Perception of Simulated Local Shapes Using Active and Passive Touch

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Smith AM, Chapman CE, Donati F, Fortier-Poisson P, Hayward V. Perception of simulated local shapes using active and passive touch. *J Neurophysiol* 102: 3519–3529, 2009. First published October 14, 2009; doi:10.1152/jn.00043.2009. This study reexamined the perceptual equivalence of active and passive touch using a computer-controlled force-feedback device. Nine subjects explored a 6×10-cm workspace, with the index finger resting on a mobile flat plate, and experienced simulated Gaussian ridges and troughs (width, 15 mm; amplitude, 0.5 to 4.5 mm). The device simulated shapes by modulating either lateral resistance with no vertical movement or by vertical movement with no lateral forces, as a function of the digit position in the horizontal workspace. The force profiles and displacements recorded during active touch were played back to the stationary finger in the passive condition, ensuring that stimulation conditions were identical. For the passive condition, shapes simulated by vertical displacements of the finger had lower categorization thresholds and higher magnitude estimates compared with those of active touch. In contrast, the results with the lateral force fields showed that with passive touch, subjects recognized that a stimulus was present but were unable to correctly categorize its shape as convex or concave. This result suggests that feedback from the motor command can play an important role in processing sensory inputs during tactile exploration. Finally, subjects were administered a ring-block anesthesia of the digital nerves of the index finger and subsequently retested. Removing skin sensation significantly increased the categorization threshold for the perception of shapes generated by lateral force fields, but not for those generated by displacement fields.

INTRODUCTION

The debate over whether tactile stimuli sensed during active and passive touches are processed similarly by the brain has persisted for many decades. Nevertheless, despite continued disagreement, experimentation has clarified several important issues related to this controversy. Gibson (1962), an early advocate of active touch, emphasized that active touch is a self-generated exploratory process. For this reason he rejected the notion that active touch merely reflects a simple summation of kinesthetic and cutaneous stimuli because it fails to include the intentional and directed aspects of the behavior. Likewise, Gordon (1978) noted that a complex object moved passively in the hand is unintelligible, largely because the program of movement is known only to the experimenter and not to the subject. He argued, "*The subject needs a record of his own program of movement against which to interpret what he feels.*"

During active tactile exploration, an individual obtains cues about an object's shape not only from skin deformation and limb displacements, but also from the temporal changes in net forces resulting from friction between the skin and the explored surface. In everyday tactile interaction, these shape cues are all intercorrelated. As a result there has been a continuing debate about whether a spatial or a rate intensity code is involved in the subjective perception of texture and local spatial form (Connor and Johnson 1992; Hollins and Reisner 2000; Johnson and Hsiao 1994). Since these tactile stimuli are normally interrelated, it is difficult to identify their separate contributions to tactile perception. Yet it is possible to systematically analyze their characteristics and to design specific experimental protocols aimed at identifying their respective contributions (Hayward 2008).

A novel technique was introduced by Robles-De-La-Torre and Hayward (2001) who devised a manipulandum that allowed them to dissociate the geometric cues from the force vectors in the perception of local Gaussian shapes using the finger tip. In this study, the two parameters were dissociated by asking subjects to actively use the finger to displace a flat plate laterally as a tool to explore a rectangular workspace. Subjects experienced Gaussian shapes, either convex (bumps) or concave (holes), that were simulated using either a modulated lateral force field or a modulated vertical displacement field. Either simulation method elicited recognizable shapes. However, when the two simulation methods were used to combine holes and bumps, the subjects consistently felt the shape simulated by the lateral force field indicating a dominance of the tangential force cues over the displacement cues for the range of shapes investigated. The apparatus used in the present study is similarly capable of dissociating displacement cues from force cues.

The influence of the mode of touch, active or passive, on the ability to classify shapes generated by lateral force fields was subsequently investigated by Robles-De-La-Torre (2002). Based on the results from a small number of subjects ($n = 4$), he suggested that lateral force fields were inherently ambiguous because the subjects could not identify the shapes with the finger stationary (i.e., passive), although they had no difficulty in identifying the same shapes when the subjects actively moved the manipulandum themselves.

This latter observation has important implications for how the nervous system processes haptic information derived from active and passive touches. The present study had two main objectives. The first was to revisit the question of the perceptual equivalence of active and passive touches by comparing the exploration of shapes simulated with either lateral force fields (with no vertical movement) or displacement fields (vertical movements with no lateral force field), using an apparatus that could generate a wide range of Gaussian shapes.

We expanded on the work of Robles-De-La-Torre (2002) by quantifying performance using two measures of performance: categorization threshold and magnitude estimates. The second objective was to determine the contribution of cutaneous afferents from the exploring finger tip to the perception of these simulated shapes, by testing performance after local anesthesia of the index finger.

METHODS

Subjects

A total of nine right-handed subjects (five women, four men; age, 18 to 35 yrs) were tested. Two of these participated in a pilot experiment (one man, one woman); seven participated in the main experiment with two sessions of about 2 h each. None of the subjects reported any neurological or other medical conditions affecting the sensation or mobility of their preferred hand. The protocol was approved by the institutional ethics committee of the Université de Montréal and all subjects signed an informed consent form prior to participation in the experiment.

Apparatus

The apparatus, illustrated in Fig. 1, was composed of a mobile exploration plate supported by two articulated arms that in turn were linked to the shafts of two computer-controlled torque motors, each equipped with a high-resolution optical position encoder. Together, these motors could generate lateral force fields as a function of the position of the exploration plate, carrying the finger, as it moved about the 6×10-cm workspace. The motors were programmed to generate a virtual Gaussian ridge or trough extending the width of the workspace in the sagittal direction. The force-feedback device was mounted on a servo-controlled vertically moving platform that could also be raised or lowered under computer control. As a result, the finger plate could be raised or lowered to generate Gaussian ridges or troughs by vertical displacement separately from the programmed lateral force field. The plate could be moved with negligible friction and the operation of the device was completely silent. A load cell beneath the device measured the normal component of the finger contact force. Additional details can be found in Campion et al. (2005).

