The role of spatially selective attention in the tactile perception of texture

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During manual sensing of object attributes like surface texture, the tactile receptor sheet is conjointly activated at numerous loci. What is the role of spatially selective attention in perception under these conditions? We show that the requirement for spatial focus of attention is minimal in the detection of an abrupt change in texture. In contrast, spatial attention may help in a variety of other tasks of comparable difficulty. These include detecting the absence of a texture change at one of many loci, distinguishing its direction, and discriminating between different textures. Attentional demand appears to vary along a continuum in these tasks, rather than being all-or-none.

Attention is considered to be the process by means of which the brain selects one of several competing stimuli to be processed most fully (Allport, 1989; Heilman, Watson, Valenstein, & Goldberg, 1987; Posner & Presti, 1987). The requirement for such selection is usually taken to be due to some form of capacity limitation in central processing (Heilman et al., 1987; Posner & Presti, 1987). Allport (1989) points out, however, that attention might more fruitfully be regarded as a "selection-for-action." Spatially selective attention can be demonstrated by the selectively enhanced efficiency of perceptual processing that occurs at a cued location (Posner, 1986). This is termed orienting of attention and has most often been studied in vision.

The extent to which perception demands attention varies. This has been shown in experiments involving visual search of a display for a target item embedded among distractors. In some of these experiments, the target is found very rapidly (Julesz, 1984), independently of the number of distractors (Treisman, 1988). Treisman described this quick perception of targets in terms of "popout." Such perception of targets appears to be independent of focused attention and has been termed "pre-attentive" (Julesz, 1984; Treisman, 1988). In other cases, the time to detect the target increases linearly with the number of distractors, as if search requires serial shifts of attention (Treisman, 1988). The phenomena of "pop-out," texture segregation (Beck, 1982), and perceptual

grouping (Ramachandran, 1988) may depend on specific features that are explicitly coded in the visual system (Julesz, 1984; Treisman, 1988).

Treisman and co-workers have reported "search asymmetries" that depend on the specific role of an item as target or distractor. When the target item is distinguished from distractors by the presence of a particular feature, it pops out. In contrast, search demands serial attentional shifts if the target and distractors interchange roles so that the distractors now possess the feature that is absent from the target (Treisman & Gormican, 1988; Treisman & Souther, 1985). For instance, a circle with an intersecting line (a Q) pops out of a field of circles lacking such intersecting lines (Os), but not vice versa. The feature here is one conferred on the Q by the intersecting line (Treisman & Souther, 1985). These asymmetries in visual search are consistent with the notion that preattentive perception is mediated by specific feature detectors.

Another popular experimental approach has been the study of conjunctions of features. Treisman and her collaborators reported that search times for targets characterized by conjunctions of properties such as color and shape (e.g., a pink O among green Os and pink Ns) increase with the number of distractors (Treisman & Gelade, 1980). Illusory conjunctions are perceived when attention is overloaded (Treisman & Schmidt, 1982). Treisman and her colleagues interpreted these findings as indicating that single-feature search is a parallel preattentive process, whereas conjunction search is a serial attentive process. This has been called into question by findings that conjunction targets will pop out under a variety of conditions (Duncan, 1989; Duncan & Humphreys, 1989; Nakayama & Silverman, 1986; McLeod, Driver, & Crisp, 1988; Sagi, 1988; Wolfe, Cave, & Franzel, 1989). It is argued that the ease of target detection varies along a continuum determined by similarity between items in the display rather than whether search occurs for features or their conjunctions (Duncan, 1989; Duncan & Humphreys, 1989; Pashler, 1987). Thus, a target is easiest to find when it is highly dissimilar from a homogeneous group of dis-

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tractors (Duncan & Humphreys, 1989). Others have explained these results with a two-stage model, in which a rapid parallel search guides the results of a slower serial search (Wolfe et al., 1989).

In contrast with the extensive literature on visual attention, there has been little study of attentional processes in the tactile system. Attention can be oriented in touch (Butter, Buchtel, & Santucci, 1989; Posner, 1986), in a manner similar to visual orienting. Recent experiments have demonstrated variable attentional demand for vibrotactile stimuli. Detection of an increase in vibratory amplitude at one of four digits was found to be unaffected by the locus of attention. In contrast, detection of the absence of such an increase demanded attention (Whang, Burton, & Shulman, 1991). The limited information that is available on tactile attention has accrued entirely from studies done with taps or vibratory stimuli. Textured surfaces have recently been used in psychophysical and neurophysiological studies of the tactile system (Sathian, 1989). Texture perception is an important aspect of stereognostic object identification (Sathian, 1989), and touch may excel vision in this domain (Heller, 1989). During manual sensory exploration to assess common object properties such as texture, multiple simultaneous and sequential stimuli bombard the tactile system (Sherrington, 1900). Yet it is not known what role spatially selective attention plays in tactile texture perception. Lederman, Browse, and Klatzky (1988) addressed this problem, using texture and orientation as dimensions along which their stimuli varied. However, they did not find clear differences in attentional demand among the tasks they studied. In the present study, we demonstrate variations in the requirement for spatially selective attention during tactile texture perception. We used a different stimulus set and behavioral paradigm adapted from the work of Posner (1986) and of Whang et al. (1991).

Textures were presented simultaneously to multiple fingerpads of human subjects, manipulating the spatial locus of attention with an 80% probability cue (Posner, 1986). The goal was to determine whether tactile texture perception in this simulation of active tactile exploration mandates spatially selective attention, or whether certain classes of stimuli can be perceived without the need to focus attention spatially.

GENERAL METHOD

Stimulus Materials

The textures were 40×20 mm gratings of alternating ridges and grooves. To prepare the gratings, the desired pattern was first generated in the laboratory on a computer-driven plotter, at approximately four times the desired size. A photographic matte negative was prepared at actual size and used to generate the gratings by a commercial printing process. As described elsewhere (Darian-Smith & Oke, 1980), this involved placing the matte negative in contact with a rigid plastic material (Nyloprint) in a vacuum, and photoetching the plastic through the negative with ultraviolet light.

