation errors also varied with the orientation of the lines. Figure 13 shows this pattern of errors as a function of the orientations of line 1 (*A*) and line 3 (*B*) in the same format used in Fig. 12. As was the case for length errors, errors in orienting line 1 depended only on its own orientation [$F(3,1,861) =$ 32.17, $P < 0.001$], but those for line 3 varied with the orientation of both lines 1 and 3 [$F(3,1,861) = 12.63$, $P < 0.001$; $F(3,1,861) = 16.41$, $P < 0.001$]. Although the orientation of the second line was constant, subjects tended to draw this line more CW as the orientation of the preceding line 1 varied from 70 to 130° [$F(3,1,861) = 30.74$, $P < 0.001$].

Figure 14 illustrates these orientation errors for a select combination of line orientations: when line 1 was oriented 70 and 130° (*top 2 panels*) and when line 3 was oriented 70 and 130° (*bottom panels*). Dashed lines are the veridical outline, whereas the colored lines represent the average orientation of the reproduction. In the *top 2 panels*, one can see that subjects drew lines 2 and 3 tilted more CCW when line 1 was oriented 70° (*first panel*) than when it was oriented 130° (*second panel*). The amount of error in the orientation of the third line also depended on its own orientation. When the first line was at 70°, the error for line 3 was largest at 130°, with a CCW bias. Conversely, when the first line was at 130°, the error for line 3 was largest at 70°, with a CW bias. The same was not true for line 1 reproductions. The *bottom panels* show little difference in the orientations of lines 1 and 2 when line 3 was oriented 70° compared with when it was at 130° (*third* and *fourth panels*). This illustrates that orientation errors of a particular segment depended only on the orientations of the

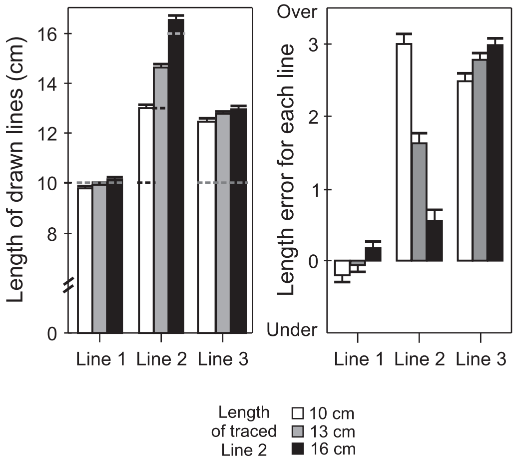

FIG. 11. Mean length estimates for each line segment in Experiment III, as a function of the length of line 2. *A*: reproduced line lengths. Horizontal dashed lines indicate veridical length values. *B*: length errors. Error bars denote the SE.

