Haptics-e, Vol. 4, No. 2, April 21, 2006
http://www.haptics-e.org

HAPTIC EXPLORATION AND THE PERCEPTION OF TEXTURE ORIENTATIONS

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ABSTRACT

The perceptual sensitivity of touch to orientation differences in adjacent segments of textures with different configurations was measured in two experiments. We found that sensitivity to the orientation difference was not only a function of the magnitude of that difference but of the reference orientation. In Experiment 1, we examined the exploratory patterns that were used to make these judgments and found that distinct exploratory patterns were used early but tended to converge on one dominant pattern. In Experiment 2, constraining exploration trajectories to previously unobserved patterns and halving exploration time only slightly lowered perceptual accuracy but did not alter the pattern of effects. That the configuration of the texture elements influenced accuracy more than did the exploratory procedure used has implications for how texture is encoded through the skin and the procedural knowledge underlying haptic texture exploration.

1. INTRODUCTION

1.1. Exploratory procedures. If asked to identify an unseen object, people undertake one or more of a small number of manual actions over the object. In contrast to acts that serve behavioral goals (such as reaching for the object), these manual activities are notable for being intentionally perceptual and are executed in specific ways according to the perceptual objective. Collectively, such manipulations are termed “exploratory procedures,” or EPs (*e.g.*, Klatzky & Lederman, 1990, 1995; Lederman & Klatzky, 1987, 1990, 1998).

There are at least three reasons to think that EPs are knowledge-driven. First, the precise EP used to recover a particular object property is specific and predictable; *e.g.*, a person asked to judge the roughness of a surface will use an EP termed LATERAL MOTION, comprising skin contact and motion across and orthogonal to the surface. Second, the repertoire of EPs is restricted in number[1] and choosing among EPs in

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[1] In addition to LATERAL MOTION, the repertoire includes STATIC CONTACT for temperature, ENCLOSURE for global shape and volume, PRESSURE for hardness, HOLDING (or HEFTING or WIELDING) for weight

order to satisfy a particular task goal implies knowledge of that repertoire, including whether a given procedure is necessary or sufficient or inappropriate for a particular task. More than one procedure may be recruited for a task, multiple procedures can be executed in sequences and some, but not all, procedures can be combined (Lederman & Klatzky, 1996). Hence, third, the knowledge base for EPs apparently includes information as to whether procedures are compatible and, if so, how EPs may be linked in time and space.

That EPs are knowledge-driven need not imply that EPs are planned entirely in advance. EP selection may be influenced by new task demands and other novel constraints, such as whether, at that moment, a given EP can be physically executed, how much time is available to reach a perceptual conclusion (*e.g.*, Klatzky & Lederman, 1995, 1998) or whether contact occurs indirectly via gloves, sheaths or probes (*e.g.*, Klatzky & Lederman, 1999, 2004; Lakatos & Marks, 1999). Hence satisfying immediate task constraints may be an important feature of perceptual success (see also Klatzky & Lederman, 1993). Constraints can have differential effects on EP efficacy. For example, shape perception may deteriorate if only a single finger is used, but texture perception may be unaffected by the same restriction (Klatzky & Lederman, 1993, 2004). We examine how the EP LATERAL MOTION is used in the perception of the orientations of areas of texture elements that comprise a surface, as well as the extent to which constraining exploration affects accuracy.

1.2 Texture perception, touch and motion. When an area of skin sweeps across a textured surface, the proximal pattern of stimulation changes rapidly. This sensory event is a function of both the geometry of the texture elements (including elemental shape and configural spacing and orientation) and the relative motion between skin and surface. Experiments reveal that when textures are explored with the fingerpads, judgments of roughness are almost equivalent when the surface is moved against static skin (passive touch) and when actively explored (see, *e.g.*, Lamb, 1983; Lederman, 1974, 1981, 1982, 1983). Moreover, since large differences in movement velocity have only slight effects on perceived roughness (Taylor & Lederman, 1975; Taylor, Lederman & Gibson, 1973), it may be concluded that either (a) cutaneous sources of information are necessary and sufficient for texture perception or (b) that relative skin velocity is “taken into account” during exploration.

Johnson and colleagues (*e.g.*, Connor & Johnson, 1992; Connor, Hsiao, Phillips & Johnson, 1990; Johnson, Hsiao & Twombly, 1995) have argued that relative motion between skin and textured surface activates slowly adapting (SA) receptors whose projections to area 3B of somatosensory cortex results in the cortical derivation of the spatial variation in the discharge of adjacent peripheral afferents. By this, they argue, the extraction of the spatial distribution of texture elements is achieved independently of the velocity or other characteristics of the movements and that no such taking into account of them is necessary. According to this model, while the execution of the EP LATERAL MOTION (a) generates activity in other cutaneous mechanoreceptors, (b) gives rise to proprioceptive discharge from the muscles and joints involved and (c) in the case of active exploration, is based on efferent discharge, none of these sources carries information for perception more precisely than that contained in the cutaneous SA discharge.