The gratings were of the rectangular-wave type, with alternating ridges and grooves. These gratings are simple, specifiable surfaces that have been well characterized as tactile stimuli in psychophys-

ical and neurophysiological studies (reviewed by Sathian, 1989); they are completely described by two independent spatial parameters: ridge width and groove width. Groove width is the principal determinant of perceived grating roughness, which increases monotonically as groove width increases up to ~2 mm (Lederman & Taylor, 1972; Sathian, Goodwin, John, & Darian-Smith, 1989). Perceived roughness also varies with ridge width, increasing as the ridges narrow (Lederman & Taylor, 1972; Sathian et al., 1989). The effect of changing ridge width on grating roughness is only about a third of that obtained by changing groove width (Sathian et al., 1989). In the present report, textures were manipulated principally by varying grating groove width, with ridge width kept constant at 0.25 mm (Experiments 1-4). Some of the experiments were repeated using gratings; in these experiments, ridge width varied while groove width was held constant at 1.0 mm (Experiments 5 and 6). Details of the spatial parameters are presented in Table 1. The spatial parameters were chosen to fall within the range used in prior psychophysical and neurophysiological studies of touch done with gratings. The grating size (40×20 mm) was chosen to enable a rapid, simultaneous scan of four adjacent gratings with the fingerpads of the index and middle digits of both hands.

The gratings were mounted on wooden blocks (see Figure 1). Four gratings were mounted in a row on each block. The blocks were held in a recess on a platform, using a spring-loaded arrangement that permitted their rapid interchange. A bar, attached to a freely moving slide, was engaged with the thumbs and pulled using proximal musculature. The subjects held their fingers extended with the pads in contact with the gratings. There was no independent finger movement during proximally directed strokes. The two outer gratings on each block were offset distally by 10 mm from the two inner ones. This enabled the tips of the index (second) and longer middle (third) fingers of both hands to be initially positioned at the distal ends of the gratings (see Figure 1). The subjects scanned the four gratings simultaneously with the second and third fingerpads of both hands, using a single quick stroke. Any view of the slide and attached surfaces was prevented by a screen during testing.

Subjects

Twelve young adult humans volunteered as subjects after giving informed consent. They were naive about the aim of the experiments and the textures used. A pool of 6 subjects (3 males and 3 females) was used for Experiments 1-4. A different 6-subject pool (3 males and 3 females) was used for Experiments 5 and 6, with only 1 subject being common to both pools. The subject who was common to both pools did not participate in all of Experiments 1-4. A minimum of 5 subjects participated in each experiment. The order

Table 1
Nominal Values of Grating Spatial Parameters

Experiment	Constant Parameter	Varying Parameter			
		Baseline	% Change		
1A	0.25	1.0	33	50	
1B	0.25	2.0	33	50	67
2A	0.25	1.0	50	67	
2B	0.25	2.0	33	50	67
3A-B	0.25	1.5	20	33	50
4A-B	0.25	1.0	10	20	25
5A	1.0	0.25	250	400	700
5B	1.0	2.0	60	75	85
6A	1.0	0.25	400	700	
6B	1.0	2.0	75	85	

Note—Actual values differed slightly from nominal but were constant with sets of the same percentage change. In Experiments 1-4, the constant parameter was ridge width and the varying parameter was groove width. In Experiments 5 and 6, the constant parameter was groove width and the varying parameter was ridge width. Parameters are given in millimeters.

Figure 1. Drawing of apparatus. Gratings were mounted in groups of four on wooden blocks. The blocks were held in a recess on a platform, with a spring-loaded arrangement that permitted their rapid interchange. A bar, attached to a freely moving slide, was engaged with the thumbs and pulled using proximal musculature, causing the subject's fingerpads to move proximally across the gratings without independent finger movement.

of experiments was varied for each subject. The subjects' hand preferences for writing were ascertained; for each subject, this hand was considered dominant in some of the subsidiary analyses performed. In Experiments 1-4, 4 subjects were right-handed and 2 were left-handed; in Experiments 5 and 6, 3 were right-handed and 3 were left-handed.

Procedure and Experimental Design

The experimental design was a two-interval forced choice. Each trial consisted of two intervals, which followed each other in rapid succession. During each interval of a trial, a different grating-bearing block was presented. One of the blocks on each trial bore a single target grating. Since there were four gratings to a block, the gratings other than the target grating (three in the target-present interval and four in the target-absent interval) served as distractors. The subjects scanned the four gratings on a given block simultaneously, as described above. At the end of each trial, the subjects verbally reported which interval contained the target grating—either the first or the second. A forced choice was required.

Before stroking in each interval, one of the four digits was manually tapped on its dorsal surface, cuing the likely target location and also providing a "go" cue. The target appeared on the cued digit (valid cue) on 80% of the trials, and equiprobably on one of the other digits (invalid cue) on the remaining 20% of the trials. The underlying rationale was that performance should differ between validly and invalidly cued trials if spatially selective attention (directed to the cued digit) is required to detect a target (Posner, 1986). In contrast, if performance is unaffected by cue validity, the perceptual decision can occur even if attention is not focused on the target-bearing digit—that is, when attention is distributed between multiple loci of stimulation (Julesz, 1984; Treisman, 1988).

Performance was expressed as the fraction of correct responses. We used accuracy as the measure of performance, rather than reaction time. The latter has been employed in many studies of visual attention. Treisman (1988) has described experiments which indicate that similar results can be obtained with either of these two variables. Furthermore, Whang et al. (1991), using a measure of

accuracy, reported results consistent with the framework of many experiments on visual attention in which reaction time was employed. We chose to use accuracy rather than reaction time, because of its relative simplicity from a technical standpoint. Furthermore, reaction time measures were impractical because we employed extended surfaces that were actively explored over a period of about .5 sec.