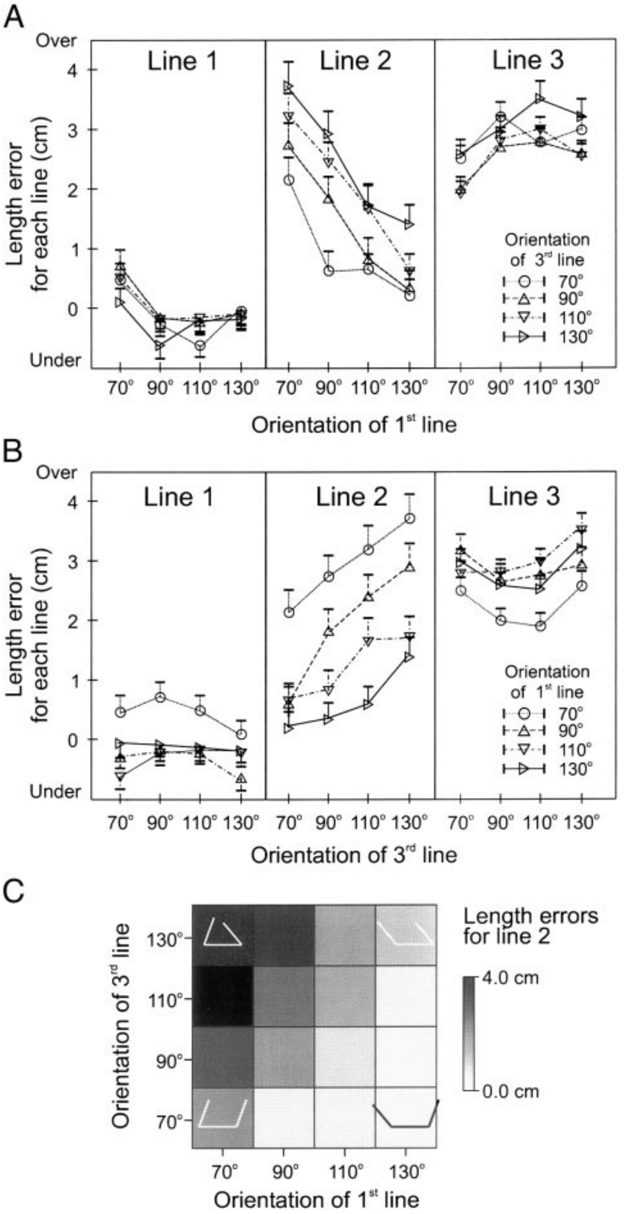

FIG. 12. Mean length errors for each line segment as a function of line orientation. *A*: errors for the sizes of lines 1, 2, and 3, in each case plotted vs. the orientation of line 1, with different curves for different orientations of line 3. *B*: same size errors for lines 1, 2, and 3, now plotted vs. the orientation of line 3. *C*: grayscale grid represents errors in drawing the length of line 2 as a function of the orientations of line 1 (abscissa) and line 3 (ordinate). Black indicates an overestimate of length, whereas white indicates accuracy. Traced shapes are depicted in the corners. Error bars denote the SE.

current and preceding lines, and not on the veridical orientations of subsequent lines.

In summary, errors in reproducing the lengths and orientation of each of the segments reflected the serial nature in which the task was executed. For the most part, errors in reproducing a particular segment depended only on the characteristics of that segment and on those of the preceding segments. The results presented in Figs. 11–14 are summarized schematically in Fig. 15. In these diagrams, α denotes the orientations of each of the segments (α_1, α_2, α_3), whereas the l's denote their lengths. Arrows indicate the direction of influence, in the *top diagram* for errors in length and in the *bottom diagram* for errors in orientation. All significant influences are shown. In the *top panel*, the arrows show that the errors in estimating the length of line 2 (l_2) are influenced by its own length (l_2), as well as by the orientation of α_1 and α_3. The errors in estimating the length of the third segment are influenced by the length of the preceding segment (l_2), by its own orientation (α_3), as well as by the orientation of the first segment (α_1). The *lower panel* shows that the orientation of the first segment influenced the errors in orienting all 3 lines, but that the influence of the third segment was restricted. Note that all influences on orientation, except for self-influences, are in the forward direction.

DISCUSSION

In this study, we assessed how well people can synthesize information about shape. Our subjects haptically explored multifaceted shapes with a manipulandum and then reproduced them in the same horizontal plane with the manipulandum, or on a vertical touch screen. In some ways the reproductions were remarkably good: on average, line orientations were misestimated by just 10°, and line lengths (expressed as a fraction of the perimeter of the whole shape) by just 4%. These errors are no larger than those seen when single lines, rather than complex shapes, are perceived haptically (Appelle and Gravetter 1985; Henriques and Soechting 2003). Further, when subjects reproduced closed shapes with their eyes shut, the drawn shapes were very nearly closed.

Shape reproductions were not perfect, however. Subjects tended to reconstruct the shape as more symmetrical or regularly proportioned than it really was, misperceiving the lengths of lines or the angles between the lines as being more similar. Although shapes were stretched along different axes in the 2 methods of reproduction, the pattern of errors was otherwise similar for the 2 experiments. This similarity suggests that most of the errors in the reproduced shapes were not caused by motor factors, but were instead attributed to distortions in haptic synthesis. Subjects did about as well when estimating the geometry of open shapes, although the pattern of errors was somewhat different. This difference may be in part ascribed to the effect of the sequence in which subjects felt and produced the shapes, so that the orientation and length of the preceding segments introduced errors in reproducing segments that followed.