Shape simulation by displacement and lateral force fields

During the *active touch condition*, Gaussian ridges and troughs, 15 mm wide, were simulated perpendicular to the scanning direction and aligned parallel to the long axis of the finger (see Fig. 1). The ridges and troughs were generated using either a displacement field (vertical
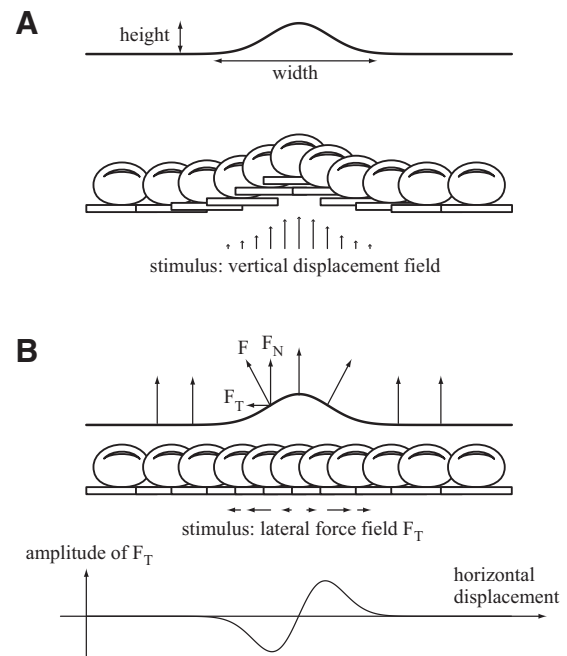
FIG. 2. Stimuli used in the experiments. *A*, *top*: a Gaussian shape generated by vertical displacement of the finger. The shape was defined by its height (variable, 0.5–4.5 mm) and width (fixed, 15 mm). *Bottom*: a sequence of frames shows how the subject's finger was vertically displaced while exploring this stimulus. *B*, *top*: Gaussian shape generated by lateral force fields. *Middle* and *bottom*: sequential modulation of F_T during a scan. Assuming a frictionless surface, an interaction force is always normal to that surface. In this condition, the stimulus had no vertical movement component. The shape information was entirely contained in the lateral force field, as illustrated at the *bottom* of the panel, and which was generated by the force-feedback device from horizontal position readings. The strain gauge measured the vertical force component F_N, applied by the subject. The intensity of the tangential component was computed to simulate the behavior of a frictionless surface by multiplying the intensity of the vertical component by the slope at any given location.

movement of the finger plate) or a lateral force field (tangential force fields applied to the finger plate). The choice of heights and depths was arbitrary (range, 0.5 to 4.5 mm), although a pilot study showed that these amplitudes were readily distinguishable and the motors were able to respond smoothly. The shapes generated by vertical movement involved programming the elevator to track a smooth, position trajectory to simulate ridges or troughs as shown in Fig. 2A. Lateral force-field shapes (Fig. 2B) were generated as a function of the normal contact force (F_N) exerted by the subject on each trial. In general, the contact forces were somewhat greater than what others
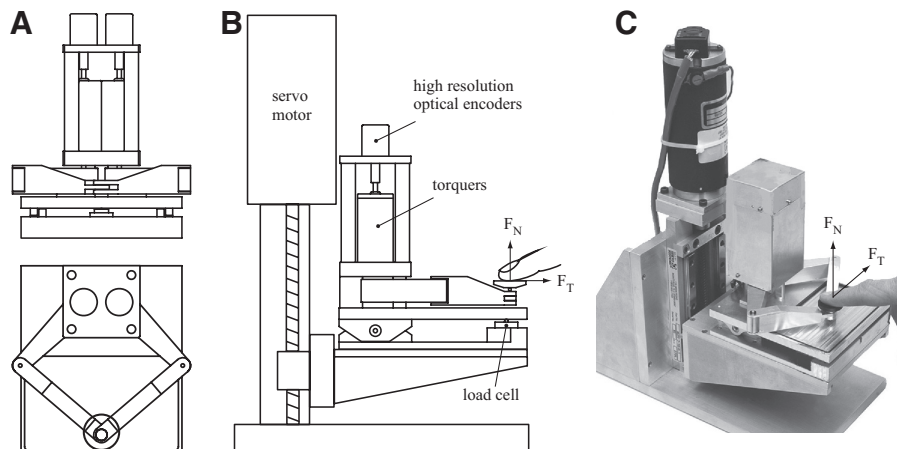
FIG. 1. Experimental apparatus. *A*: front (*top*) and overhead (*bottom*) views. The apparatus consisted of 2 arms supporting a small disk (exploration plate) that was free to move in the horizontal plane. *B*: side view. Precision optical angle encoders and programmable torque motors are attached to the 2 articulated arms holding the plate on which the finger rested. The motors are capable of providing lateral programmable force fields (F_T) to the finger as a function of the position of the disk determined from readings of the encoders. A load cell measured finger pressure (F_N) on the mobile disk. The vertical position of the finger plate was controlled by an elevating servo mechanism. *C*: photo of the complete system showing a subject's finger interacting with the plate.

have reported (Meftah et al. 2000; Smith et al. 2002; Voisin et al. 2002), but we have observed that people tend to use greater finger pressure when exploring a nearly frictionless surface. The position-modulated lateral force field (F_T) was calculated to produce a resultant force (F) equivalent to the desired profile (Gaussian ridge or trough). The applied F_N was continuously measured with a load cell at 259 Hz (see Fig. 1) and these values were used to calculate the F_T needed to produce the desired resultant force and, subsequently, to generate a Gaussian shape. During each trial, the lateral force profiles and the vertical displacement of the finger plate were recorded by the computer. These lateral force profiles and vertical displacements were later applied to the stationary finger of the same subject in the same order in the *passive touch condition*. Thus identical stimuli were presented during active and passive touches.

Task and experimental design

The subjects were informed that they were to participate in an experiment comparing shape discrimination using both active and passive touches. An initial pilot study involved two subjects using a two-alternative forced choice between a ridge and a trough. Both subjects reported that the surfaces frequently felt "flat." To give the subjects sufficient latitude in their responses, and thus allowing uncertainty, we asked the following seven subjects to categorize the test stimuli as a ridge, a trough, or flat and the threshold estimates were within the same range as those found using the two-alternative forced-choice method, indicating that the main threshold measures provided an accurate estimate of sensory-discrimination capacity. The subjects were never informed that their responses were either correct or incorrect.

The subjects were seated comfortably in a chair, with the right forearm flexed at 90° and fastened to a padded armrest at the elbow and wrist to eliminate movement at the elbow and shoulder. The apparatus was placed on a table, directly in front of the subject's right shoulder. The right index finger rested on the finger plate (Fig. 1C). The subjects were not allowed to see the apparatus before or during the experiment and they also had no information about the nature of the shapes. All subjects wore a cap, which completely occluded vision of the apparatus, and they were never told that the shapes they were about to touch were simulated rather than real. In addition subjects wore a sound-attenuating ear protector to minimize auditory cues. The subjects were assisted in placing their right index finger on the exploration disk positioned at the extreme left of the work space. At a signal from the experimenter, the subjects used the index finger to displace the exploration disk back and forth across the 10-cm work space twice using finger and wrist muscles. The largest amplitude shapes simulated by the lateral force fields in the passive condition produced a modest amount of finger abduction–adduction but the smaller-amplitude shapes produced no visible movement. The shapes simulated by vertical displacement moved the index finger up and down at the metacarpophalangeal joint.