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and CONTOUR FOLLOWING for global shape (Lederman, 1991; Lederman & Klatzky, 1987, 1997), although other so-called test procedures whose purpose is to determine whether the object has a special function (such as can-hold-liquids; see, *e.g.*, Lederman & Klatzky, 1997) have been proposed.

However, the possibility that scanned element frequency encoding (involving rapidly adapting afferents) also occurs, or that relative movement velocity is factored into computations of texture, has not been ruled out completely (*e.g.*, Cascio & Sathian, 2001; Gamzu & Ahissar, 2001; Mefta, Belingard & Chapman, 2000; Wang & Hughes, 2005), especially with respect to surfaces with highly concentrated or highly dispersed elements (*e.g.*, Bensmaïa & Hollins, 2003; Hollins & Risner, 2000, but see Yoshioka, Gibb, Dorsch, Hsiao & Johnson, 2001).

Research on the perception of surface roughness has tended to involve the use of surfaces that are absolutely regular (*e.g.*, raised dots, machined gratings) or stochastically so (*e.g.*, sandpaper). However, regular textures may confound the perception of the texture with the perceiver's prior knowledge or expectation of regularity. Knowing *a priori* that a surface is regular might affect the subsequent exploration(s) of the surface (*e.g.*, by encouraging partial sampling), or perceptual accuracy (*e.g.*, any perceived variation in a surface property may be ignored), or both. Therefore, textures comprising higher order configurations have the power to test the capacities of the haptic system to extract textures in ways that regular textures cannot (Holmes, Hughes & Jansson, 1998; Hughes, 1997; Hughes & Jansson, 1994).

1.3 Experimental rationale. We focus on the details of the EP LATERAL MOTION used in the perception of texture and ask: With what accuracy can higher order levels of texture configurations (differences in orientation) be extracted by active haptic exploration? With what degree of consistency within and between participants is the EP executed? Is perceptual accuracy a function of the surface geometry, the actions by which that surface is explored, or both?

We asked participants to make decisions about the relative orientations of adjacent semicircular areas of texture elements. Under the presumption that perceivers would explore in ways that they know in advance, or come to know by exploration, are most efficient and/or accurate, and not in ways known not to be, we measured perceptual accuracy under two quite different conditions: the first with few constraints on exploration, the second with stricter constraints applied to movement directions and exploration durations.

2. EXPERIMENT 1

Imagine unsighted participants being asked to explore by touch the surface depicted in Figure 1 in order to judge whether the orientation of the dots is equal (*i.e.*, parallel) in the circle's left and right halves. The dots in each circular pattern correspond to raised elements that indent the skin surface when touched. Each surface's texture elements are equally and evenly spaced (approximately 3 mm in each direction) so each semicircle likely feels equally rough. Given the task demands, a multitude of specific exploration patterns, *prima facie*, could generate information sufficient to make a decision, including discrete explorations of each semicircle or full-contact sweeps (in any direction) across the boundary between semicircles.

2.1 Method

2.1.1 Stimulus surfaces. Software versions of 24 circular surfaces, each of 10.0 cm diameter, comprising an arrangement of circular dots, were developed. The surfaces were segmented into left and right semicircles such that the orientations of the dot rows/columns corresponded to upright (or 0º), or 30º or 60º away from upright

