Search Efficiency for Tactile Features Rendered by Surface Haptic Displays

John Ware, *Member, IEEE*,
Elizabeth Cha, *Member, IEEE*,
Michael A. Peshkin, *Senior Member, IEEE*,
J. Edward Colgate, *Fellow, IEEE* and
Roberta L. Klatzky, *Senior Member, IEEE*

Abstract—Haptic interfaces controlled by a single fingertip or hand-held probe tend to display surface features individually, requiring serial search for multiple features. Novel surface haptic devices, however, have the potential to provide displays to multiple fingertips simultaneously, affording the possibility of parallel search. Using variable-friction surface haptic devices, we investigated the ability of participants to detect a target feature among a set of distractors in parallel across the fingers. We found that searches for a material property (slipperiness) and an illusory shape (virtual hole) were significantly impaired by distractors, while search for an abrupt discontinuity (virtual edge) was not. The efficiency of search for edges rendered by surface haptics suggests that they engage primitive detectors in the haptic perceptual system.

Index Terms—Haptic perception, search efficiency, surface haptics

1 Introduction

In recent years, increasing attention has been given to "surface haptic" technologies suitable for deployment on touch screens, touch pads, and other touch responsive surfaces [1], [2], [3], [4], [5]. Surface haptic displays may be used to render patterns and textures on the touch surface, potentially in conjunction with graphics, sound, and even other forms of haptics (e.g., vibration). Haptically rendered features might be useful, for example, to guide blind users to informative regions on a webpage [6], or tangible and visible textures might redundantly define controls or text boxes for sighted users [1]. In the context of such applications, it becomes important for functionally different regions of the surface to be readily apprehended through touch. In other words, haptically defined regions should be efficiently parsed and identified.

Highly efficient haptic search may, however, prove challenging. One reason is that some surface haptic devices, like the TPaD [5] considered here, require the fingertips to be in motion. The TPaD is a variable friction device, so the only way to feel effects is to slide the fingers across the surface as the friction is modulated. While a wide variety of effects can be produced, they all require some degree of spatio-temporal integration.

A second reason is that today's touch interfaces typically support multitouch. The combination of multitouch and surface haptics raises a number of interesting questions. For instance, how do haptic features presented to multiple fingertips integrate perceptually [7]? In the present research, however, we ask a more basic question: is the efficiency of search at a given fingertip influenced by the presence of features (distractors) at other fingertips? This question is important to interface designers for two reasons. First, designers should be aware of the extent to which search efficiency (in the surface haptics context) may be impaired by distractors. Second, it is valuable to identify features that are readily differentiated from their surroundings, as these potentially serve as primitive building blocks for higher-order structural representations. By way of analogy, primitives such as visual edges may be used to construct shapes, while phonemes may be used to create words.

The efficiency of detecting and identifying spatial patterns has been extensively studied in visual perception and attention. A commonly used task asks participants to search for a target feature in the context of distractors. Efficiency is measured by the slope of the function relating detection time to the number of stimuli (N). At an extreme, the response time is statistically invariant over N, at least within the power of the experiment. This occurs, for example, when participants search for a horizontal line in a visual display of verticals.

In a now classic paper, Treisman and Gelade [8] suggested that search-time invariance identifies features that are extracted in parallel across the visual field, without need for attentional control; such features constitute perceptual primitives. A further diagnostic for primitives is demonstrated by search asymmetries, where feature A is easily detected in a field of Bs but B is not so in A. According to Treisman and colleagues [9], [10] this pattern indicates that A has a primitive component not present in B. For example, by virtue of its added yellow component, orange emerges in a field of red, but not the reverse. This example illustrates the point that a search for the *absence* of a feature generally will not occur in parallel.