After receiving the instructions, the subjects were allowed a practice period to familiarize themselves with using the apparatus to explore several different shapes generated using both simulation methods. The session was divided into two blocks of trials: active touch was tested first and passive touch was tested second, playing back the stimuli experienced during the active touch trials.

ACTIVE TOUCH. The subjects were encouraged to use a moderate constant scanning speed and to exert a steady contact force with the index finger on the mobile plate throughout the experiment. Subjects were presented with the shapes generated by displacement and lateral force fields. Together, there were five replications of five amplitudes of convex (ridge) and concave (trough) shapes generated using both methods, for a total of 100 trials. The order of presentation of the stimuli was quasi-random, interleaving the two methods of shape simulation. On each trial, the subjects made two complete to-and-fro sweeps (from left to right and right to left, twice) across the simulated ridge or trough. At the conclusion of the sweeps, the subject was asked to categorize the shape as convex, concave, or flat and to estimate the magnitude of its height/depth using a numerical scale of their choosing. On each trial, for each subject, a computer recorded the force and position changes during the 10 s allotted to complete the trial. All subjects were able to complete the two back-and-forth sweeps within 10 s.

PASSIVE TOUCH. Following a rest break, subjects were then tested in the passive condition. They were informed that the test surface containing the same stimuli would be swept back and forth twice beneath the stationary index finger resting on the mobile plate. No information was given about the direction of motion but this was the same as that in the active testing. The subjects were asked to keep their finger relaxed during the stimulus presentation. After each trial, subjects were again asked to categorize the shape as convex, concave, or flat and to estimate its magnitude using the same numerical scale used during the active testing.

The subjects performed the active and passive tasks followed by a retest, 1 wk later, with the right index finger anesthetized. A 2% lidocaine solution was injected at the base of the index finger (2–4 ml) to achieve a ring-block anesthesia of the digital nerves. This eliminated cutaneous sensation from the entire finger for the duration of the testing, without affecting the intrinsic muscles of the hand. The depth of anesthesia was periodically monitored using calibrated monofilaments. Since the subjects could not see the apparatus, some had difficulty maintaining the index finger in contact with the exploration plate and occasionally assistance was provided by the experimenter.

Data analysis

Each response was categorized as either correct or incorrect. The latter included errors in the sign of the response (i.e., miscategorization: describing a convex shape as concave or vice versa) and all "flat" responses. Differences according to the mode of touch or the method of generating the stimuli were evaluated using χ^2 tests applied to the pooled data.

For each subject, a categorization threshold was estimated for each mode of touch and each method of shape simulation. Separate estimates were made for the concave and convex stimuli. Threshold was defined as 67% correct categorization, which corresponds to a level halfway between chance (33%—because there were three possible responses: concave, convex, or flat) and 100% correct. Threshold was interpolated from the individual plots of the proportion of correct categorizations as a function of the amplitude of the stimulus. If all of the stimuli were correctly categorized, then an arbitrary threshold value of 0.4 mm was assigned (just less than the smallest stimulus used). If performance was <67% correct for all stimuli, then an arbitrary value of 4.6 mm was assigned (just greater than the largest amplitude tested). Thresholds were compared across conditions using the Wilcoxon test (level of significance, $P < 0.05$ for this and all other tests).

To compare the magnitude estimates across subjects, the data of each subject were first normalized by dividing their raw estimates by the grand mean of all of the correct trials in the session. Note that since the effects of anesthesia were tested in a separate session, these data were normalized separately from the data acquired during the other session (intact sensation). This approach did not mask any difference across the two sessions: an ANOVA indicated that the raw estimates did not vary across the two sessions (intact, anesthesia: $P = 0.716$) and this lack of effect was maintained for the normalized data ($P = 0.961$). Linear regression analyses (subjective magnitude vs. stimulus amplitude) were applied to the data of each subject, with separate curves for each mode of touch (active and passive) and each method of simulating the shapes (lateral force and displacement fields). The regression parameters (slope, intercept, r^2) were compared across conditions using the Wilcoxon test.

RESULTS

Active exploration

Figure 3 shows sample trials from one subject during active exploration of small and large shapes generated using the displacement field and the lateral force field. When the subject scanned the shapes generated with the displacement field (Fig. 3*A*), there was a smooth progression of the digit across the work space (oblique trace, *x*) that was closely similar for the two shapes explored, concave and convex, and the two amplitudes, one near threshold (1 mm) and the other suprathreshold (3 mm). There was no change in F_T and some small variation in F_N, with no obvious differences related to the amplitude of the shape. During scanning of the shapes generated by the lateral force field (Fig. 3*B*), the applied F_N was continuously measured and these values were used to calculate the position-modulated F_T. Inspection of the traces shows that the movement trajectory was similar to that for active touch of the shapes generated with the displacement field and that the force changes were limited to F_T.

The results from the first session (intact sensation, solid line) are plotted in Fig. 4*A* (displacement field) and Fig. 4*C* (lateral force field), where the data were pooled across the concave and convex shapes since there was no difference in threshold. Trial performance is divided (left to right) into correct responses, flat responses, and miscategorizations. Using active exploration, the subjects identified the simulated shapes as either convex or concave with a high degree of accuracy, regardless of whether they were generated by displacement or lateral force fields. The lateral force field shapes were identified with 79% accuracy, compared with 64% overall for the displacement field ($P <$ 0.0005). We were able to interpolate the threshold in some of the subjects (four of seven) and the results confirmed that the categorization threshold was significantly lower for the lateral force field shapes (lateral force field, 1.2 mm; displacement field, 1.7 mm; $P = 0.034$; see Table 1 and Fig. 4).