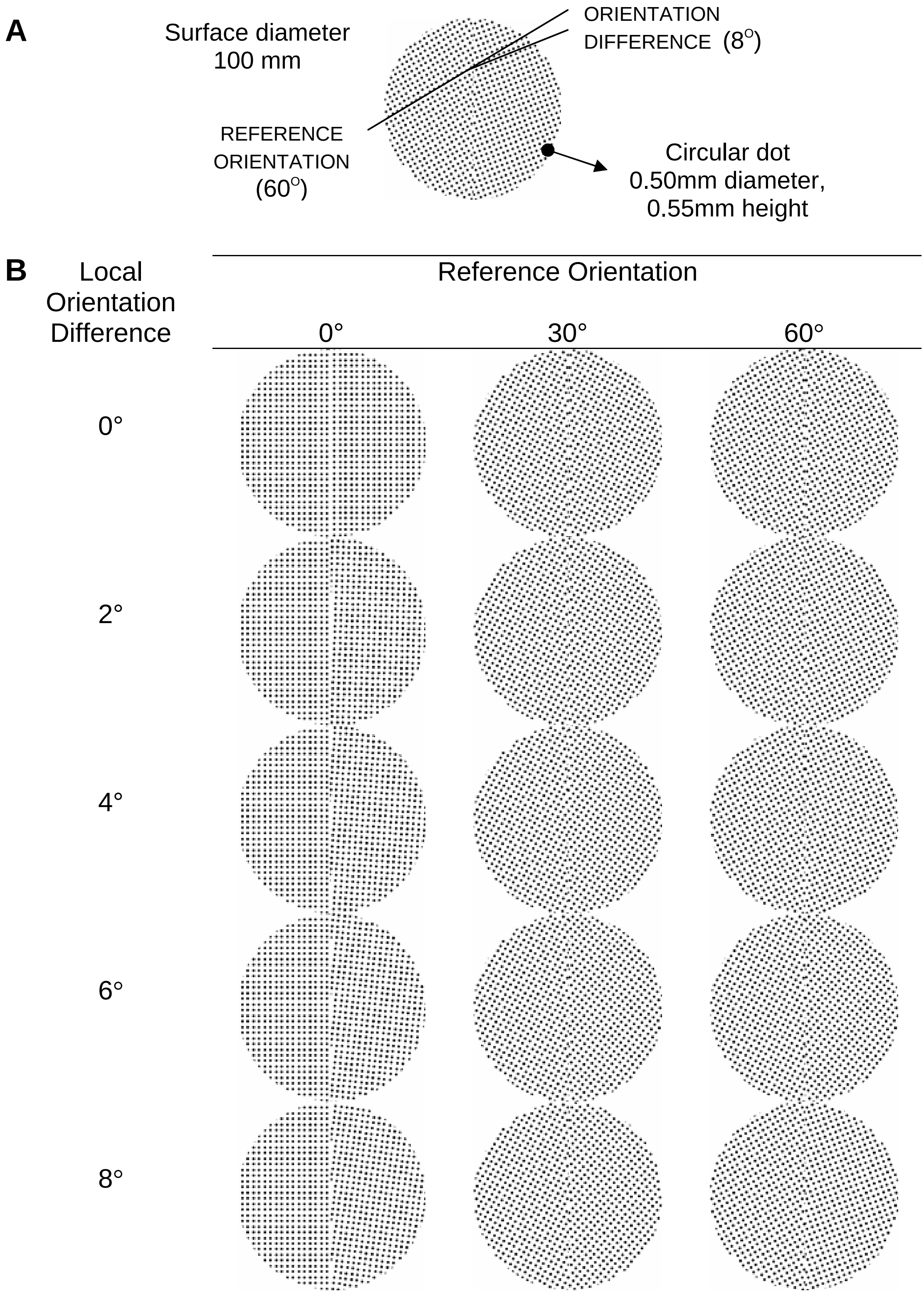

Figure 1. Panel A: Schematic representation of surface segmented by an invisible vertical boundary. The elements were of uniform size height and spacing. In the left semicircle, the elements are arranged in 'columns' whose orientation is 60° clockwise from upright. Relative to this arrangement, the configuration in the right semicircle is oriented a further 8° clockwise. Panel B: Set of surfaces used in both experiments.

(in a clockwise direction)[2]. In half the surfaces, for each of these *left* (or *reference*) orientations, the local orientation of the dots in the right semicircle were rotated clockwise by an additional 2º, 4º, 6º, or 8º, creating local orientation differences of these magnitudes. For each of the 12 surfaces that contained a local orientation difference, we created a matching set of 12 surfaces with no local difference (0º). The digital images were realized as textured surfaces on a smooth nylon plate through a photoetching process, generating surfaces whose elements measured 0.50 mm in diameter with a 0.55 mm relief height.

2.1.2 Participants. All the procedures described below received prior approval of the University of Auckland Human Participants Research Committee and all participants gave informed consent prior to participation. Twelve sighted volunteers (9 women and 3 men, ranging in age from 19 to 50 years) took part and were compensated with book vouchers. All were right-hand dominant, free from cutaneous or motor impairments and non-readers of Braille. None saw the surfaces until his or her participation was complete.

2.1.3 Procedure. Working under blindfold and wearing a sound-attenuating headset, participants explored one surface at a time so as to be able to make a two-alternative, forced-choice (2AFC) decision: that the surface either did or did not contain an orientation difference in dot alignment between semicircles. Participants explored and judged each of the 24 surfaces in three phases (of which they had no knowledge): one exposure to the 24 surfaces in random order, followed by a randomly ordered set of 240 trials (involving 10 replications), followed by a single replication of the 24 surfaces randomly ordered. We made videotape recordings of the first and last complete replications. These trials were recorded using a tripod-mounted, digital video camera (Panasonic NV-DS28) linked via a firewire kit to a laboratory computer for storage and analysis.

Participants were required to use a single fingerpad (not a fingertip or fingernail) of the dominant hand[3], but were free to explore without restriction as to movement speed, direction, force, or duration. Having explored a surface, each participant made the 2AFC decision and then rated the confidence with which that decision was made. For our purposes, a *hit* occurred if the surface contained a local orientation difference and the participant responded that s/he detected it; a *false alarm* corresponded to a report of an orientation difference when the surface contained none. Participants were aware that the probabilities of the presence and absence of an orientation difference were equated but they were neither informed of nor asked to report on the left/reference orientation, nor did they receive trial-by-trial feedback as to the accuracy of their judgments.

2.2 Results

Individual participants' raw data (minus trials on which more than one finger or the fingertip was inadvertently used, which amounted to a total of 17 trials across 5 participants) were transformed into z-scores from which mean estimates of perceptual sensitivity (*d'*) and response bias were calculated. Response confidence estimates were averaged (but not normalized) across replications prior to statistical analysis.