Lederman and Klatzky [11] extended search tasks to the haptic domain, where target and distractor stimuli were surfaces presented to individual fingers. They found, for example, that search is highly efficient (statistically flat slopes occur) when a rough surface presented to one finger is detected among smooth surfaces presented to other fingers, and vice versa. In other cases, e.g., searching for a raised horizontal edge amid verticals, the response time increased linearly with N. The authors suggested that targets distinguished by stimulation intensity could be detected essentially in parallel, whereas finger-by-finger processing was needed for spatial-pattern distinctions. Overvliet et al. [12] confirmed this general trend in haptic search tasks where participants could anticipate the number and location of targets. Their data for spatial searches fit a serial, self-terminating model, whereby the time for positive detections depended on the single finger contacting the target, but target-absent searches reflected the slowest processing across all stimulated fingers. Haptic search has further been extended to features of fully three-dimensional shapes grasped in the hand. With this method, Plaisier et al. [13] found that edges and vertices appear to constitute primitives. For example, a low slope was found for positively detecting a cube target among spheres, whereas there was slower search on target-absent trials or for detecting a sphere among cubes (i.e., search asymmetries).

While a distinction has often been made between parallel search, leading to response-time invariance across N, and item-by-item search, leading to positive slopes, the literature on visual and haptic search makes clear that a strict dichotomy is inappropriate. In a review of visual search covering approximately a million trials, Wolfe [14] found that the distribution of slopes was overall unimodal (not bimodal as predicted by two distinct search processes). Moreover, search tasks varied broadly in efficiency, as measured by slope. The possibility of a broad range of efficiency in search seems particularly relevant to the haptic domain, where the primitives are extracted by distinct populations of receptors and may require active exploration, factors that promote variability. Evidence for such variation is reviewed below in the context of the present results.

- *J. Ware is with the Department of Mechanical Engineering, MIT, MA 02139. E-mail: jakeware@gmail.com.*
- *E. Cha is with the Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213. E-mail: lizcha@cmu.edu.*
- *M.A. Peshkin is with the Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208. E-mail: peshkin@northwestern.edu.*
- *J.E. Colgate is with the Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208. E-mail: colgate@northwestern.edu.*
- *R.L. Klatzky is with the Department of Psychology and Human-Computer Interaction Institute, Carnegie Mellon University, Pittsburgh, PA 15213. E-mail: klatzky@cmu.edu.*

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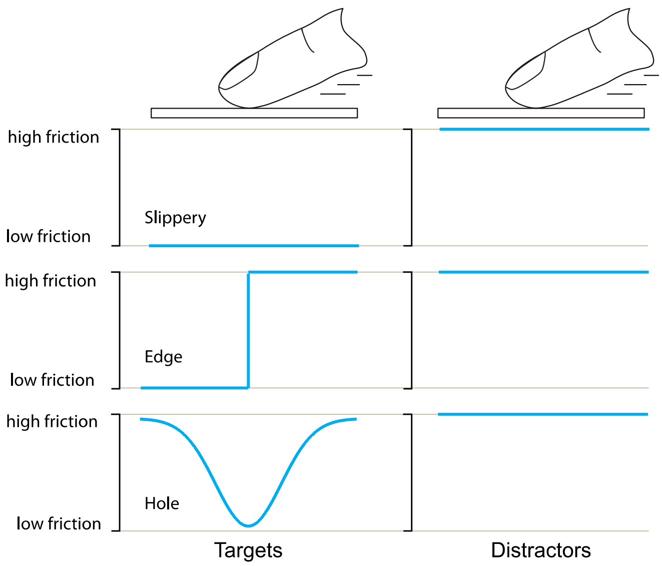

Fig. 1. The three target-distractor pairs considered in this work. Targets are exemplars of material, abrupt-surface discontinuity, and 3D continuous surface types from [11]. The distractor in each pair is the flat glass surface with its native friction.