Linear regressions applied to the data of each subject—normalized magnitude estimates versus amplitude (restricted to correctly categorized stimuli)—showed that all subjects were able to scale the magnitude of the shapes independent of the
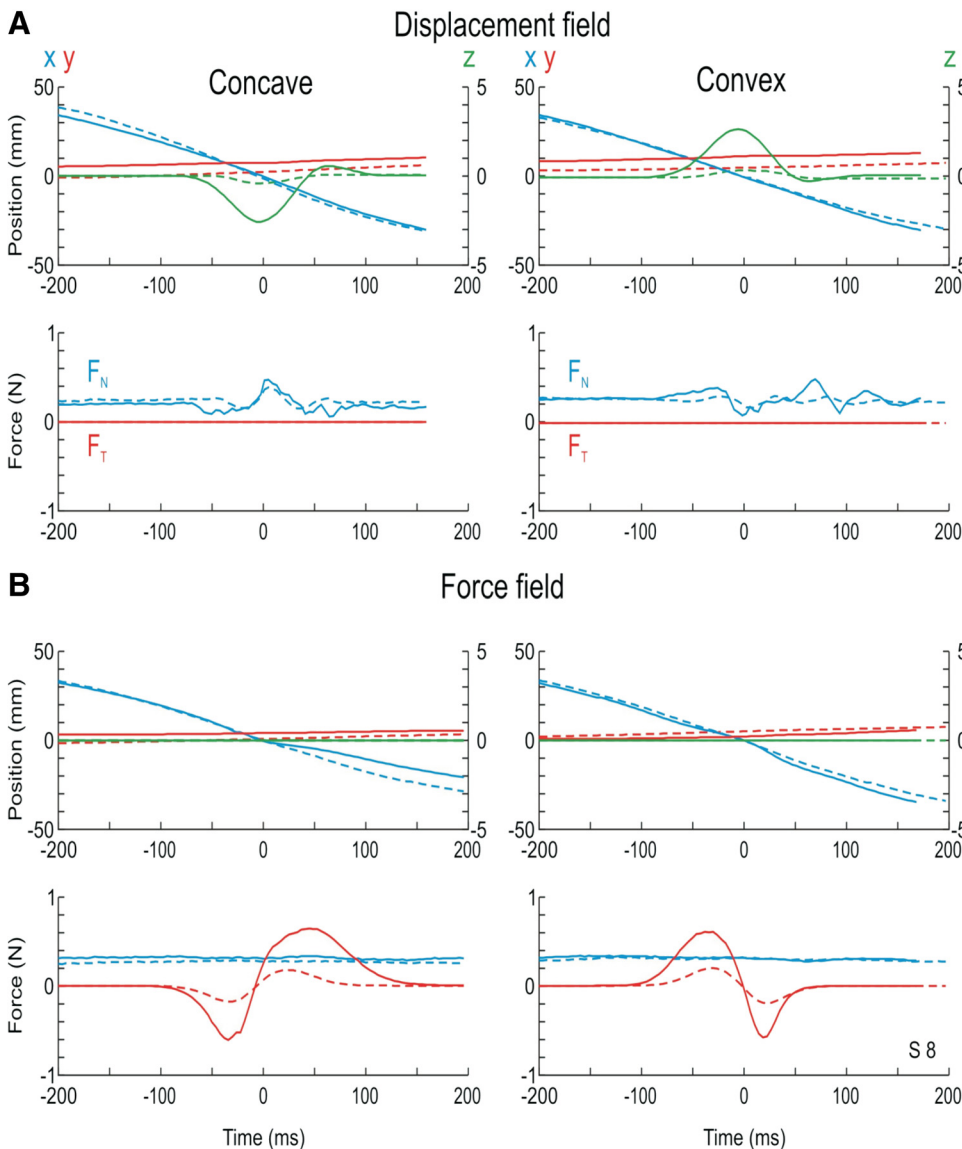

FIG. 3. Sample traces from one subject during individual active scans of near-threshold (1 mm, dotted lines) and suprathreshold (3 mm, solid lines) concave and convex shapes generated with the displacement field (*A*) and the lateral force field (*B*). Note the change in scale for the vertical displacement axis (*z*, green) compared with the *x* (blue) and *y* (red) axes. Data in all panels are aligned on the peak of the shape. These data were replayed to the subject during the subsequent passive testing.
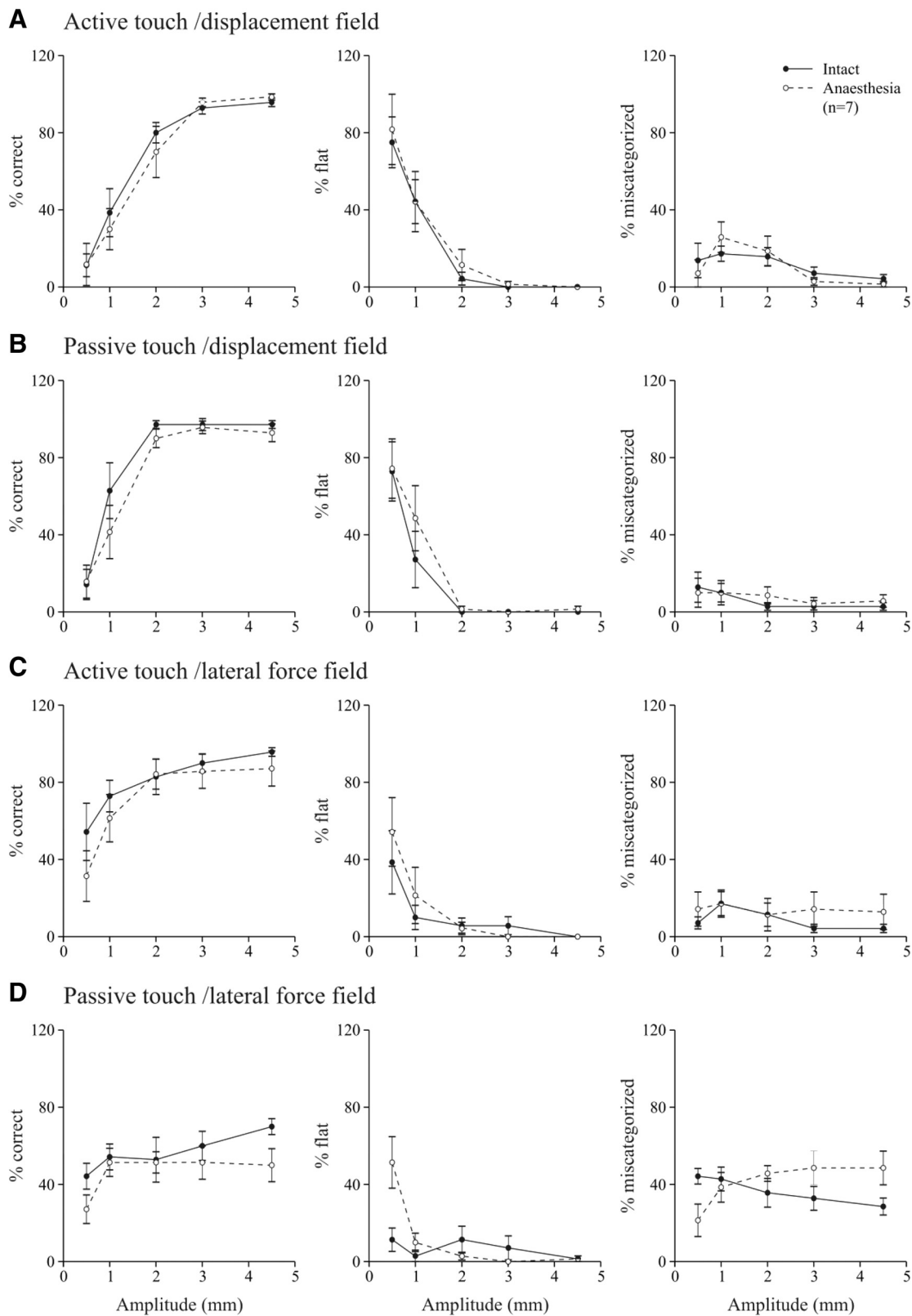
FIG. 4. Mean % performance (±SE) in 7 subjects is plotted as a function of the absolute amplitude of the stimulus (concave and convex shapes pooled). From *left* to *right* are shown the mean % correct categorizations, mean % flat (missed trials), and mean % miscategorized (wrong sign given). Results are shown for each method of generating the shapes. *A* and *B*: displacement field. *C* and *D*: lateral force field; for each mode of touch, active (*A*, *C*) and passive (*B*, *D*), both with intact sensation (solid line) and with digital anesthesia (dotted line).