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[2] Given that rows and columns were arranged orthogonally, a 30° clockwise rotation is equivalent to a 60° counterclockwise rotation and a 60° clockwise rotation is equivalent to a 30° counterclockwise rotation

[3] The constraint of a single fingerpad was made following pilot work in which we found universal preference for using a single fingerpad in this task, a preference that is not well understood.

Estimates of perceptual sensitivity to the texture differences are shown in Figure 2 (panel A). Analysis of variance (ANOVA) revealed that sensitivity increased with the magnitude of the local difference in orientation, $F(3,33) = 15.30$, $p < .01$. Sensitivity was also strongly influenced by the orientation of the dots in the left semicircle, $F(2,22) = 15.98$, $p < .01$. These factors also interacted, $F(6,66) = 2.42$, $p < .04$. Sensitivity tended to increase as the size of the orientation difference increased although when the left orientation was 0º, sensitivity to orientation differences was uniformly high ($d' > 3.0$) and did not change (linear regression revealed a slope of 0.032). When the reference orientation was oblique (*i.e.*, 30º or 60º), participants were not capable of reliably detecting orientation differences of less than 8º although sensitivity increased across the range (regression slopes: 0.138 and 0.249, respectively).

ANOVA showed that neither local differences in orientation nor the reference orientation altered the relative proportion of yes and no responses: $F(3,33) = 1.83$, $p > .16$, and $F(2,22) < 1$, respectively, suggesting that response decisions conformed well to presentation probabilities across all conditions (see Figure 2, panel B).

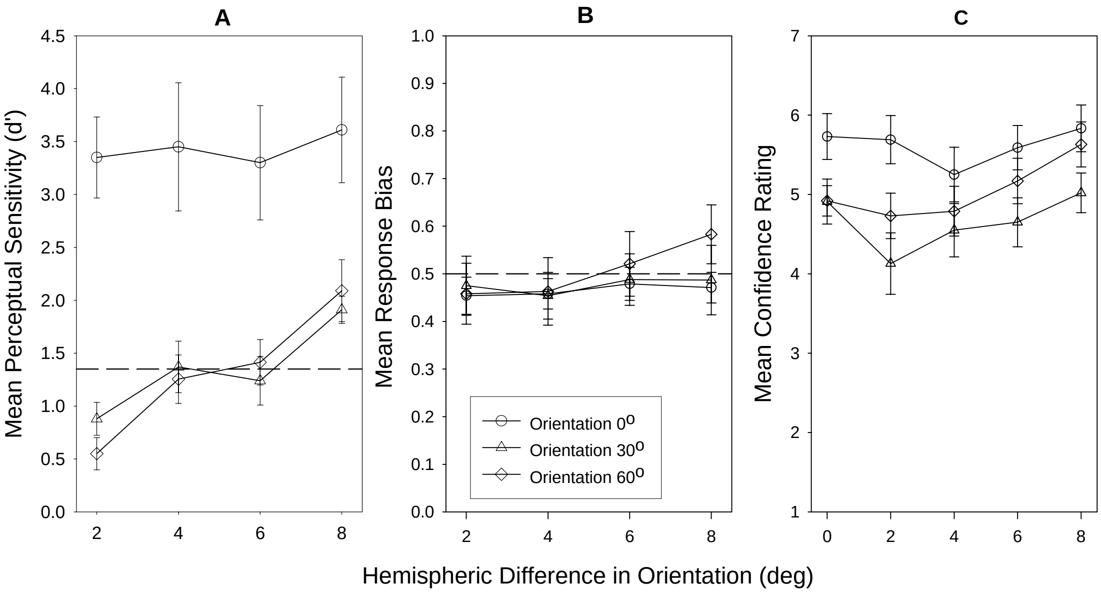

Figure 2. Mean data (with standard errors) from Experiment 1. Panel A depicts mean perceptual sensitivity (*d'*) as a function of reference orientation and local orientation differences. Panel B depicts response bias and Panel C depicts mean confidence estimates for each level of these factors.

Participants' mean confidence ratings, by condition, are shown in panel C of Figure 2. ANOVA revealed main effects for both local orientation differences, $F(4,44) = 3.36$, $p < .02$, and the reference orientation, $F(2, 22) = 9.44$, $p < .01$. These factors did not interact: $F(8,88) = 1.93$, $p > .06$. While participants were more confident in their judgements of orientation differences when the left orientation was 0º, they were less confident in their judgments of surfaces with oblique reference orientations.