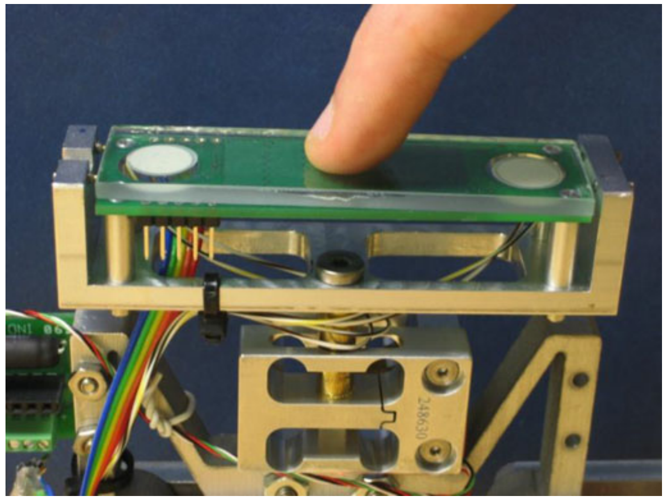

Fig. 2. One of six identical surface haptic assemblies used in this study. The touch surface is a TPaD made of glass with piezo disks glued to either end. Immediately beneath the TPaD is a capacitive sensor for measuring finger position. These are mounted in an aluminum frame that is supported on load cells.

The surface haptic technology we used for this work is the TPaD, or Tactile Pattern Display. The TPaD is a variable friction device: ultrasonic vibrations of the touch surface act to reduce the effective coefficient of friction between the touch surface and a fingertip [5], [15], [16]. Friction can be reduced by as much as one order of magnitude [2]. By amplitude modulation of the ultrasonic excitation, complex tactile effects with frequency components from DC to several hundred Hertz can be produced. Additionally, if friction is modulated in response to measured fingertip position, illusory 3D features such as virtual edges and virtual bumps may be produced [2]. But it should be appreciated that, in addition to the limitations mentioned earlier, no variation of force within the fingerpad is possible, and forces can act only in a direction opposite to the motion of the finger.

The stimuli used to test search efficiency with the TPaD were based on the studies of Lederman and Klatzky [11], which categorized target-distractor pairs into four groups: Material (e.g., rough/smooth); abrupt-surface discontinuities (e.g., no edge/edge); relative orientation (e.g., right slant/ left slant); and 3D continuous surface (e.g., flat/curved). The TPaD is poorly suited to display relative orientation; thus we did not use that category. We tested one comparison from each of the other three categories (Fig. 1), focusing on targets that might be useful building blocks for higher-level patterns. For material, we tested a slippery (low friction) target among high friction distractors. For abrupt-surface discontinuity we tested an edge among no-edge distractors. For 3D continuous surface, we tested a virtual hole among flat distractors, as the hole represents one of the most compelling 3D illusions achievable with the system. In each case the distractor is flat glass with its native friction, unmodulated.

These choices were made on the basis of an initial study in which the participant indicated which of two features was presented. Over five participants with 128 trials each, discrimination accuracy was very high for edge versus no-edge, bump versus no-bump, and bump versus hole (hit rate of .99, false alarm rate of .02 or less). Discrimination between a slippery surface versus native glass friction was only slightly less accurate (hit rate of .93, false alarm rate of .01). Additional pilot testing showed participants had high accuracy in a search task with up to six stimuli for discriminating edge and bump against null (native) surfaces. Given the ease of discrimination and search, the three contrasts we selected seemed excellent candidates for efficient search.

The present stimuli depart from most visual search tasks, in that they contrast the presence vs. absence of a feature rather than two levels on some continuum. This approach has a precedent in previous haptic search studies [11]. Moreover, given preliminary results with the TPaD display, present/absent features appeared to represent the best prospects for efficient detection, and if these are not detected efficiently, there is little reason to make the task more difficult. A more pragmatic rationale is that the state of the art in the technology does not guarantee exact matches in feature rendering across different TPaDs. The use of native glass friction for distractors essentially guarantees that all stimulated fingers produce comparable percepts.