TABLE 1. *Mean categorization thresholds (in mm) and range (in parentheses) for the correct categorization of shapes generated by displacement and lateral force fields in experiments 1 (n = 10) and 2 (n = 7) using active touch (A) and passive touch (P)*

	Displacement Field			Lateral Force Field		
	Active	Passive	A vs. P P Value*	Active	Passive	A vs. P P Value
Normal sensation	1.7 (1.1–2.4)	1.3 (0.8–1.9)	0.128	1.2 (0.4–2.2)	2.9 (1.4–4.1)	0.018
Anesthetized	1.8 (0.8–2.6)	1.4 (0.7–1.8)	0.091	1.6 (0.4–2.7)	3.3 (2.5–4.6)	0.018
Intact vs. anesthetized, P value*	0.72	0.499	—	0.028	0.027	—

*Wilcoxon test.

method of generating the shapes ($P < 0.05$). The pooled data from the seven subjects are plotted in Fig. 6A (*top*). Separate curves were produced for each method of generating the shapes. Inspection indicates that the two curves are superimposed—i.e., the subjective amplitude estimates were closely similar for the two methods of generating the shapes. Comparisons of the regression parameters (slope, intercept, r^2) confirmed that there were no differences across the two methods for generating the shapes (Table 2). This observation suggested that the subjective amplitudes of the stimuli were closely similar for both methods of generating the shapes.

Passive exploration

In the passive condition, the subjects were told that the same shapes would slide beneath their stationary finger, although no information about the direction of movement was provided. The lateral force profiles and vertical displacements recorded during the active explorations were played back to the passive and initially stationary finger of the same subject. The larger lateral forces produced lateral movement of the finger, which undoubtedly cued the subjects to the scale of larger stimulus amplitudes. Moreover, in the passive condition, the subjects were certainly aware of the larger upward and downward displacements of the index finger. The results were very different from those obtained with active touch because the performance was now dramatically poorer with the lateral force field (56% accuracy, Fig. 4D), compared with the displacement field (78% correctly categorized; Fig. 4B). For the lateral force field the subjects correctly perceived that a stimulus was present, but this was miscategorized (84% of errors), and the subjects tended to perceive convex shapes (positive amplitudes) more often than concave. The mean categorization thresholds were 1.3 mm for the displacement field shapes and 2.9 mm for the lateral force field shapes (Table 1 and Fig. 5). In both cases, concave and convex results were averaged because there was no significant difference.

Even though the subjects had considerable difficulty in correctly categorizing the lateral force field shapes, regression analyses applied to the correctly categorized trials indicated that all subjects were nevertheless able to scale the stimuli generated by both methods of simulation. The data are plotted in Fig. 6B (*top*). As for active touch, the two curves are superimposed and the regression parameters from the individual curves were likewise similar (Table 2).

Active versus passive touch

The mode of tactile exploration, active or passive, modified the ability of subjects to perceive and scale the amplitude of the simulated shapes. Although the subjects were more accurate in categorizing the displacement field shapes with passive touch (χ^2 tests, $P < 0.01$), the opposite result was obtained with the lateral force field shapes for which the same subjects were better using active touch ($P < 0.0005$). The threshold measures from the individual subjects showed the same trend. Figure 7 plots, for individual subjects, the mean thresholds for each subject during active touch with that measured during passive touch, and this for both the lateral force fields and the vertical displacement simulations. The data from passive touch were all below the equality line for the lateral force fields (filled symbols), whereas those for active touch/displacement fields were mostly above the line. Finally, the mode of touch had no effect on scaling the amplitude of the shapes generated by the lateral force fields. In contrast, the slopes were significantly lower for the displacement field shapes explored using active touch compared with passive touch (respectively, 0.27 vs. 0.35; $P = 0.018$). Thus the perceived magnitude was reduced for active touch.

Effects of local anesthesia

Anesthetizing the finger diminished the ability to correctly categorize the shapes generated by lateral force modulation,

TABLE 2. *Mean values of the parameters (±SE) describing the linear regressions and mean normalized magnitude estimates versus amplitude*

	Active Touch			Passive Touch		
	Slope	Intercept	r^2	Slope	Intercept	r^2
Intact sensation						
Displacement field (0.01)	0.27 (0.02)	−0.02 (0.05)	0.88 (0.04)	0.35 (0.03)	−0.04 (0.05)	0.93
Lateral force field (0.05)	0.31 (0.03)	−0.05 (0.05)	0.85 (0.04)	0.30 (0.04)	0.08 (0.03)	0.84
Anesthesia						
Displacement field (0.04)	0.27 (0.02)	0.00 (0.04)	0.90 (0.02)	0.36 (0.02)	−0.05 (0.04)	0.90
Lateral force field (0.05)	0.29 (0.03)	−0.04 (0.07)	0.87 (0.02)	0.24 (0.04)*	0.12 (0.05)	0.79