We extracted from the video recordings estimates of the exploration durations required by participants to make their decisions in the early trials (1-24) and late trials

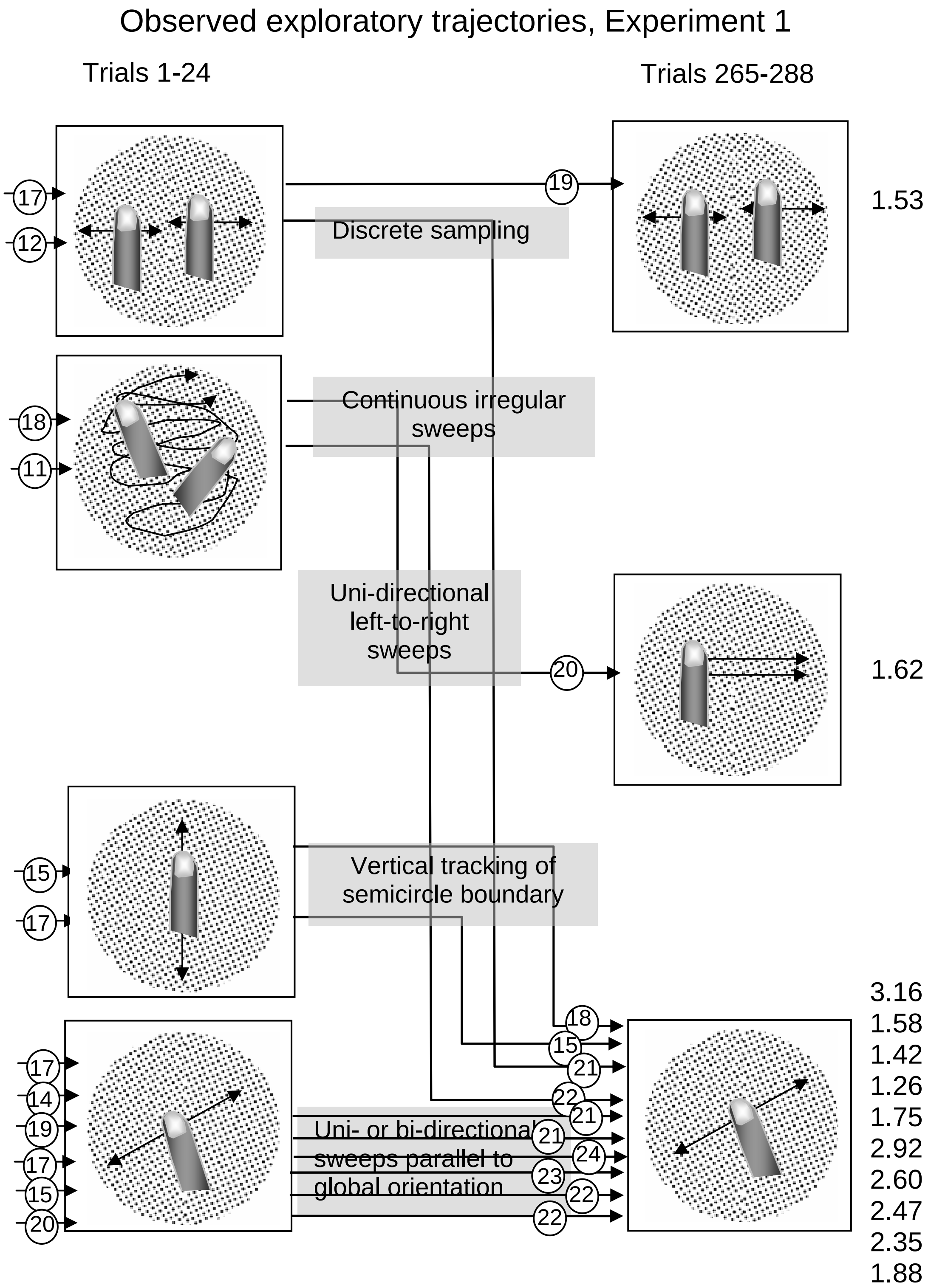

Figure 3. Schematic representation of exploration types, observed during first 24 trials (left panel) and last 24 trials (right panel) in Experiment 1. The circular areas represent a textured surface superimposed by a schematic exploring finger. The arrows to and from exploration types indicate the number of participants for whom this was the modal type of exploration and the circled numbers indicate the number of trials (of 24) for which this was the sole mode of exploration observed. The numbers arrayed vertically on the far right are mean *d'* scores for each participant, pooled over condition.

(265-288). Participants explored for durations anywhere between 3 and 25 s before making a decision, with a mean exploration time of 8.1 s (standard deviation: 3.9 s). Figure 3 depicts the types of explorations observed, by participant. Participants adopted distinct variants of the EP, LATERAL MOTION, each of which could have permitted detection of the local orientation differences. No participant engaged in explorations incompatible with the task (*e.g.*, no one explored only one semicircle).

A variety of exploration patterns was observed in the initial phase and these patterns were diverse in several respects (the left panel of Figure 3). Among them were those in which surface contact was maintained and others in which more discrete sampling of semicircles occurred; some explorations were along the vertical boundary, some were across it. The exploration patterns of two participants were quite irregular. In the most common exploratory pattern (adopted by half of the participants) participants sought to locate and then follow the reference orientation across the vertical boundary, presumably seeking to discriminate orientation differences as they moved. These sweeps were observed to take both unidirectional (sweeping across the surface in one direction, breaking surface contact and returning the finger to sweep again) and bi-directional forms and participants often combined lateral motion with a rotation of the finger that made the finger's long axis perpendicular to the reference orientation.