2 Methods

2.1 Participants

Fourteen young adults from the university community completed the experiment (five female, nine male). An additional three participants were eliminated because they could not master the apparatus during training (one female, two male). The protocol was approved by the Northwestern University Institutional Review Board and all participants gave informed consent.

2.2 Apparatus

The apparatus used in this study (Fig. 3) is based on the Q'Hand device created by Moore et al. [17]. It is capable of presenting six fingers with unique stimuli and removing all stimuli from inactive fingers. It also offers some adjustability to the participant's posture. A graphical user interface guides the participant through the experiment and foot pedals are used for response indication. Each finger interacts with one of six identical surface haptic devices. These devices (Fig. 2) each consist of a TPaD, finger position sensor, load cells for normal and shear load measurement, a four bar linkage and linear actuator for lifting/lowering the touch surface, and associated electronics. Complete details are provided in [18].

Each TPaD was 2.22 cm wide by 7.62 cm long with a usable length of 3.81 cm. Vibrations were excited by two 10 mm diameter, 1 mm thick piezoelectric disks mounted at the ends of the glass touch surface. The combination of these glass dimensions, piezo dimensions, locations, and material properties was selected to allow for a resonant mode shape giving uniform performance across the usable surface and being well into the ultrasonic frequency range (~33 kHz) to avoid audible noise. This mode shape has a nodal region along the long axis of the glass with two parallel nodal lines straddling the edges of the piezos. In order not to impede vibrations, the TPaDs were mounted at the termini of the nodal lines where vibration amplitude is expected to be minimal.

The finger position sensor in this device is a one-dimensional projected capacitance sensor using the Cypress CY8C24894 microcontroller. The sensor operates from beneath the touch surface without interfering with the resonant friction-modulation system. Our design uses a total sensed area of 1.91 cm by 3.81 cm with six sensing traces. We obtained a good finger position signal through a 3 mm thick glass overlay at an update rate of 200 Hz. The measured finger centroid was linear to less than 3 percent of full scale.

2.3 Features Tested

Participants indicated whether a target feature was present among otherwise null TPaDs. As described above, three features were tested: slippery (low friction), edge, and hole. Voltage activation levels were controlled in lieu of actual (measured) friction levels. These are known to be monotonically related [5], [19], [20]. For the slippery target, the activation level was set to its maximum value, corresponding roughly to a one order of magnitude reduction in friction coefficient compared to bare glass. For the edge target, the activation level was set to its maximum value over the distal half of the TPaD surface, and zero over the proximal half. As such, a participant would encounter an abrupt transition from slippery to sticky when drawing a finger toward the torso. For the hole target, the activation level was Gaussian with a maximum at the center of the TPaD and a standard deviation 30 percent of the finger travel. This shape was selected by the experimenters to feel like a hole, and was validated in the discrimination task described above.

2.4 Design and Procedure

Our experimental design was factorial with the factors being: target (three levels: slippery, edge, hole), set size (four levels: one, two, four, and six fingers) and target presence within the set (two levels: yes, no). Trials were done in blocks of 32, in each of which there were four trials for each combination of set size and target presence, randomly ordered, and the target feature was held constant. Four blocks for each feature were run, rotating over a feature order that was held constant for a participant and varied across participants in a Latin Square (as nearly as possible given the participant *N*). The first block (Block 0) was treated as practice, and only data from Blocks 1-3 were analyzed.

Participants sat at the device with their hands resting on the area above the TPaDs and their feet on the foot pedals. Their hands were hidden with a curtain to prevent them from seeing how many TPaDs were raised on a given trial. Participants wore headphones to block out any noise from the device. At the beginning of each session, the participant was allowed to feel each of the target effects for as long as desired, to become familiar with it.