The target occurred equiprobably in the two intervals of a trial and among the four digits. The probability of occurrence of the cue on each digit was equal in the target-present interval. Since four digits were used (the second and third digits of each hand), there were three subcategories of invalid cue, which were based on the relation of the cued and target digits. The invalid cue and target could occur on homologous digits of opposite hands, or on non-homologous digits of the same or opposite hands. In the target-absent interval, the cue occurred equiprobably on the four digits, irrespective of its location in the other interval (i.e., it was a dummy cue). For each experiment, 120 trials were presented to each subject in one session, after 15-30 practice trials. A different computer-generated pseudorandom sequence was used for each session. The subjects did not know whether a given trial was validly or invalidly cued, only that the overall probability of a valid cue was 0.8 in one interval.

In each of the experiments, a different target-distractor combination was employed, as will be detailed in the presentation of the individual experiments. Each experiment consisted of two parts, as will also be described later.

For each experiment, the grating parameters were adjusted to yield two to three levels of percentage change distinguishing target from distractors (Table 1). Examples of grating types are shown in Figure 2. Each subject was presented with one to two levels per experiment. The level was constant in any given session. The levels of percentage difference used for each subject in each experiment were chosen during the practice trials with the aim of obtaining average performance in the region of the classical threshold (75% correct). Some subjects ran at two levels in a given experiment, with average performance above and below 75% correct. Others ran at only

Figure 2. Illustration of the types of gratings used. All gratings measured 40×20 mm. Details of the spatial parameters of the gratings used are presented in Table 1. (A) Grating with uniformly narrow grooves and ridges. (B) Grating bearing a 5-mm-long segment with grooves wider than those on the rest of the grating. (C) Grating with uniformly wide grooves. (D) Grating bearing a 5-mm-long segment with grooves narrower than those on the rest of the grating. (E) Grating bearing a 5-mm-long segment with ridges wider than those on the rest of the grating. (F) Grating with uniformly wide ridges. (G) Grating bearing a 5-mm-long segment with ridges narrower than those on the rest of the grating.

one level at or close to 75% correct. This constraint was necessary to avoid floor and ceiling effects that would render uninterpretable any results from sessions with average performance near 50% or 100% correct. To this end, sessions yielding average performance near 50% (arbitrarily taken as less than 55%) or near 100% (arbitrarily taken as more than 95%) were omitted from the analysis. This meant that, in some instances, a subject would have to be dropped from one or both halves of a particular experiment. However, at least 5 subjects participated in any given experiment. When a subject ran in the same experiment at two levels, the data from the two levels were treated as within-subjects replicates in the analyses. The level of percentage difference was not used as an independent main-effect variable in the analysis of variance (ANOVA) models, because not all subjects ran at more than one level.

Before each session, the subjects were given verbal instructions reminding them of the general task specifications and the probability of a valid cue. They were also instructed on the specific target-distractor combinations to be used and allowed to see and touch the gratings on a target-present block before beginning testing. This was done to assure that the subjects had a clear understanding of the task. It is of interest that many subjects reported that initial viewing of the grating set allowed development of "visual images" that

aided their judgments. As pointed out before, there was no visual feedback during the actual trials. No time constraints were placed on the subjects' verbal responses. These were recorded manually and later entered into a computer for storage and analysis.

Analyses

Data from individual experiments were examined for statistical significance ($\alpha = .05$) with repeated measures ANOVAs. Scheffé's test (which imposes a stringent criterion for significance, thereby to minimize Type I errors; see Keppel, 1982) was used for post hoc comparison of mean performance values under different conditions. Statistical analysis was performed with SAS. The dependent variable was the fraction of correct responses, and the principal independent variable was the cuing condition (valid vs. invalid). Details of the additional main-effect variables used in the ANOVA models are presented with the descriptions of individual experiments. A separate repeated measures ANOVA was performed for each experiment, with a four-level cuing variable substituted for the two-level variable used in the primary analysis. In this secondary ANOVA, analysis was restricted to the effect of the cuing variable. The four levels of this variable depended on the specific relation of target and cued digit. On validly cued trials, the target and

Table 2
Effect of Cuing on Performance

Experiment	Performance		ANOVA	Invalid Cuing Performance			ANOVA
	Valid Cuing	Invalid Cuing		C-HD	I-NHD	C-NHD	
1	75.1	68.1	$F(1,5) = 2.88, p = .15$	70.0	69.2	65.0	$F(3,15) = 2.2, p = .13$
2	75.2	57.8	$F(1,5) = 14.58, p = .01^*$	62.5	52.2	58.8	$F(3,15) = 3.13, p = .06$
3	80.1	66.9	$F(1,5) = 13.45, p = .01^*$	67.2	65.6	68.0	$F(3,15) = 2.79, p = .08$
4	78.4	65.4	$F(1,6) = 7.63, p = .03^*$	73.7	64.5	57.9	$F(3,18) = 7.27, p = .002^*$
5	76.6	69.7	$F(1,5) = 3.00, p = .14$	75.0	65.8	68.3	$F(3,15) = 1.65, p = .22$
6	70.2	56.7	$F(1,5) = 11.34, p = .02^*$	59.6	60.6	50.0	$F(3,15) = 4.84, p = .01^*$

Note—Performance is expressed as the percentage of trials on which a correct response was obtained, for each cuing condition. Columns 2-4 present the results in terms of valid versus invalid cuing; in columns 5-8, the invalidly cued trials are broken down into three subgroups, which are based on the relation of the cued digit to the target-bearing digit. C-HD = homologous digit on hand contralateral to target location. I-NHD = nonhomologous digit on hand ipsilateral to target location. C-NHD = nonhomologous digit on hand contralateral to target location. $^*p < .05$.

cued digit were on the identical digit. On invalidly cued trials, the target and cue occurred on homologous digits of opposite hands or on nonhomologous digits of the same or opposite hands. The purpose of the analysis with the four-level cuing variable was to assess possible differences between invalid cues on different digits. Type III sums of squares were used in all analyses because of unequal cell sizes (i.e., 80% validly cued vs. 20% invalidly cued trials) and because some subjects did not participate in both halves of a given experiment.