*Wilcoxon test, displacement vs. lateral force field, $P < 0.05$.
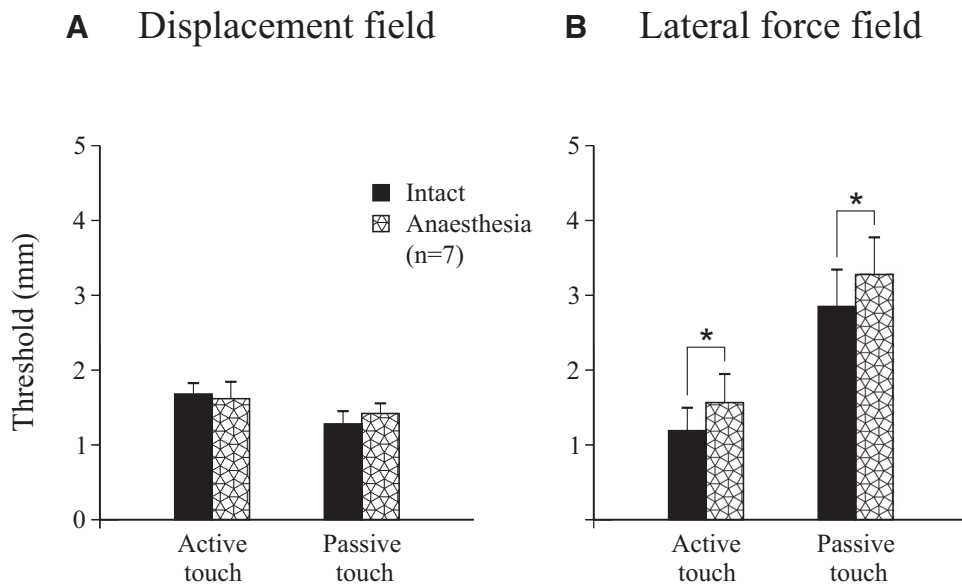
A   Displacement field
B   Lateral force field

FIG. 5. Mean categorization thresholds ($\pm$SE). *A*: for the displacement field shapes, thresholds were low for both active and passive touch and showed no significant change in the presence of anesthesia (filled, intact sensation; textured, anesthesia). *B*: for the lateral force field shapes, thresholds were significantly higher for passive touch compared with active. In contrast to *A*, digital anesthesia led to a significant increase in threshold for both active and passive touches (*$P < 0.05$).

with little or no effect on the ability to correctly categorize those generated by vertical displacements. The results are plotted in Fig. 4 (dotted lines). Although the difference was not great, there were significantly fewer correct categorizations for the lateral force field shapes using both active touch (intact, 79% correct; anesthesia, 70%; $P = 0.005$) and passive touch