A trial began with the participant placing his or her fingers into a set of grooves just beyond the TPaD area. A screen with a countdown was shown, at the end of which one, two, four or six TPaDs were raised into position. The fingers stimulated for each set size and the position of the target, if present, were randomly determined by the control program. The participant then slid his or her fingers down the grooves to make contact with the TPaDs, and continued to slide across the surface of the TPaDs in a proximal direction. To promote efficient search, participants were discouraged from exploring the TPaDs in sequence. A participant's response was made by lifting a foot from the pedal, indicating "present" (if any finger encountered the target haptic effect) or "not present" (if none did.) Labels corresponding to the foot pedals were shown in boxes on the screen. After the response, the border of the chosen box transitioned to green or red to indicate correct or incorrect. The response time was recorded as the interval between the end of the countdown and the foot response.

Fig. 3. Participant seated at apparatus. The TPaD assembly for the ring finger of the left hand is lowered in this picture, while the other five assemblies are raised. Both feet are placed on foot switches, but only one switch was used in this experiment.

3 Results

Our analysis focuses on the function relating response time to the number of items in the display, particularly the slope, which is an indicator of efficiency. One correct response time was eliminated by the criterion of being greater than 3 s.d. from the participant mean. Fig. 4 shows the response time (correct responses only) versus set size, for each target type. Table 1 shows the results of least-squares regressions fit to these functions.

Analyses of variance (ANOVAs) were performed for each target type, with two within-participant factors: response (positive, negative) and set size (four levels). The ANOVA for slippery-vs.-native friction showed significant effects of response, $F(1,13) = 22.43$, $p < .001$, and set size, $F(3,39) = 11.95$, $p < .001$. The ANOVA for hole-versus-no-hole similarly showed significant effects of response, $F(1,13) = 20.67$, $p < .001$, and set size, $F(3,39) = 20.58$, $p < .001$. In both cases the interaction did not reach significance, indicating the slopes for positive and negative responses were statistically equivalent. In contrast, the ANOVA for edge-versus-no-edge showed not only effects of response, $F(1,13) = 37.12$, $p < .001$, and set size, $F(3,39) = 8.79$, $p < .001$, but also a significant interaction, $F(3,39) = 5.15$, $p = .004$. This interaction reflected the fact that there was a significant set-size effect for negative responses, $F(13,39) = 9.71$, $p < .001$, but not positives, $F(13,39) = 1.30$, $p = .28$. The finding that the positive slope did not significantly deviate from zero is consistent with the model that participants were able to detect edge targets, when present, in parallel across the fingers. However, here we claim only efficient search for edge.