EXPERIMENT 1 Detection of the Presence of an Abrupt Change in Texture

In this experiment, we studied the role of spatially selective attention in tactile detection of an abrupt texture change. If such texture change is a feature preferentially processed by an early or preattentive perceptual system, then as previous work (Julesz, 1984; Treisman, 1988) suggests, its detection may occur irrespective of where attention is directed in the stimulus field.

Design

Gratings. The distractor gratings in this experiment had uniform texture (groove width) along their (40-mm) length. The target grating bore a 10-mm-long segment that differed in roughness (groove width) from the rest of the grating, which had a groove width equal to that of the distractor gratings. The experiment was conducted in two parts. In Part A, the distractors were uniform smooth gratings (Figure 2A), and the target grating bore a segment that was rougher (wider grooves, Figure 2B) than baseline. In Part B, the distractors were uniformly rough (Figure 2C), and the target bore a smoother segment (Figure 2D). In Table 1 are listed the values

of the spatial parameters and the magnitudes of the percentage change in groove width on the target gratings. The changed-roughness segment commenced abruptly either 5 or 15 mm from the distal end of the grating—that is, near the distal end of the grating or at the middle. The two positions were equally likely.

Subjects. Five subjects participated in each part of this experiment. The results of 1 subject's sessions on Experiment 1A had to be dropped, owing to ceiling effects (see General Method). Another subject (the one common to the two pools; see General Method) was recruited for Experiment 1A. This subject did not participate in Experiment 1B.

Analysis. The repeated measures ANOVA model included the following main-effect variables: subject, cuing condition (valid vs. invalid), position of the changed-roughness segment (distal vs. central), digit on which the target occurred (the second or third digit of the dominant or nondominant hand), interval in which the target occurred (first or second), and task subtype (Part A vs. Part B). Also included in the model were the interactions of cuing condition with each of the other main-effect variables. In the repeated measures ANOVA for the effect of the four-level cuing variable, the four-level cuing variable was substituted for the two-level cuing variable.

Results and Discussion

In this experiment, performance was a little better when cuing was valid rather than invalid (Table 2). However, the difference in performance as a function of cuing condition was not significant (Table 2). Neither was there a significant effect of the specific relation of cued and target digit (the four-level cuing variable; see Table 2).

The only independent variable to have a significant effect in this experiment was the digit on which the target occurred (Table 3). As Table 3 shows, target detection appeared to be better on the index finger than on the mid-

Table 3
Effect of Target Location on Performance

Experiment	Location				ANOVA
	Dominant D2	Dominant D3	Nondominant D2	Nondominant D3	
1	75.4	69.6	74.9	63.7	$F(3,15) = 3.4, p = .045^*$
2	65.3	58.5	63.9	61.0	$F(3,15) = 0.73, p = .55$
3	80.8	70.1	72.0	65.9	$F(3,15) = 4.93, p = .01^*$
4	77.8	67.3	69.7	59.6	$F(3,18) = 4.91, p = .01^*$
5	73.3	73.3	79.1	64.1	$F(3,15) = 2.60, p = .09$
6	53.4	63.7	58.2	65.1	$F(3,15) = 0.89, p = .47$

Note—Performance is expressed as the percentage of trials on which a correct response was obtained for each target location. These were the second or third digit (D2 or D3) of the dominant or nondominant hand. $^*p < .05$.

Table 4
Effect of Target-Present Interval on Performance

Experiment	Performance		ANOVA
	Interval 1	Interval 2	
1	72.0	69.8	$F(1,5) = 0.69, p = .44$
2	62.2	62.3	$F(1,5) = 0.02, p = .89$
3	75.5	68.9	$F(1,5) = 0.61, p = .47$
4	72.9	64.4	$F(1,6) = 27.12, p = .002^*$
5	74.2	70.8	$F(1,5) = 0.45, p = .53$
6	62.2	58.0	$F(1,5) = 1.19, p = .33$

Note—Performance is expressed as the percentage of trials on which a correct response was obtained for each interval (i.e., the first or second). $^*p < .05$.

dle finger. However, the differences between mean performance values for target detection on the different digits were not significant according to Scheffé's test.

The effect of the position of the altered-roughness segment was not significant [$F(1,5) = 0.06, p = .82$], and neither was that of the target interval (Table 4) or of the task subtype (Table 5). The interactions of cuing (valid vs. invalid) with the other independent variables—particularly, the interaction of cuing with task subtype (Table 5)—were not significant.

The absence of a spatial cuing effect on performance in this experiment suggests that detection of an abrupt texture change can occur independently of spatially selective attention even when attention is deliberately misdirected to an incorrect locus by an invalid cue. Of course, the subjects may not have actually directed their attention to the invalidly cued digit. They may have chosen a strategy of ignoring the cue and distributing attention equally among the four stimulated digits. This possibility is still consistent with the interpretation that spatially selective attention is not necessary for the detection of abrupt texture change. We do not claim that performance in this task is independent of selective attention. Attention must be focused on task specifics, and in the tactile spatial domain it is presumably narrowed to the stimulated digits. Strictly speaking, then, perception is not *pre-attentive*, although this term has been applied in similar conditions (Julesz, 1984; Treisman, 1988). The small difference in performance as a function of cue validity in this experiment might have assumed statistical significance with a larger sample size. However, there are differences in attentional requirement between this task

and other tasks under similar conditions (see below). Our results show little need for spatially selective attention within the stimulus field in this task (Experiment 1).

The significant effect of target digit is interesting, for it suggests differences between digits in sensitivity. However, the means for performance with different target digits were not significantly different according to the more stringent Scheffé test. This will be addressed further in the analysis of data pooled across experiments (see below).

The lack of a significant effect of the task subtype and of its interaction with cuing verifies that the two subtypes of the task (Parts A and B) were equivalent. Thus, it does not matter whether the abrupt texture change is in the direction of increasing or decreasing roughness. However, each altered-roughness segment introduced *two* step changes of opposite direction on the grating concerned. The present experiment does not reveal which direction, if any, is more important. Experiments with single step changes in texture ought to be performed to address this issue in the future.