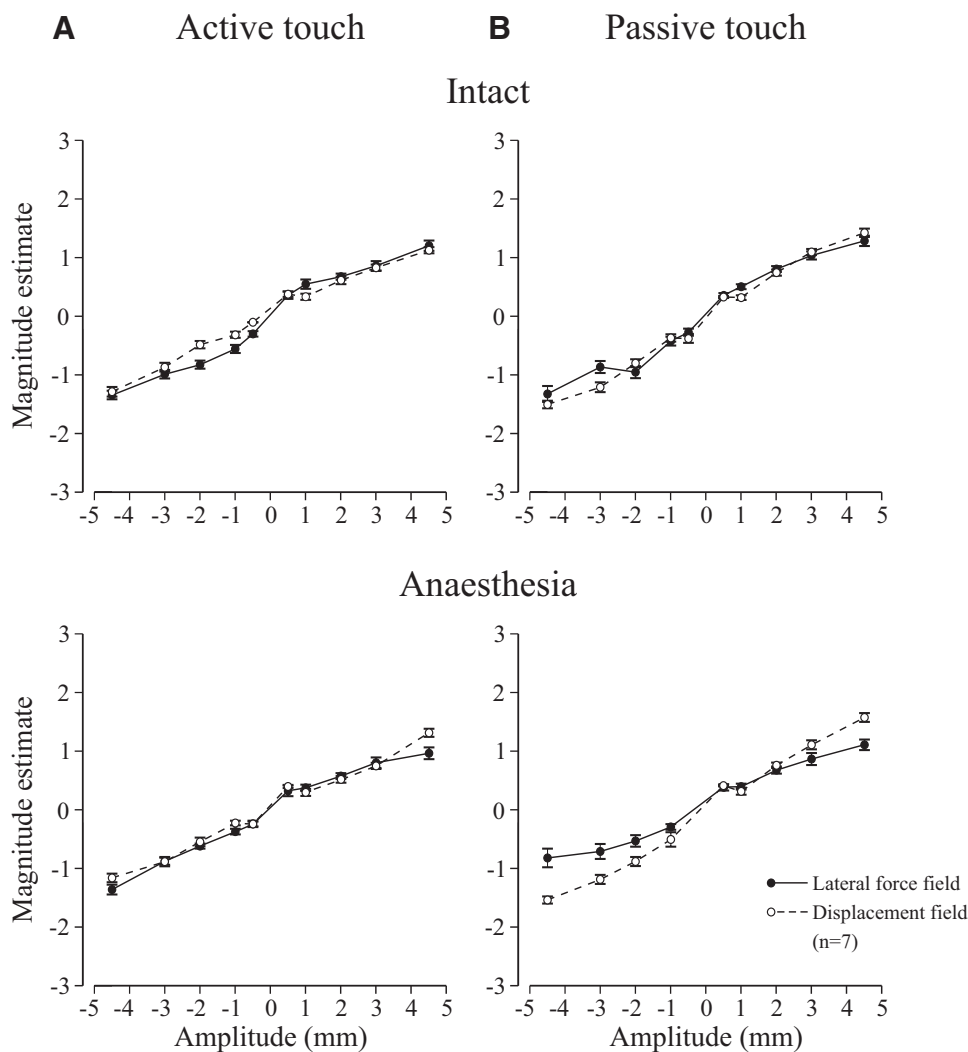## A   Active touch
B   Passive touch

FIG. 6. Mean normalized magnitude estimates $\pm$ SE for each subject plotted as a function of the amplitude of the stimulus for the displacement field shapes (dotted line) and the lateral force field shapes (solid line). *A*: active touch. *B*: passive touch. *Top*, intact sensation; *bottom*, digital anesthesia.
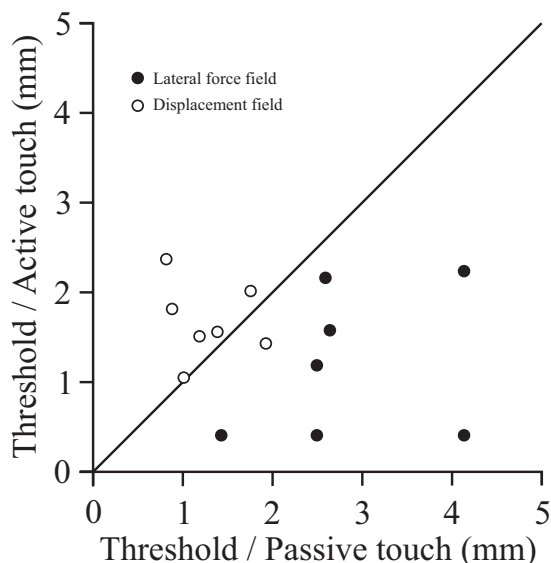
FIG. 7. Mean thresholds for each subject using active and passive touches for both the lateral force and vertical displacement simulations.

(respectively, 56 and 46%; $P = 0.008$). No significant change was seen with the displacement field shapes with either mode of touch, active (64 and 61%, $P = 0.48$) or passive (74 and 67%, $P = 0.057$; see Table 2).

With the finger anesthetized, the types of errors (flat, miscategorizations) did not change across most of the conditions tested (Fig. 4, respectively, *middle* and *right columns*). The only exception was for passive touch/lateral force fields (Fig. 4*D*), for which there were significantly more stimuli categorized as flat with the finger anesthetized (24% of the errors) compared with sensation intact (16%, $P = 0.046$). In other words, the subjects more frequently failed to detect the presence of the stimulus when the digit was anesthetized.

Mean thresholds for shapes generated by vertical displacements showed no change with anesthesia (Table 1 and Fig. 5*A*). This result was expected since the anesthesia left proprioceptive feedback (muscle and metacarpophalangeal joint afferents) intact. In contrast, for the lateral force field shapes (Fig. 5*B*), thresholds were significantly increased with anesthesia for both modes of touch: active (from 1.2 to 1.6 mm, $P = 0.028$) and passive (from 2.9 to 3.3 mm, $P = 0.027$). This observation was consistent with the interpretation that cutaneous feedback had a small, but not negligible, impact on perceptual judgments.

The effects of anesthesia on the subjective scaling of the shape amplitude are shown in Fig. 5 (*bottom*). Inspection indicates that performance using active touch was scarcely changed from the results obtained in the intact condition (*top*). For active touch, the regression parameters from the individual subject analyses showed no change as a function of the method used to generate the shapes in either condition, intact or anesthetized (Table 2). In contrast, there was a significant decrease in the slopes of the psychometric curves for the passive/anesthetized condition associated with the lateral force field shapes compared with the displacement field shapes ($P = 0.043$; see Table 2), reflecting the loss of cutaneous feedback.

We had expected that the finger anesthesia would increase the normal contact force on the mobile plate. However, the contact force was in fact slightly smaller as a result of the anesthesia. Importantly, there was no difference in the contact forces between lateral or displacement force fields either before or after finger anesthesia.

Exploration speed

Mean scanning speed during active touch was calculated from the position signal. The results (Table 3) showed that there was no difference in exploration speeds for the two methods used to simulate shapes (ANOVA, $P = 0.61$). Table 3 also demonstrates that exploration speeds were slightly lower in the anesthetized condition (90 mm/s), compared with the intact condition (109 mm/s) ($P < 0.0005$), likely reflecting increased uncertainty in the absence of cutaneous sensation. Note that the same speeds were experienced in the passive mode, since the force and displacement profiles recorded during active touch were played back to the subject.

DISCUSSION

The present study showed that, for identical stimulation conditions, active touch had an advantage over passive touch, with Gaussian shapes simulated by modulated lateral force fields, although the reverse was true for shapes simulated by vertical displacements of the finger. Categorization thresholds were lower with active touch (vs. passive) for the shapes simulated by lateral force fields, but higher when the shapes were generated using vertical movements of the finger. Finally, cutaneous anesthesia of the digit decreased the perception of shapes simulated using lateral force fields, but not those generated by vertical movements.

General considerations

Since a plate was inserted between the finger and the explored "surface" in these experiments, the tactile exploration resembled the exploration of a surface using a tool, as noted by Flanagan and Lederman (2001). Although this may have contributed to the results, Yoshioka et al. (2007) recently reported that roughness estimations performed with the bare finger or with a probing tool gave very similar results.

In these experiments, the subjects were required to choose between three alternatives—flat, concave, or convex—to allow them to express their uncertainty, although the "flat" choice was invariably incorrect. It is possible that the three-alternative forced choice may have biased a "conservative" subject to report flat when unsure of the sign of the shape, thus showing performance lower than his or her actual sensory-discrimination capacity. The fact that the threshold estimates were closely similar when a two-alternative forced-choice method was used (pilot data) suggests that our method, essentially giving the subjects a chance to express uncertainty, proved an accurate measure of sensory detection. Consequently, the increased threshold when the digit was anesthetized most likely reflects

TABLE 3. *Mean exploration speeds, mm/s (±SD), during active touch (seven subjects)*

Condition	Method of Shape Simulation	
	Lateral Force Field	Displacement Field
Intact	109 (±4.6)	109 (±4.7)
Anesthetized	90 (±2.7)	91 (±3.2)

a change in detection sensitivity and not a change in subjective criterion or bias.

Perception of simulated local shapes

Although active exploration of real shapes normally involves combined proprioceptive and cutaneous feedback (including modulated forces on the skin at the skin/object interface), the present study confirms that either cue can be used alone to generate a realistic illusion of shape when explored using *active touch*. As a consequence, subjects were able to discriminate the concave and convex shapes, giving closely similar threshold measures independent of the method used to simulate the shape. Subjects were also able to scale the subjective magnitude of these simulated shapes, again independent of the method used to generate the shapes.

In contrast, subjects had considerable difficulty with the lateral force field shapes presented to the immobile digit (*passive touch*). They could not discriminate the sign of the shape (concave or convex). This was in striking contrast to the results with active touch, in which case three of seven of the subjects had a threshold *smaller* than the smallest amplitude presented, 0.5 mm, using the same method to generate the shapes. The large proportion of miscategorizations seen with passive touch can easily be explained by the ambiguity of the modulated force shapes. Without knowledge of the direction of movement (not provided to our subjects), subjects could not distinguish between a convex shape moving left to right and a concave one moving right to left. The present results extend the findings of Robles-De-La-Torre (2002) by showing that thresholds were significantly higher with passive touch than those with active touch (lateral force field shapes), although magnitude scaling was unchanged. Thus subjects could accurately scale the perceived intensity of the stimulus (when correctly identified) but not its shape (concave vs. convex).