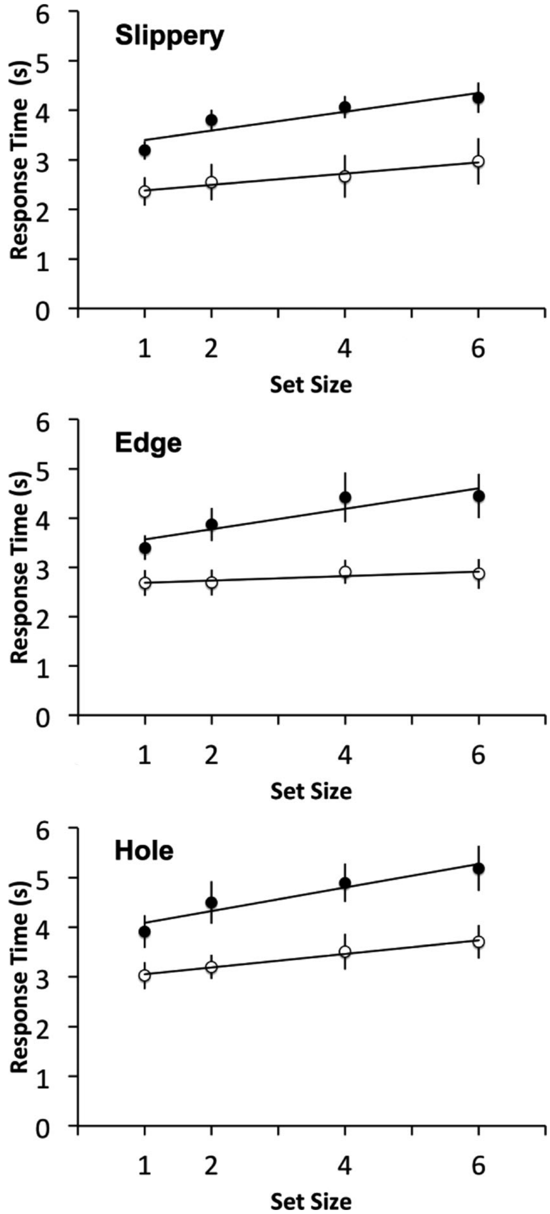

Fig. 4. Response time versus set size. Open circles are target-present data and filled circles are target-absent data. Error bars represent one standard error and lines the best fit linear regression.

The relatively efficient search for edge was echoed by comparisons between effects. The slope of the target-present search function for edge was smaller than that for hole $t(13) = 2.71$, $p = .01$, or friction, $t(13) = 1.82$, $p = .04$ (1-tailed tests). Similarly, the error rates were lowest for the edge targets. Comparisons of edge and hole yielded $t(13) = 2.30$ and 3.18, $p = .02$ and $< .01$, and comparisons of edge and slippery yielded $t(13) = 2.12$ and 1.96, $p = .03$ and .04, for false positives and negatives, respectively.

In contrast to the search efficiency found for edge stimuli when a target was present, the significant negative slope indicates that participants could not reject the possibility of an edge without finger-by-finger analysis. This pattern is consistent with the general assumption that search asymmetries arise because the absence of a feature is not detected in parallel across the display even if target presence is strongly signaled. The difficulty of target-absent trials is also indicated by the finding that all target types yielded substantially greater negative than positive intercepts. Although a strictly serial model predicts that single-item displays will yield equal response times for target-present and target-absent trials (see [12]), a larger intercept for negative responses is often found in search tasks (e.g., [21]). This is generally attributed to greater load at the decision stage when targets are absent. Here, participants were frequently observed to take an additional whole-hand pass at the end of target-absent trials to confirm that the surface was uniform, which is consistent with the approximately 1-s intercept effect observed.

Although slippery and hole targets showed evidence of finger-by-finger analysis for both positive and negative responses, the negative:positive slope ratio, 1.7:1 in both cases, departs from the 2:1 slope ratio that would be expected by a strictly serial, self-terminating search (where on average, targets are found halfway through the set). Moreover, the slope difference was not statistically reliable. Wolfe [14] noted that slope ratios in search tasks are highly variable (mean 2.3, s.d. 2.2), with the most efficient searches producing a high ratio because of the low slope for target-present trials. The present slope ratios are clearly within the visual-search norms.

Further insights can be found by examination of the slopes for individual participants. Fig. 5 shows the cumulative proportion of individuals' slopes that fall within a range of up to 300 ms/item. Although the aggregate differences in conditions are clear, participants clearly vary in the extent to which they can search efficiently within each condition, and even the condition with the highest slope, hole-target negatives, indicates that some participants are capable of essentially parallel search. Participants who did well (low slope) on one comparison did not necessarily do well on others: The correlation between slopes for a given pair of features ranged from .24 to .42 for positives and –.12 to .41 for negatives; none reached significance. The basis for these differences cannot be determined from these data and could reside in factors ranging from sensory to strategic.