Effect of the mode of reproduction

In Experiment I, subjects could have accomplished the task by merely reproducing the initial movement, that is, by relying on a motor memory rather than synthesizing the shape of the traced object. To eliminate this possibility, in Experiment II we had subjects trace and reproduce the outline of these quadrilaterals in different planes, with vision of their movement. Although the experimental design introduced several variants that could have influenced the results, the fact that the errors in the 2 experiments were of comparable magnitude leads us to conclude that subjects did synthesize a percept of the geometric shape on the basis of haptic cues. In the following we discuss the possible effect of some of the variants on our results.

Although subjects were exposed to different gravitational influences for the 2 types of planar movements, the few studies that have measured accuracy of arm-pointing direction in the

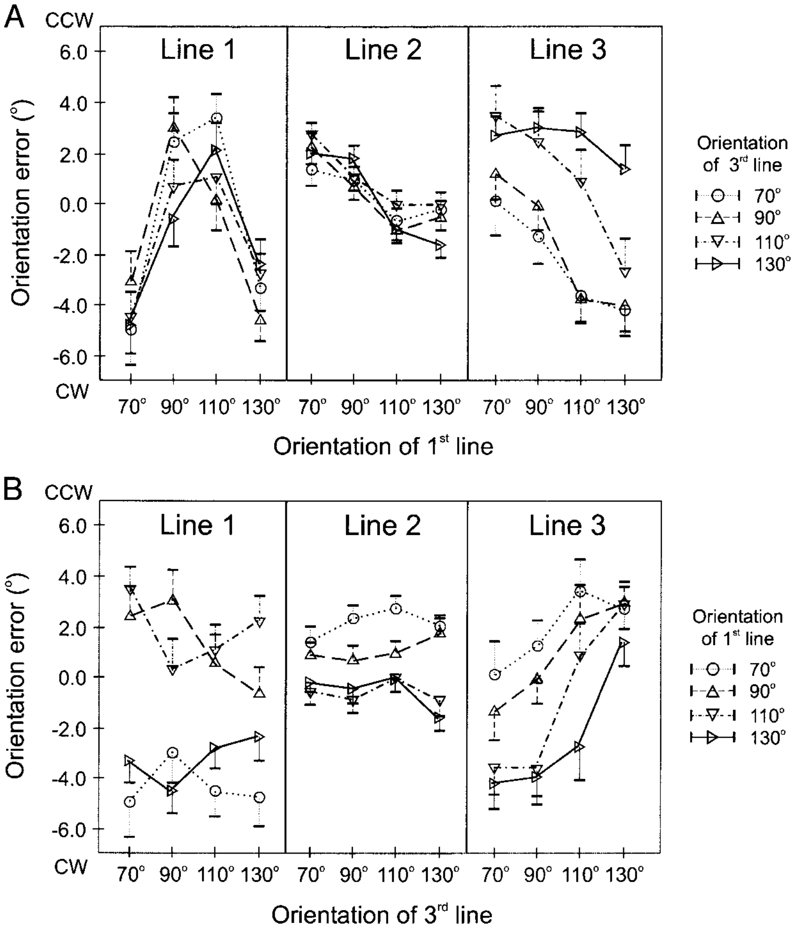

FIG. 13. Mean orientation error for each line segment as a function of line orientation.

frontal plane have not shown any differences in accuracy for horizontal versus vertical movements (Crawford et al. 2000; Medendorp et al. 2000; Soechting and Flanders 1989). This suggests that people are well adapted for moving accurately within the natural gravitational forces associated with motion in 3 dimensions.

Drawing the shape's contour on the touch screen with an extended finger potentially involved different joints than those used during tracing and drawing with the manipulandum. However, Lacquaniti et al. (1987) showed that wrist and finger motions contribute very little to drawing and handwriting as long as the figures span more than 10 cm. Accordingly, in both Experiment I and Experiment II, the task was achieved primarily by moving the proximal joints (i.e., the shoulder and elbow).

Finally, in Experiment II subjects drew the polygon with their eyes open. We made this change in experimental design because subjects needed to change their posture to draw on the screen. It is possible that vision affected the distortions in the reproductions.