The circled numbers in Figure 3 indicate the number of trials (of a maximum of 24) in which a perceiver's modal exploratory pattern was observed, in the early and late phases. These numbers suggest that participants were more likely to execute different movements early in practice and more likely to have settled on a stable pattern late in practice. The modal pattern was adopted on an average of 16.0 (66.7%) early trials and an average of 20.7 (86.1%) later trials. The recordings revealed that five of the 12 participants changed the exploration pattern between the first 24 trials and the last 24 trials. Of the six participants who adopted the modal exploration pattern, all were observed to be persisting with that pattern at the end of the experiment. By the last 24 trials, all but two participants had adopted the exploration pattern that involved tracking the reference orientation across the vertical boundary and, of those two, one continued to engage in discrete sampling of the semicircles in turn and the other engaged in unidirectional left-right sweeps (irrespective of reference orientation) across the boundary.

The numbers on the right of Figure 3 indicate individual mean *d'* scores (averaged over condition). Although the overwhelming preference for one mode of exploration complicates interpretation, it is nonetheless clear that adopting the preferred mode and accuracy are strongly but not perfectly matched: participants adopting the preferred mode did not produce systematically higher levels of accuracy (e.g., this group includes the best and worst performed).

2.3 Discussion

The evidence of this experiment suggests that unsighted participants, given a particular perceptual task, explore textured surfaces in a variety of ways, with different degrees of success. Under minimal constraints, the EP LATERAL MOTION appears to be deployed variably, according to task demands, strategic factors, as well as perceived success of prior explorations. We observed differential levels of perceptual accuracy and confidence, as well as a convergence on a single way to explore.

The dependence of the discriminability of local orientation differences on the reference orientation of the textures (as well as on the magnitude of the orientation difference) suggests a potential anisotropy in texture perception; namely that textures with oblique configurations could not be as accurately judged as containing orientation differences. If confirmed, this raises the prospect that exploratory movements induce orientation-specific percepts. Oblique effects in the haptic perception of orientation are not new (see Gentaz & Hatwell, 1999; Kappers, 2003; and Kappers & Koenderink, 1999, for recent treatments) but such an oblique effect with textures has not been previously reported.

Degrees of freedom of exploration did not alter the effect: participants' sensitivities were lower with oblique reference configurations regardless of the method of exploration. Participants were free to explore the surfaces with trajectories and for durations of their choosing. Most converged on an exploratory procedure that involved locating and the moving the fingerpad along a ridge of dots at that semicircle's (perceived) orientation then seeking to determine whether a local orientation shift was present. Despite this preference, the reference orientation was a significant factor in detecting a local orientation difference.

A further test of the nature of haptic sensitivity to textures was sought in a second experiment. Could the expressed preference for one exploratory procedure be attributed to a knowledge that this specific way of exploring would lead to greater perceptual sensitivity than any other? One way to establish the coherence of the exploration mode with the resultant perceptual accuracy is to constrain explorations severely and measure whether accuracy diminishes (generally or condition-specifically) as a result. If the knowledge that underlies EPs includes a known (or acquired) appreciation for the strategy most likely to maximise sensitivity (whatever its absolute level), then forcing participants to explore in a quite different way (and without the opportunity to change that mode of exploration) should significantly diminish sensitivity.

3. EXPERIMENT 2

Constraining participants' explorations enables us to determine if the levels of performance observed in Experiment 1 were owing more to (a) how perceptual exploration took place or (b) the structure of the surfaces being explored. Two additional constraints on exploration were applied in this experiment: we required that all participants use a single trajectory type --one rarely observed in Experiment 1 (and never in the later trials)-- throughout the experiment. We constrained movements to smooth cyclical left-right sweeps with the single contact finger pointing directly forward. In addition, we restricted exploration duration to half the mean observed in Experiment 1; i.e., approximately 4 s. We hypothesized that if a preferred exploration method is important for accuracy it would likely be one of those observed in Experiment 1, and if participants were prevented from deploying that method, sensitivity would diminish, perhaps to near-zero levels. On the other hand, if sensitivity is unchanged by these restrictions, then we may infer that the precise characteristics of the movements have a less causal role in perception and that textural information can be extracted regardless of exploration trajectories. Such an outcome would invite the question of why any single exploratory mode was preferred in Experiment 1.

3.1 Method

The methods were the same as those of Experiment 1 with the following exceptions.

3.1.1 Participants. Twelve new right-hand dominant volunteers (9 women and 3 men, ranging in age from 19 to 36 years) were recruited.

3.1.2 Procedure. Participants were restricted to non-stop, left-right cyclical sweeps for 4-5 s. We did not prevent up-down shifts of the sweeps, nor did we restrict velocity in any way except that we asked participants not to stop moving until trial completion. Such movements ensured approximately equal sampling of the two semicircles. The experimenter confirmed that these directions were followed. No videotape recording of explorations was undertaken.