EXPERIMENT 2

Detection of the Absence of an Abrupt Change in Texture

Experiment 2 was based on the notion of "search asymmetry" introduced by Treisman and her co-workers. The gratings were the same as those in Experiment 1, but the roles of target and distractor were switched. The target was now a grating of uniform texture, while a segment of altered texture characterized the distractor gratings. The subjects' task was therefore detection of the *absence* of texture change. Experiment 1 suggests that an abrupt texture change is a candidate feature that might be preferentially processed to the level of perception without spatially focused attention. Previous experiments resulting in search asymmetry (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991) lead to the prediction that detection of the absence of this feature would require attention—that is, search is asymmetric for feature presence/absence.

Design

Gratings. This experiment also contained two parts. In Part A, the target was a uniformly smooth grating (Figure 2A) and the distractor gratings each included a segment that was rougher (wider

Table 5
Effect of Task Subtype

Experiment	Performance		ANOVA	
	Part A	Part B	Task Subtype Effect	Task Subtype × Cuing Interaction
1	72.7	68.9	$F(1,3) = 0.53, p = .52$	$F(1,3) = 0.01, p = .93$
2	60.4	64.1	$F(1,5) = 4.39, p = .09$	$F(1,5) = 4.72, p = .08$
3	72.1	72.3	$F(1,4) = 0.07, p = .81$	$F(1,4) = 0.56, p = .50$
4	71.2	66.3	$F(1,3) = 3.63, p = .15$	$F(1,3) = 0.0, p = .96$
5	74.9	69.6	$F(1,4) = 8.56, p = .04^*$	$F(1,4) = 2.12, p = .22$
6	58.4	62.1	$F(1,4) = 0.40, p = .56$	$F(1,4) = 0.06, p = .82$

Note—Performance is expressed as the percentage of trials on which a correct response was obtained for Part A and B of each experiment. $^*p < .05$.

grooves, Figure 2B) than baseline. In Part B, the target was uniformly rough (Figure 2C), and the distractors each bore a smoother segment (Figure 2D). In each case, the baseline groove width on the distractors equaled the groove width of the target grating. In Table 1 are listed the values of the spatial parameters and magnitudes of the percentage change in groove width on the distractor gratings. The changed-roughness segment commenced abruptly at 5, 15, or 25 mm from the distal end of the grating (i.e., the segment was located distally, centrally, or proximally). To provide uncertainty about the positions of the changed-roughness segments, two equiprobable combinations of distractors (with the altered-roughness segment in varying positions) were used in the target-absent condition and for each target digit in the target-present condition.

Subjects. Six subjects participated in this experiment; all of them participated in both parts.

Analysis. The results of this experiment were analyzed with a repeated measures ANOVA similar to that in Experiment 1. However, the variable representing the position of the changed-roughness segment on the target in Experiment 1 was omitted, since the target was of a single type in Experiment 2A and in Experiment 2B.

Results and Discussion

In Experiment 2, the effect of cuing was larger than it was in Experiment 1, and it was significant (Table 2). Scheffé's test confirmed the superiority of the valid cue. The specific relation of cued and target digit was short of significance (Table 2).

None of the other main-effect variables (target digit, Table 3; target interval, Table 4; task subtype, Table 5) had a significant effect on performance. The interactions of cuing with the other main-effect variables—particularly, with task subtype (Table 5)—were also not significant.

Thus, detection of the absence of a roughness change is aided by spatial cuing, since the deliberate misdirection of attention with an invalid cue degraded performance. The results of Experiments 1 and 2 demonstrate asymmetrical attentional demands for detection of the presence and absence of abrupt texture change. Analysis of the interaction of cuing and task will be deferred to a later section.

These findings recall the search asymmetry that has been described in other contexts (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991). By analogy with these experiments, the asymmetry of attentional requirement noted here is consistent with the hypothesis that texture change is a feature perceived without attention's being narrowly focused in the spatial domain. Perception of this feature may depend on detectors (individual cells or networks) specifically sensitive to texture change. The texture change in Experiments 1 and 2 was based on changes in groove width. A rate code has been proposed to underlie discrimination of textures that differ in groove width (Sathian, 1989; Sathian et al., 1989), because this variable is represented in the discharge rate of primary afferent fibers (Sathian et al., 1989) and cells in primary somatosensory cortex (Sinclair & Burton, 1991). On these grounds, the detectors might be sensitive to *changes* in the firing rate of other cells whose rate encodes groove width. Such detectors have not thus far been described.

The lack of a significant effect of task subtype and of its interaction with cuing shows that Parts A and B can be considered similar, although the *p* values were less than 0.1 and could have been significant with a larger sample size.

EXPERIMENT 3

Distinguishing the Direction of Texture Change

The results of the previous two experiments support the hypothesis that an abrupt change in texture can be perceived independently of spatially selective attention. Is information about the *direction* of texture change—that is, whether roughness is increasing or decreasing—also accessible without the spatial focus of attention, or does this impose a greater requirement for selective attention? This was the question addressed in Experiment 3.

Design

The experimental design paralleled that of the two previous experiments.

Gratings. In Experiment 3, all gratings had segments with a change in texture from a constant baseline. The change on the target grating was opposite in direction to that on the distractor gratings. The experiment again comprised two parts. In Part A, the target had a rougher segment (Figure 2B), and the distractors had a smoother segment (Figure 2D). The baseline groove widths of target and distractor gratings were equal, as were the percentage changes in groove width between baseline and changed segments. Target and distractors switched roles in Part B. In Table 1 are listed the values of the spatial parameters and magnitudes of the percentage change in groove width on the gratings. As in the previous experiments, the changed-roughness segment commenced 5 or 15 mm from the distal end of the target and 5, 15, or 25 mm from the distal end of the distractors. As in Experiment 2, two equiprobable target-absent blocks were used with different combinations of changed-roughness segment positions. For each target digit, there were again two combinations of distractors as in Experiment 2, but here these were presented in two independent subessions of 60 trials each (unknown to the subjects). Hence there was again uncertainty about the position of segments of altered texture.