Distortions in haptic synthesis

Earlier studies, using single lines or angles rather than complex shapes, have revealed consistent errors in haptic perception. One such error is the tangential–radial effect (analogous to the horizontal–vertical effect for visual estimates of length) where subjects misperceive lines oriented orthogonal to the chest (in the radial direction) as longer than equal-length lines oriented in the sideways (or tangential) direction in a forced-choice discrimination task (e.g., Armstrong and Marks 1999; Hogan et al. 1990). Another typical haptic misperception is the oblique effect: people are poorer at orienting rods along a diagonal or oblique direction than at orienting them along cardinal ones in vertical planes (Hermens and Gielen 2003; Kappers and Koenderink 1999; Newport et al. 2002). Individuals also misestimate the angles between felt edges, although the errors vary with the task (Fasse et al. 2000; Klatzky 1999; Klatzky and Lederman 2003; Lakatos and Marks 1998). As mentioned in the INTRODUCTION, these distortions of haptic perception are not always geometrically consistent. Given that the spatial relations of segments of closed objects must be geometrically coherent, we assessed how well people resolved these inconsistencies when synthesizing the percept of a closed object.

In the current study, subjects made scaling errors that differed for the 2 modes of shape reproduction. They made the shapes about 15% larger than the veridical when using a manipulandum (Experiments I and III) and 45% smaller when drawing on a touch screen (Experiment II). The larger manipulandum reproductions may have arisen because subjects exerted force against edges when exploring the shape. This constraint was absent when they reproduced the shape with the force set to zero. A lack of compensation for the removal of the force field would lead to a larger drawn figure. When subjects used the touch screen, we gave them no instruction about size.

Subjects may have drawn the quadrilaterals smaller because the screen, at 33 × 24 cm, although larger than the traced shapes, was smaller than the workspace covered by the manipulandum.

In all 3 experiments, relative to the total length of the outline, subjects tended to overestimate the lengths of short lines and underestimate long ones. Similar results were obtained in the few previous studies that looked at length estimates as a function of the length of the hand path (Klatzky and Lederman 2003; Lederman et al. 1985). Our subjects also tended to overestimate the inner angles of the polygon when the angles were acute, but underestimate them when they were obtuse. It appears that subjects were reconstructing the lengths and angles closer to their average values for the whole shape. As we will discuss in a later section, it also appears that in some instances subjects reproduced a shape that was more symmetrical than the original (see the *lower panels* in Fig. 3).

Errors in reproducing the lengths of segments of quadrilaterals varied with their orientations and with the mode of reproduction: manipulandum or touch screen. Subjects drew quadrilaterals wider (in the mediolateral, or sideways, dimension) with the manipulandum but narrower on the screen. Both of these findings can be attributed to the tangential–radial effect if we consider that distortions of haptic perception affect the drawing as well as the percept of object shape. Because of the tangential–radial effect, a square will be perceived as a slightly narrow (i.e., tall) rectangle. In fact, this is the type of distortion that subjects drew on the touch screen with visual feedback.

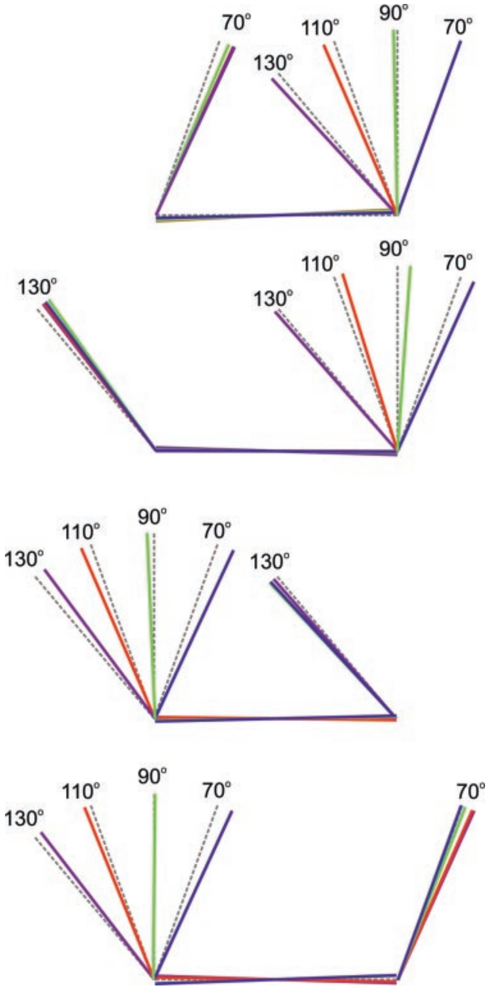

FIG. 14. Mean orientations of drawn lines when the traced shape incorporated the most extreme (orientation 70 and 130°) of line 1 (*top 2 panels*) or of line 3 (*bottom 2 panels*). Color indicates how the drawn lines varied with the orientation of line 3 (*top panels*) or line 1 (*bottom panels*). Dashed contours are the veridical orientations of the corresponding segments.