3.2 Results

Individual participants' raw data were transformed in the same way as Experiment 1. Estimates of perceptual sensitivity to the texture differences are shown in panel A of Figure 4. ANOVA revealed main effects of the difference in orientation, $F(3,33) = 14.34$, $p < .01$, and of the reference orientation of the dots in the left semicircle, $F(2,22) = 14.40$, $p < .01$. These factors also interacted, $F(5, 55) = 3.22$, $p < .01$. Perceptual sensitivity increased as the size of the orientation difference increased, although not when the reference orientation was 0º (linear regression slope: 0.055), when sensitivity was uniformly high (*d'* near 3.0). When the reference orientation was oblique (*i.e.*, 30º or 60º), participants' sensitivity increased steadily with the orientation differences (regression slopes: 0.137 and 0.171, respectively), although only with differences of 8º could discrimination be described as reliable. These data essentially replicate those of Experiment 1: the absolute levels of sensitivity and the statistical effect sizes are similar.

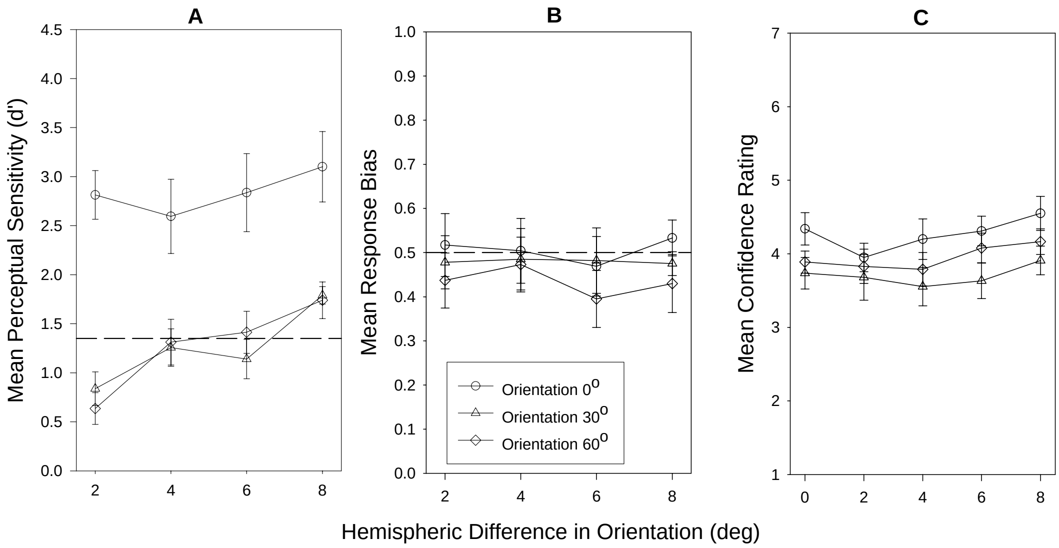

Figure 4. Mean data (with standard errors) from Experiment 2. Panel A depicts mean perceptual sensitivity (*d'*) as a function of reference orientation and local orientation differences. Panel B depicts response bias and Panel C depicts mean confidence estimates for each level of these factors.

No clear bias in participants' decisions was evident: neither local differences in orientation, $F(3,33) < 1$, nor the reference orientation, $F(2,22) < 1$, significantly altered the relative proportion of yes and no responses (panel B, Figure 4). Participants' mean confidence ratings, by condition, are shown in the panel C of Figure 4. ANOVA revealed a main effect of reference orientation, $F(2, 22) = 6.30$, $p < .01$, but not of the local orientation difference, $F(4,44) = 2.46$, $p > .05$. These factors did not interact: $F(8,88) < 1$. Response confidence was higher for surfaces with a 0° orientation in the left semicircle; confidence appeared to be determined more by this reference orientation of the textures than by the magnitude of the local difference.

3.3 Discussion

Relative to the data of Experiment 1, constraining exploration trajectories and durations did little to change the overall pattern of results. Participants' mean accuracy in detecting local orientation differences were again strongly influenced by both the local orientation difference, and by the reference orientation of the texture elements, an interaction suggesting an oblique effect. At a left orientation of 0º, discrimination of all local differences was routinely high but at oblique orientations sensitivity was lower and only the largest differences in orientation were reliably discriminable. Applying exploratory constraints had the effects of reducing confidence in only those judgments that were already high in accuracy (*i.e.*, those of surfaces with a reference orientation of 0º) and suppressing confidence in the judgments made, but otherwise did remarkably little to diminish performance.

4. GENERAL DISCUSSION

The models of haptic object-exploration developed by Klatzky and Lederman (*e.g.*, 1993; Klatzky, Lederman & Balakrishnan, 1991; Lederman, Klatzky & Balakrishnan 1991) suggest that procedural knowledge of what to do (to get property information) and information acquired 'on-line' during exploration both contribute to the fidelity and precision of haptic perception. Yet roughness constancy is a robust finding: modes of exploration contribute little to textural roughness judgments (little, that is, relative to the geometries of the textures, which contribute substantially). We asked whether modes of exploration also contribute little to judgments of higher order spatial organization, such as orientation differences? We reasoned that if the independence of texture perception and movement type extends to more complex surfaces, then exploration mode should contribute little to texture element orientation judgments either. On the other hand, if each EP is knowledge-driven and sensitive to task demands, then particular modes of exploration may be observed more often and to greater perceptual effect.