Subjects. Six subjects participated in this experiment; 1 of them did not participate in Part A.

Analysis. The repeated measures ANOVAs were as those for Experiment 1.

Results and Discussion

Performance on this task was again much better with valid than with invalid cuing (Table 2). The difference was significant, as was shown by the ANOVA (Table 2) and confirmed by Scheffé's test. The specific relation of cued to target digit was not significant (Table 2).

The only other main-effect variable to have a significant effect in this experiment was the digit on which the target occurred (Table 3); there was a trend toward better target detection on the index finger than on the middle finger. According to Scheffé's test, only the largest difference in mean performance was significant (when the target occurred on the index finger of the dominant hand vs. the middle finger of the nondominant hand).

No significant effects were seen for target interval (Table 4), position of the changed-roughness segment [$F(1,5)$

= 0.76, $p = .42$], or task subtype (Table 5). No interactions were significant, including that of cuing with task subtype (Table 5).

Experiment 3 shows that when multiple loci encounter similar texture changes, the ability to distinguish the direction of texture change is affected by the locus of attention. Hence, this characteristic is not a candidate feature that could be processed preferentially without spatially focused attention, unlike the mere detection of a texture change.

Further, target detection was again better with the second than it was with the third digit (see below). The lack of a significant effect of task subtype and of its interaction with cuing supports the belief that Parts A and B of this experiment are equivalent.

EXPERIMENT 4 Discrimination Between Textures

In Experiment 4, we looked at the role of spatially selective attention in discrimination between different gratings of uniform texture. The idea was to test whether texture can be described as a feature of the substitutive type, analogous to color. In vision, a red target pops out of a field of green distractors with the same facility as a green target pops out of a field of red distractors (Treisman & Souther, 1985). Thus, removal of such a feature (e.g., roughness or redness) implies replacement with another feature (e.g., smoothness or greenness) along the same dimension (texture or color).

Design

Gratings. Each grating used in Experiment 4 had uniform texture along its length. The distractors were identical to one another; the target grating differed in roughness from the distractors. In Experiment 4A, the distractors were smooth (narrow grooves, Figure 2A) and the target was rougher (wider grooves, Figure 2C). The roles of target and distractor were reversed for Experiment 4B, in which the target was smoother than the distractors. In Table 1 are listed the values of the spatial parameters and magnitudes of the percentage change in groove width between target and distractor gratings.

Subjects. Five subjects participated in Part A. Six subjects participated in Part B, including 4 subjects who also participated in Part A. The 5th subject of Part A also participated in Part B, but his results from Part B had to be dropped, owing to floor effects (see General Method). He was therefore replaced by another subject (the 1 common to the two pools) in Part B. A 6th subject also participated in Part B. This subject was recruited later than the others and did not take part in any other experiments after the series was terminated. His results were included in the analysis of this experiment but were dropped from the pooled-data analyses reported later.

Analysis. The ANOVAs for Experiment 4 were as those for Experiment 2.

Results and Discussion

Cue validity again exerted a significant effect on performance in this task (Table 2), with performance being better on validly as opposed to invalidly cued trials (Table 2; Scheffé's test).

This time, the relation of cued and target digit was also significant (Table 2). Scheffé's test revealed that perfor-

mance on validly cued trials was significantly better than performance on trials cued invalidly on the nonhomologous digit of either hand. Performance was also significantly better when the invalid cue was on the digit homologous with the target digit than when it was on the nonhomologous digit.

As in Experiment 3, the effect of which digit received the target was significant (Table 3). There was a trend toward better target detection on the index finger than on the middle finger. Only the largest difference in mean performance (when the target occurred on the index finger of the dominant hand vs. the middle finger of the non-dominant hand) was significant.

The effect of target interval was significant, with performance being better when the target occurred in the first interval as opposed to the second interval of a trial (Table 4).

There were no significant effects of task subtype, nor was its interaction with cuing (Table 5) or the interaction of cuing with the other main-effect variables significant.

This experiment demonstrates that discrimination between the global texture of surfaces simultaneously touched by different digits is aided by selective attention to the digit encountering the particular surface differing from the others. This contrasts with the perception of an abrupt texture change encountered by one of multiply stimulated digits (Experiments 1 and 2). Thus, texture does not emerge as a "substitutive feature" in the Treisman and Souther (1985) sense, unlike color in vision. This is not surprising, since texture may be represented along intensive continua (Sathian, 1989), rather than dependent on the relative stimulation of distinct receptor types as is the case in color perception.

The finding that target detection was better when the cue and target occurred on homologous digits, and better with the index than with the middle finger, will be discussed below.

The effect of target interval in Experiment 4 shows a response bias favoring the first interval. There was, however, no interaction of this effect with cuing. This effect was not seen in any of the other experiments, and it will not be discussed further.

The lack of a significant effect of task subtype and of a significant interaction of task subtype and cuing again shows that the direction of texture difference does not affect performance or attentional demand.

ANALYSIS OF DATA POOLED ACROSS EXPERIMENTS 1-4

Since a common subject pool was used in Experiments 1-4 (see General Method), the data from these experiments were pooled and examined in different ways with repeated measures ANOVAs.