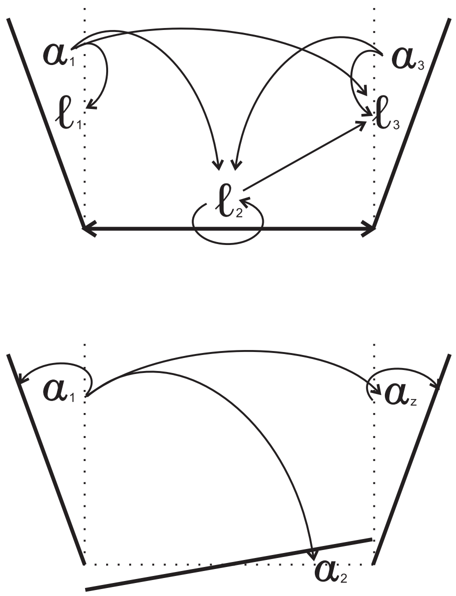

FIG. 15. Diagram showing how, in Experiment III, the traced shape's actual geometry influenced errors in reproduced line lengths (*top*) and orientations (*bottom*). Arrows indicate the direction of influence of one segment's length (l_1, l_2, l_3) or orientation (α_1, α_2, α_3) on drawing errors. In the *top diagram*, for example, the arrows from α_1 to l_1, l_2, and l_3 indicate that the orientation of line 1 influenced subjects' errors in drawing the lengths of lines 1, 2, and 3.

It is possible that when subjects reproduced the shape with the manipulandum without vision, they also misperceived the extent of their drawing motions, underestimating sideways excursions. If so, they would have continued sideways lines longer than intended, producing a shape that was wider than their percept. Thus the distortion in the drawing phase should cancel the distortion in the exploratory phase. In our subjects, the drawing was actually wider than the original shape, suggesting that the distortion during drawing was more extreme than it was during exploration. This tendency to draw tangential axes longer than radial ones is consistent with other studies where subjects drew circles with their unseen hand: they produced wide ellipses when asked to draw circles with a manipulandum (Fasse et al. 2000) or with a pen on a digitizing table (Verschueren et al. 1999) in the horizontal plane.

As its name suggests, the tangential-radial effect applies only to the sensation of exploratory movements made in the tangential and radial directions. The illusion does not arise when comparing edges oriented in the tangential and vertical directions, that is, for movements made in the frontal plane (Day and Avery 1970). Accordingly, in Experiment II we would expect subjects to misperceive line lengths during tracing, but not during reproduction. If so, vertical lines should be drawn too long and horizontal lines should be drawn too short, as observed in our study. The story is slightly more complicated, however, because a similar length illusion, called the horizontal–vertical effect, arises when people compare visual stimuli in the frontal plane: vertical lines are seen as longer than horizontal lines of equal length. This illusion would apply in Experiment II because subjects saw the quadrilateral's segments while they drew them. Our finding that subjects made vertical lines too *long* shows that this visual effect was not strong enough to cancel the haptic tangential–radial effect. Taylor (2001) also found that the haptic tangential–radial illusion tends to be stronger than the visual horizontal–vertical illusion. Likewise, other errors in the haptic perception of space, like mislocalizing remembered visual and tactile dots toward the corners of the workspace or the ends of a bar, tend to be twice as large for felt object as for seen ones (Lederman and Taylor 1969).

Not only the lengths but also the orientations of reproduced lines varied with line orientation, with some differences for the 2 methods of reproduction (Fig. 9). These differences are consistent with the same tangential–radial stretching we have just discussed. Stretching a shape sideways, as in the manipulandum drawings, will rotate diagonal lines toward the mediolateral direction. Accordingly, positively oriented lines will be biased in the CW direction, and negatively oriented lines in the CCW direction. The opposite was true for touch-screen drawings, but also notice that the peaks and troughs of the smoothing fits to these orientation errors are aligned for the 2 modes of reproduction, suggesting that some of the errors in orienting lines were independent of the mode of reproduction. The results of Experiment II resembled those of an earlier experiment by Lederman and Taylor (1969). When their subjects haptically explored the orientation of a single line (relative to a horizontal line in the frontal plane), and then rotated it until it seemed to match the remembered orientation of another, visually observed line, they misadjusted positively oriented lines more CCW and negatively oriented ones more CW.