Sources of feedback

The ring-block anesthesia removed skin sensation from the entire index finger while leaving the muscle, joint, and tendon afferents intact. In this study, proprioceptive feedback was presumed to be the major source of afferent input for the shapes generated by vertical displacements of the disk on which the digit rested (displacement fields). Consistent with this, we found no major changes in performance during the ring block for these shapes.

For the shapes generated by lateral force fields, performance was partly dependent on cutaneous feedback since all performance measures (accuracy, threshold, scaling) declined to various degrees during digital anesthesia. As a result, accuracy was reduced for both modes of touch, whereas the thresholds were increased. In addition, more stimuli were categorized as flat (i.e., not perceived), especially for passive touch. The scaling results were more puzzling. For passive touch, subjective intensity was reduced, although subjects could still scale the stimuli. It is unlikely that cutaneous feedback from the digit was responsible for this because the completeness of the block was regularly verified. It seems more likely that proprioceptive feedback arising from lateral displacements of the digit cued the subjects to the magnitude of the stimulus. Moreover, magnitude estimates during active touch were not modified by

the ring block, again suggesting that proprioceptive cues must have substituted for the absent cutaneous feedback.

Role of the efference copy in local shape perception

In the absence of movement (passive touch), the subjects were aware that a stimulus was present, but the shapes themselves were ambiguous since the subjects did not know (and were not informed) as to whether the lateral forces were simulating a left-to-right or right-to-left motion of the surface beneath the exploration plate. Without these cues, the subjects had considerable difficulty in interpreting the shapes generated by the lateral force fields to the extent they were unable to correctly categorize even the largest amplitudes presented. A significant implication of the present study is that active movement is critical for providing the perceptual context for interpreting sensory inputs.

This command—to move the finger in a to-and-fro sequence while interacting with the force field—was essential to interpreting the ambiguous sequence of forces acting on the exploring finger. Where this interaction occurs within the CNS is not known at present. These results do, however, strongly argue against the notion forwarded by Vega-Bermudez et al. (1991) that sensory inputs acquired during active and passive touches are processed in a similar way within the CNS. Instead, it appears more reasonable to think that the efference copy, or corollary discharge, is combined with sensory signals to effectively generate percepts (Chapman 1994; Gordon 1982).

The efference copy has long been proposed to be the means by which the CNS can distinguish between stimuli generated by the organism's own motion and external stimuli arising from the environment (Bell 1981; Sperry 1950; von Holst and Mittelstaedt 1950; Wurtz and Sommer 2004). The efference copy is thought to participate in computations needed to cancel out the feedback arising from self-generated motion. The present results add an important new observation regarding the role of the efference copy in tactile perception. By providing the direction of relative motion between the finger and a sequence of lateral forces, these results imply that the motor command can actually *participate* in the integration of afferent signals that establish a perception of shape.

Active versus passive touch revisited

There is now considerable evidence indicating that both cutaneous and proprioceptive inputs are gated, or suppressed, during active movements (Chapman et al. 1988; Collins et al. 1998; Ghez and Lenzi 1971; Seki et al. 2003). In contrast, some studies comparing active and passive touches have found that tactile perception is equivalent for both modes of touch. However, these studies were fraught with several weaknesses (reviewed in Chapman 1994). Importantly, the majority of earlier studies used tactile-discrimination tasks, dependent on the ability to perceive relative and not absolute differences in the intensity of stimuli so that performance would not be expected to be modified by the presence of sensory gating since the stimulus–response function is preserved. Chapman suggested that future experiments should concentrate on comparing active and passive touches under identical exploratory conditions. Difficulties with previous experiments include the failure to provide identical stimuli to the same skin area during

both modes of touch and the failure to match the exploratory conditions across the two modes, particularly regarding matched exploration times. Neither of these criticisms applies to the present study. The sensory testing included both measures of categorization threshold and magnitude estimation. The experimental design was such that we stimulated identical skin regions during both modes of touch. Moreover, the stimuli presented during passive touch corresponded to the lateral force profiles and vertical displacements recorded during the active touch condition in the same subject and, as a result, the exploration times were identical for each mode of touch.

The present study sheds new light on the difference between active and passive touches since the effects on the perception of local shape depended on the method used to simulate the shapes. For the shapes generated by the lateral force fields, it appears that active movement was needed to interpret these otherwise ambiguous shapes. For those shapes generated by the displacement field, in contrast, there was evidence for a superiority of passive touch over active touch. Accordingly, subjects correctly categorized a higher proportion of stimuli with passive touch than that with active touch and the categorization thresholds were also lower (passive, 1.2 mm; active, 1.7 mm). Finally, the slopes of the linear regressions were significantly higher for passive touch, i.e., the same amplitude of stimulus was interpreted as being larger during passive touch than that during active touch.

Taken together, these results are consistent with the presence of active movement-related suppression of the sensory inputs modulating the perception of these shapes and thus diminishing performance during active touch. Local digital anesthesia had virtually no effect on the perception of the displacement field shapes, indicating that muscle spindle afferents would be the most likely source of feedback (reviewed by Gandevia 1996), although a role for cutaneous afferents responding to lateral stretch in skin areas spared from the ring block cannot be discounted (Edin and Abbs 1991).

The gating of afferent signals to somatosensory cortex during active movement is a prime example of this efference copy (Jiang et al. 1991; Williams and Chapman 2000; Williams et al. 1998). Moreover, Jiang et al. (1990) showed that weak intracortical microstimulation of primary motor cortex mimics the effect of voluntary movement in gating cutaneous inputs to somatosensory cortex.

Concluding remarks

The present results provide new insights into the debate over active and passive touch. The motor command is obviously critically important for interpreting the ambiguous shapes generated by modulated force fields. Although these were artificial stimuli, representing only a portion of the rich sensory feedback generated during tactile exploration of real shapes, the results strongly suggest that the efference copy contributes to interpreting these inputs. Further experiments are required to address this suggestion. In particular, it would be interesting to determine whether cognitively cueing the subjects as to the direction of motion of the surface containing the shape would improve their ability to categorize the shapes in the passive condition. Other cues (visual, auditory, tactile slip) might also help to

define the direction of movement over the frictionless background surface used here.

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