Effect of Task

Each of the four experiments was treated as an independent task. There was a significant interaction between task

Table 6
Results of Statistical Analysis of Data Pooled across Experiments 1-4

Independent Variable	Dependent Variable	ANOVA	Category	M
Task	Cuing effect	$F(3,15) = 5.4, p = .01^*$	Absence of change (Experiment 2)	17.7
			Direction of change (Experiment 3)	13.9
			Rough versus smooth (Experiment 4)	12.0
			Presence of change (Experiment 1)	7.2
Task	Performance	$F(3,15) = 2.6, p = .09$	Absence of change (Experiment 2)	71.4
			Direction of change (Experiment 3)	78.0
			Rough versus smooth (Experiment 4)	75.5
			Presence of change (Experiment 1)	74.1
Relation of cued to target digit	Performance	$F(3,15) = 7.6, p = .003^*$	Valid	78.0
			C-HD	68.3
			C-NHD	60.3
			I-NHD	60.2
Target digit	Performance	$F(1,5) = 26.9, p = .004^*$	D2	72.3
			D3	64.2
Target hand	Performance	$F(1,5) = 4.1, p = .1$	Dominant hand	70.3
			Nondominant hand	66.2

Note—Analysis of the effect of the relation of cued and target digits was restricted to experiments in which a significant cuing effect (valid vs. invalid) was found. The cuing effect was computed as the difference between percent correct on validly cued trials and percent correct on invalidly cued trials. Performance is expressed as the percent correct trials in each category. D2 = second digit. D3 = third digit. C-HD = homologous digit on hand contralateral to target location. C-NHD = nonhomologous digit on hand contralateral to target location. I-NHD = nonhomologous digit on hand ipsilateral to target location. $^*p < .05$.

and cuing [$F(3,15) = 4.9, p = .01$], which confirmed that attentional demand varied between these four tasks. Further analysis of the size of the cuing effect (Table 6) demonstrated that attentional demand was lowest in the detection of the presence of texture change, highest in the detection of the absence of this feature, and intermediate on the other two tasks. This suggests that attentional demand in the perception of multiple textured surfaces varies along a continuum (Duncan & Humphreys, 1989). It also emphasizes that attentional demand can be asymmetric about the presence and absence of a feature on the target (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991). In this case, the feature is texture change.

Overall performance in this series of experiments ranged from 60%–90% correct, with the experiment-wise means being 70%–80% (i.e., around classical threshold). Mean overall performance did not differ significantly between tasks (Table 6). The small differences that were found did not covary with the variations in attentional demand. This suggests that stimulus discriminability (Duncan & Humphreys, 1989; Pashler, 1987) was probably *not* a major determinant of the varying attentional demand between the tasks in the present study (i.e., Experiments 1–4). However, stimulus discriminability was not rigorously controlled in the present study, and therefore this interpretation requires further experimental support.

Effect of Cue-Target Relation

Across the experiments in which a significant cuing effect was found (Experiments 2–4), the effect of cue-target relation was significant (Table 6). Scheffé's test showed that performance on validly cued trials was significantly

better than that on trials on which the invalid cue and target occurred on nonhomologous digits (with respect to the target digit) of either hand. In contrast, the difference in performance between validly cued trials and trials on which the invalid cue and target occurred on homologous digits of opposite hands was smaller and did not reach significance.

This superiority of the homologous over the nonhomologous digit (also noted in Experiment 4) suggests that information might be integrated bilaterally (albeit incompletely) and specifically over homologous locations. This might be served by neurons with bilateral receptive fields such as those seen in parietal opercular cortex (Burton & Robinson, 1981). The situation appears different for vibrotactile stimuli for which bilateral integration lacks digit specificity (Craig, 1985). However, these results were possibly due to propagation of vibratory stimuli from digits into the hand.

Effect of Target Hand and Digit

Across all four tasks, target detection was significantly better on the second than on the third digit. It was not significantly different between the dominant and nondominant hands (Table 6).

The superiority of the second over the third digit as a tactile detector is interesting. In the present experiments, the fingers were actively moved across the textures. Hence, motor factors could underlie possible differences in sensitivity between digits. However, Craig (1985) reported similar findings with the use of vibrotactile stimuli without motion, suggesting that there may be a true difference in sensitivity between digits. We are not

aware of any studies done to examine whether the representations of the second and third digits in somatosensory cortex differ in size or cortical magnification.

The absence of an effect of the dominant as opposed to the nondominant hand in our experiments does not negate the possibility that laterality effects might be found by comparing performance on the left and right hands of right-handed subjects. The number of right-handed subjects in our study was too small to attempt this comparison.

EXPERIMENTS 5 and 6

Detection of the Presence and Absence of Texture Change Created by Varying Ridge Width

Preattentive visual processes appear to have access to a wide range of representations of object properties (Enns & Rensink, 1990; McLeod et al., 1988; Nakayama & Silverman, 1986; Ramachandran, 1988). Is the same true of touch? In all the preceding experiments, roughness was manipulated through varying the groove width. The discharge rate of tactile primary afferent fibers increases monotonically as a function of groove width and has been proposed as one of the neural codes for grating roughness (Sathian, 1989; Sathian et al., 1989). Texture changes can also be produced by variations in ridge width, but in the direction opposite to those produced by changing groove width (Lederman & Taylor, 1972; Sathian et al., 1989) and only about a third as effectively (Sathian et al., 1989). These texture changes, unlike those due to varying groove width, are not represented in the discharge rate of tactile primary afferent fibers. Instead, spatial and/or temporal response patterns, encoding grating spatial/temporal frequency, are probably involved (Sathian, 1989; Sathian et al., 1989). We asked whether target popout in touch is exclusively linked to a peripheral neural rate code, or whether it can be generated by representations of surfaces that at least in the periphery are spatiotemporal (i.e., non-rate-code-based). The presence/absence asymmetry paradigm of Experiments 1 and 2 was chosen for this set of experiments, because it showed the clearest task-related difference in attentional demand.

Design

The design and ANOVAs of Experiments 1 and 2 were replicated in Experiments 5 and 6, respectively, with changes in ridge width (groove width constant at 1.0 mm) substituted for changes in groove width (ridge width constant). Thus, we looked for an asymmetry of attentional demand between detection of the presence and absence of texture change created by varying ridge width. In Table 1 are listed the spatial parameters of the gratings used. In Experiment 5A, the target grating was one that bore a segment with wider ridges than baseline (Figure 2E) and the distractors had uniformly narrow ridges (Figure 2A). In Experiment 5B, the distractors were gratings with uniformly wide ridges (Figure 2F), and the target grating was distinguished by a segment with ridges narrower than baseline (Figure 2G). The roles of target and distractor of Experiments 5A and 5B (presence of ridge width change) were switched in Experiments 6A and 6B (absence of ridge width change), respectively.