Cognitive factors in reconstructing shape

Although we did not design these haptic experiments to examine the role of cognition in shape perception, our findings do suggest that high-level processes contribute. For one thing, as mentioned earlier, our subjects tended to regularize shapes and make them more symmetrical—maybe because regular, symmetric shapes are more redundant and can therefore be stored more compactly in memory. This tendency to draw shapes as being more symmetrical than they are seems to depend on the orientation of the shape. For example, it appears in Fig. 10 that the shape was reproduced as being more symmetric when it was rotated 120 and 300° with an axis of symmetry in the anterior–posterior direction.

Many of the errors subjects made when reproducing the quadrilaterals with the manipulandum were similar to those made on the touch screen, suggesting that these reflect inaccuracies in the perception and synthesis of the shape rather than problems in correctly producing the desired movement. However, the errors were slightly smaller when subjects used the manipulandum, perhaps because subjects were able to rely on their remembered arm postures during tracing. Likewise, subjects in the study by Klatzky and Lederman (2003) were more accurate when they repeated a passive, guided hand path than when they estimated the extent of the path with the distance between their 2 index fingers.

Movement sequences and their internal representations

In the first 2 experiments, subjects were permitted to explore the shape in any manner they desired. In Experiment III they explored an open trilateral in a strictly serial fashion so that we could examine serial influences. It is known that in some sequences of hand and arm movements, motion at any one stage depends on previous and subsequent motions (Jerde et al. 2003; Klein Breteler et al. 2003). In our studies, we sought to determine whether such influences applied also to the perception and drawing of haptically presented shapes. In an early study by Cashdan (1968), subjects also felt segments of polygons in a fixed order. Although their subjects were able to identify which of 5 seen or felt shapes matched about 40–60% of the time, the study did not examine how serial ordering of the segments affected subjects' performance.

In our study, as summarized in Fig. 15, we found that errors in drawing any one segment depended on the lengths and orientations of the preceding segments but not the subsequent segments. There was only one exception to this rule: the orientation of the third segment influenced the length of the reproduced second segment; however, if we think of this influence in terms not of segment orientations but of angles between segments, we can say that the angles at both ends of the second segment influenced its drawn length (see Fig. 12*C*). This perspective preserves the rule that subsequent elements do not influence the reproduction of earlier ones.

Why does the forward sequence of haptic exploration influence motor recall? If, as proposed by Lashley (1951), a series of movements are simultaneously represented in the brain before execution, errors in serial movements may be explained in part by interactions between these parallel representations, so that one component of the movement pattern influences the production of surrounding parts. In support of this hypothesis, Averbeck and colleagues (2002, 2003) found when monkeys copied geometric shapes, such as triangles and squares, each shape segment and its serial order within the shape was represented in a population of cortical prefrontal neurons both before and during the drawing. At any one point in time during the drawing, the representations of individual segments overlapped, that of the present segment being strongest.

Because in our experiments there was a time delay between the tracing and the reproducing, it follows that the representation of the shape must have been stored in working memory. How the brain stores information for sequential tactile stimuli and communicates comparisons between these memory traces to the motor cortex was recently addressed by Romo and Salinas (2003) using a vibrotactile discrimination task. Monkeys were exposed to a sequence of 2 tactile stimuli of different frequencies, with a delay in between, and were required to discriminate between these remembered stimuli. Whereas neurons in primary somatosensory cortex (S1) responded only to the current stimulus, evidence of mnemonic representations of these stimuli, lasting a few hundred milliseconds, was present in the secondary somatosensory cortex (S2). These memory traces were elaborated in prefontal cortical areas (Romo et al. 1999). Although neural mechanisms for haptic shape synthesis remain to be explored, it is reasonable to hypothesize that the same cortical areas and similar mechanisms are also engaged by the task we have examined.

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