Although a preferred mode of exploration was observed in Experiment 1, the data suggest that modes of exploration indeed contribute little to objective perceptual judgments. The results of the two experiments were similar, despite the relative degrees of exploratory freedom in Experiment 1 that were absent in Experiment 2. Although subjective confidence in judgements was lower under more constrained conditions, accuracy was hardly affected. This suggests that properties, such as the orientational alignment of texture elements, may be processed via the same mechanisms that underlie roughness judgments or, to put it slightly differently, that roughness and orientation are both configural properties whose perceptual processing does not depend on particular movements or movement properties. Sensitivity to orientation differences in our surfaces depended, as do roughness judgements, on the structure of the surfaces and not in how they were explored.

The data also revealed an unexpected complication to an expected effect. If perceivers are sensitive to orientation differences, then we would have expected to find sensitivity measures increasing as the orientation difference increased. Although we found such a statistical effect, it was qualified: when the reference orientation was 0º, sensitivity was uniformly high, but with oblique reference orientations (either 30º or 60º) sensitivity was low, although it increased with larger orientation differences. This new variant of the oblique effect was not expected. Moreover, the effect was also found in the second experiment when explorations were highly constrained. A perceptual constancy for roughness does not lead to predictions of an oblique effect with textures. That the effect was replicated in Experiment 2 suggests that it is not due to movement direction effects: the effect is clear regardless of movement trajectories.

An alternative prospect, which should be examined more carefully before accepting the presence of any oblique effect, is that some feature of the surfaces with a reference orientation of 0º contributed to uniformly high levels of discriminability; that is, might account for the high accuracy with all orientation differences when the reference orientation was 0°. As it happens, the configural properties of these surfaces were distinctive in at least one way not shared by the oblique configurations. The rows and columns of the dots were arranged orthogonally in all surfaces but only with reference orientation 0º did this orthogonality and the vertical semicircle boundary coincide. Panel B of Figure 1 illustrates the difference in configurations at the vertical boundary of the two semicircles between, on one hand the 0° reference orientation and, on the other, the 30°/60° reference orientations. The surfaces had different configural aliasing properties; those associated with the 0° reference orientation were quite unlike those of either the 30° or 60° reference orientations. This difference created boundary gaps that may have made the discrimination of orientation differences easier under the former condition, especially allowing for the reduced acuity of the skin relative to vision. The demarcation of the boundary is visibly clearer with a reference orientation of 0°. Presuming the detection of the boundary aids in the perceptual comparison, if it were also haptically clearer (which we do not yet know with certainty), perceptual comparisons of orientations before and after boundary detection would favour the 0° reference orientation over both of the others. This is a possibility currently under investigation.

Participants are capable of extracting texture information via a variety of movements across a surface and not just from a preferred mode of exploration. Such a finding is consistent with data showing that other roughness judgments are also little altered by large changes in the mode of exploration. However, if the actual pattern of exploration is guided by knowledge that one particular EP variant maximizes perceptual accuracy, then the data also suggest a dissociation between what participants believe is the best exploratory strategy and what suffices. This raises the prospect that nonperceptual factors influence the choice of exploration mode. We are in no position to assert what they are, but candidates could include task-specific strategies rather than procedural knowledge, belief states rather than knowledge, or movement comfort rather than information pickup. Ten of 12 participants in Experiment 1 favored a single exploratory strategy, six of them for the duration of the experiment. In terms of accuracy, this mode was only marginally more effective than different ones over which participants exerted control of speed and force only (but not direction or duration). The confidence ratings indicated that participants in Experiment 2 felt less sure in their judgments overall although it is not possible to say whether this was due to the imposition of constraints generally or the introduction of a specific constraint.

That near-equal perceptual sensitivity emerges from constrained and unconstrained exploratory modes indicates that while perceivers believe that particular modes of exploration are more efficacious, they are not necessarily so. This disjunction between what perceivers believe will give rise to most accurate judgments, on one hand, and what will suffice, on the other, is grounds for further exploration of the knowledge base that underlies haptic exploration as well as mechanisms that contribute to tactile texture perception.

ACKNOWLEDGEMENTS

This research was supported by grants from the University of Auckland Research Committee and the Maurice and Phyllis Paykel Trust. Jarrod McClay, Charity Hui and Vanessa Lam contributed to data collection, the latter also to video analysis. Portions of the data were presented at the International Conference on Touch, Blindness and Neuroscience (Madrid, Spain, October 2002) and the 12th International Conference on Perception and Action (Surfers' Paradise, Australia, July 2003). I thank James Cutting and four anonymous reviewers of an earlier version of this report.

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