4 Discussion and Conclusions

The present experiment used the slope from haptic search as a measure of the efficiency with which regions in a surface can be differentiated on the basis of differential friction. Ultimately, of course, what can be characterized as efficient search depends on context. The level of discrimination that is needed to note that a single edge continues across contact points appears to be less than that needed to parse a surface into distinct edges [22], which in turn is quite different from the level needed to distinguish among fingertip-sized spatial patterns, as in reading braille. The surface

TABLE 1
Slopes (ms / item, $\pm$ 95 Percent CI), Intercepts (s, $\pm$ 95 Percent CI), and Goodness of Fit (r^2) for Least-Squares Regressions Relating Response Time to Set Size, by Target Type and Response

Target Type	Positive Slope	Negative Slope	Positive Intercept	Negative Intercept	r^2 positive	r^2 negative	% False Negative	% False Positive
Slippery	113 ± 74	190 ± 101	2.27 ± 0.36	3.21 ± 0.57	0.96	0.83	10.3	7.4
Edge	45 ± 48	208 ± 112	2.64 ± 0.47	3.36 ± 0.48	0.73	0.85	7.6	4.4
Hole	136 ± 70	237 ± 65	2.92 ± 0.50	3.85 ± 0.66	0.99	0.91	11.8	6.8

Also shown are the mean error rates.

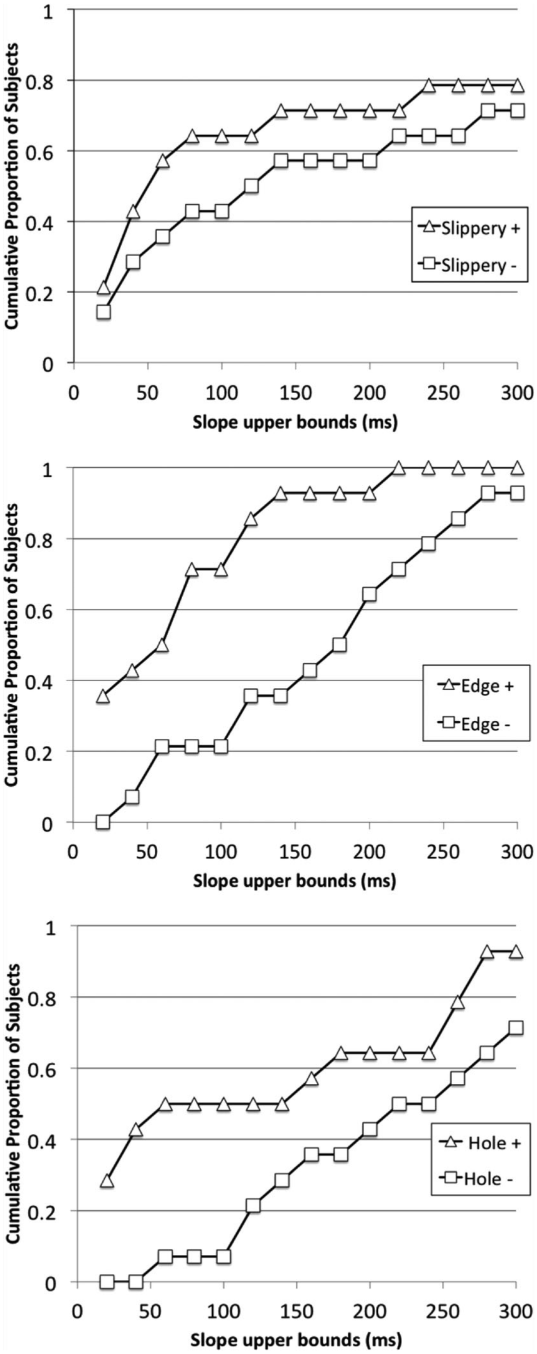

Fig. 5. Each data point represents the cumulative proportion of participants that exhibited a response time (sec/item) less than or equal to the slope upper bound. Thus, approximately 43 percent of participants could correctly determine the presence of a hole with a slope of less than or equal to 40 ms/item.

differentiation required in the present tasks might be compared to the parsing that people do in everyday life when they touch a cluttered desk without taking their gaze from a screen, and realize that one finger touches paper while another touches wood. Even this level of differentiation, however, if performed efficiently, might be useful in application domains outlined in the introduction. The question is, then, what level of efficiency did we demonstrate?