A 6-subject pool participated in these two experiments. All 6 took part in Experiments 5A and 6A, but 1 subject's results had to be

dropped from analysis for Experiment 5B and another's for Experiment 6B, owing to floor effects (see General Method).

Results and Discussion

Though the percentage changes in ridge width were higher than the corresponding changes in groove width (Table 1) for comparable performance, the results paralleled those of Experiments 1 and 2.

Cuing clearly affected detection of the absence (Experiment 6) but not presence (Experiment 5) of a grating bearing ridge-width-dependent texture change (Table 2).

The specific relation of cue and target was not significant in Experiment 5 but was significant in Experiment 6 (Table 2). The largest difference in Experiment 6 (between valid cuing and invalid cuing on the digit non-homologous with the target digit) was significant according to Scheffé's test.

Among other effects, the only significant effect in Experiment 5 was that of task subtype (Table 5). Its interaction with cuing (Table 5) was not significant, nor were any of the other main-effect variables or interaction terms. In Experiment 6, none of the effects besides cuing effects were significant.

These findings demonstrate that asymmetry of attentional demand for presence versus absence of texture change holds for texture changes based on ridge width. This shows that consideration of texture change as a tactile "feature" can be broadened to include texture changes based on non-rate-based neural codes. In other words, in the tactile system, perceptual processing independent of directed attention ("preattentive") has access to representations of surfaces coded in spatiotemporal response patterns in peripheral receptors. There are several possible explanations for this. One is that the representations of gratings differing in ridge width when groove width is constant remain spatiotemporal in the central nervous system. Preattentive processes mediating "popout" might then have access to such representations, analogous to their access to a variety of properties of the visual scene (Enns & Rensink, 1990; McLeod et al., 1988; Nakayama & Silverman, 1986; Ramachandran, 1988). Alternatively, "popout" in touch may depend solely on intensive (rate) changes in appropriate detectors. This presupposes that the peripheral spatiotemporal representation is transformed to one in the brain that is rate-based. A third possibility is that spatiotemporal representations are critical for preattentive perception of changes in groove and ridge width. Spatiotemporal response patterns in primary afferent fibers represent changes in both width parameters (Sathian et al., 1989). We cannot distinguish between these multiple possibilities at this time.

The percentage changes in ridge width were much larger than corresponding changes in groove width, for comparable levels of performance. This suggests that changes in ridge width are harder to discriminate. This is consistent with the observation that changes in ridge width alter perceived roughness only about a third as effectively as do changes in groove width (Sathian et al., 1989).

GENERAL DISCUSSION

This study showed that when textures are presented simultaneously to multiple fingerpads, the requirement for spatial focusing of attention varies along a continuum (Duncan & Humphreys, 1989) and can be small or absent in some instances. Perception of an abrupt texture change may be independent of directed attention. However, comparably difficult intertexture discriminations are aided by selective attention. This is important during manual sensory exploration, when multiple simultaneous and sequential stimuli bombard the tactile system (Sherrington, 1900). Sequential texture change could provide a preattentive signal (Julesz, 1984; Treisman, 1988) that focuses attention (presumably distributed among the exploring digits) on the appropriate locus for further action. When multiple texture changes are encountered together, the direction of attention to the correct locus is helpful for deciding whether texture change is absent (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991) or whether its direction differs from that at other loci.

Our preliminary observations reveal that variations in distractor heterogeneity might contribute to some of the intertask differences we noted. In the experiments in which the distractors had texture changes (detection of the absence or distinguishing the direction of texture change: Experiments 2, 3, and 6), the interposed segments were not aligned and hence were encountered at different intervals during the stroke. In contrast, the distractors in presence detection tasks (Experiments 1 and 5) were all identical. The differing spatiotemporal heterogeneity of distractors, then, may have caused the attentional requirements to differ in the two groups of experiments (Duncan & Humphreys, 1989). These considerations do not apply to the experiments involving intertexture discrimination (Experiment 4), in which the distractors were all uniform gratings. The differences in attentional demand between these experiments and the detection of the presence of texture change could be attributed to the targets' possessing in the latter case a specific feature (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991) that decreased their similarity to the distractors (Duncan & Humphreys, 1989). If a feature difference can be thought of (as in the present study) as a qualitative dissimilarity, then the viewpoint of Treisman and her co-workers is consonant with that of Duncan and Humphreys.

The failure of Lederman and colleagues (Lederman et al., 1988) to find task-dependent variations in tactile attentional demand probably can be attributed to their choice of stimuli. They did not use texture changes. The possibility that a changing stimulus may be preattentively perceived in touch is supported by the present study and by Whang et al. (1991). This is consistent with the possibility that attentional demand varies along a continuum (Duncan & Humphreys, 1989; and present study). Candidate preattentive features may be thought of as being at one end of the continuum, serving as "attention-

getters" that are explicitly coded in neuronal responses (Julesz, 1984; Treisman, 1988).

By analogy with previous work (Treisman & Gormican, 1988; Treisman & Souther, 1985; Whang et al., 1991), our results lead to the prediction that specific detectors of texture change exist within the part of the central nervous system that receives somatosensory inputs. Similar detectors of intensity change form a critical part of a model that accounts for presence/absence asymmetry of attentional demand in vibrotactile tasks (Whang et al., 1991). In this model, detectors of change (d) at each locus of stimulation are assumed to feed into a change detector (D) that pools activity across these loci. Hence, the presence of a change at any of the loci is detectable at D without directing attention to the specific locus (d). In detecting the absence of change, however, the activity of multiple d s introduces additional sources of variance that increase decision noise at D , so it is advantageous to direct attention by appropriately weighing the inputs from different d s. This model could account for the presence/absence results of the present study.

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