To summarize our findings, when participants searched for easily discriminable haptic targets among distractors, highly efficient (statistically parallel) search was evidenced only for the presence of edges (abrupt changes of friction). Individual participants varied, with some producing low slopes (<20 ms/item) even in conditions where the aggregate search did not match the criterion for parallel detection, and conversely, some clearly having difficulty even in the edge target condition.

The data for edge-present trials are consistent with what is expected when targets can be distinguished from distractors on the basis of an intensive difference, that is a distinction with respect to magnitude on a single dimension. As was noted above, Lederman and Klatzky [11] contrasted intensive with spatial discriminations, such as edge orientation, where magnitudes of targets and distractors are identical but spatial layout differs. Slopes in [11] did not differ significantly from zero for a step edge in flat surfaces, or vice versa, and a hole in flat surfaces. Similarly, parallel search was evidenced in [12] when participants detected a spatial target under one finger while the other potential target locations were empty. The remaining slopes observed in the present study are on the order of 100 ms/item for positives and 200 ms/item for negatives. For comparison, these resemble values found previously for spatial discriminations and relatively small intensive differences. For example, detecting the orientation of a planar edge (vertical in horizontal distractors) took around 100 ms/item in [11] and 200 ms/item in [12]; the latter value is similar to the slope in [11] for shallow hole in deep holes.

It should be noted, however, that in [11] even slopes found statistically equivalent to zero were generally positive, and some were on the order of the 45 ms/item that we observed for edge-present. Notably, the edge/flat searches tended to produce positive slopes, one as high as 37 ms/item (flat target detected among vertically oriented edges).

Other results from haptic search tasks with physical targets indicate that the discriminability between target and distractor affects search rates, even when the feature distinction is intensive. In [11] a deep hole was detected efficiently amid flat surfaces but not in shallow holes. The same phenomenon is demonstrated by the findings of Plaisier et al. [13] when search involved 3D objects held in the hand. When the distractors were spheres, a tetrahedron target yielded a slope of 25 ms/item, a cube 63 ms per item, and a cylinder 137 ms per item. These results clearly suggested that target intensity, in this case the density of vertices and edges, was inversely related to slope.

In short, while the present intensive distinctions fail to produce haptic search efficiencies as dramatic as those found with physical surfaces and 3D objects ([11]; [13]), efficient search with physical stimuli can itself be a fragile phenomenon. Our ultimate goal, however, is technological: to create surface haptics technology that supports efficient search. From this perspective, what can be learned from the present study?

Within the limitations of variable friction technology, one lesson may well be to minimize the need for spatio-temporal integration. The edges considered here were highly localized in space, while the holes were much less localized and the slippery surface offered no spatial information (while still requiring movement). It seems reasonable to expect that narrower holes as well as fine virtual gratings [2] and textures would lend themselves to efficient search. This in turn, has technological implications: highly localized haptic features require high resolution sensing and fast, low latency rendering implementations. Related to this, a second lesson may be that the bandwidth of the surface haptics technology is important. For instance, the TPaD typically exhibits a bandwidth of about 100 Hz, while that of an electrostatic display [1], [4] may be much higher.

Looking beyond variable friction, devices that can provide active forcing [3], [19] may enhance search efficiency. For instance, virtual holes created with the ShiverPaD [3] actually push the fingertip toward the "bottom" and therefore can be perceived with a minimum of spatio-temporal integration.

Finally, one goal in this research was to initiate the process of defining building blocks for higher-order percepts using surface haptics technology. The present results point to the challenge of this effort, but at the same time suggest an initial foundation on which to build. To the extent that edge onsets are detected with minimal attentional load, objects defined by the presence/absence of edges are a first step in a higher-order vocabulary.

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