Finding a Feature on a 3D Object through Single-Digit Haptic Exploration

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ABSTRACT

Humans use tactile and kinesthetic cues to easily identify the location of an object feature without vision. This preliminary work quantitatively examined the behaviors of 15 individuals locating a target on an object with a single digit (index or thumb). Search methods could be categorized into one of three search strategies, termed "scanning," "landmark," and "direct." The scanning strategy consisted of (1)back and forth scanning and (2)confirmation of the target, and was always utilized in trials in which the target location was unknown. The landmark strategy consisted of (1)contour following, (2)ballistic movement from an edge toward the target, and (3)error correction and confirmation of the target. The direct strategy consisted of (1)ballistic movement from the start position directly to the target, and (2)error correction and confirmation of the target. Follow-up relocalization trials were executed with the landmark strategy 42% and the direct strategy 58% of the time. The landmark strategy was utilized significantly more often by the index finger than by the thumb. Future work to understand how strategy selection depends on the strength of an individual's internal model of the 3D object and the uncertainty of finger location with respect to the object will inform the development of a computational model of human object exploration.

KEYWORDS: Haptic I/O, Human factors, Human information processing

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]:User Interfaces—Haptic I/O; H.1.2 [Models and Principles]:User/Machine Systems—Human factors

1 INTRODUCTION

Humans can effortlessly reach in a pocket to find a keychain and press a button to unlock the car without removing the keychain from the pocket. However mundane, this behavior points to a sophisticated set of perceptual and motor capabilities. Tactile and kinesthetic cues must be obtained and combined with prior knowledge to recognize the object, represent it in 3D, identify features on it, and guide the appropriate fingerpads to locations that enable the end goal. The long-range goal of our research is to develop computational models of these capabilities that could be used in the design and control of robotic hands. We report here on a first step: a quantitative study of single-digit haptic exploration and target relocalization task.

Much of what we know about haptic exploration comes from the work of Lederman, Klatzky, and colleagues. They showed that people can identify common objects by touch alone (no vision), with remarkable accuracy and speed [1]. They went on to show that this capability is subserved by a set of stereotypical "exploratory procedures" (EPs) such as enclosure for shape, static contact for temperature, lateral motion for texture, unsupported holding for weight, and so on [2]. Moreover, they showed that EPs are accessed hierarchically because EPs differ in terms of their duration and breadth of sufficiency for identification. For example, enclosure is generally sufficient to determine that an object is a writing instrument, while lateral motion, followed by edge following, followed by function test may be needed to determine what type of writing instrument (e.g., pencil versus pen versus marker). They went on to propose that these findings could form the basis of a computational theory of haptics [3,4].

Perhaps inspired by their work, a number of robotics researchers have studied the problem of object identification. Bajcsy worked with Lederman and Klatzky to develop a framework for robotic object exploration [5], while Allen and Roberts used superquadratics to classify objects from tactile and kinesthetic information, and performed experiments using the Utah-MIT Hand and contact sensors [6]. Stansfield implemented a set of EPs on the JPL/Stanford Hand outfitted with a 256 element tactile array on one fingertip [7]. Okamura and Cutkosky developed algorithms for feature extraction using kinesthetic data [8]. Berquist et al. used the WAM and BarrettHand to demonstrate successful identification of 50 common objects using proprioceptive information only (no tactile) [9]. Their approach made use of standard machine learning algorithms.

While these studies have contributed to the goal of robot haptics, it seems evident that there is a great deal more of a *quantitative* nature to be learned from human haptics (and then potentially transferred to robotics). By way of example, Smith et al. measured index finger normal force, tangential force and velocity in an exploration task and found interesting relationships between typical values and the nature of the task (e.g., searching for a raised feature, which led to lower normal forces, versus an indentation, which led to higher normal forces) [10]. We are interested in contributing to the quantitative analysis and modeling of haptic exploration, especially focusing on the strategies adopted to reduce uncertainty in the context of 3D exploration.

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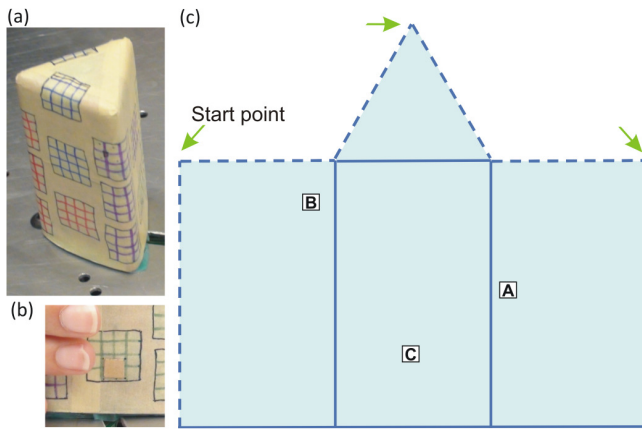[**]email: yoky@cs.washington.edu

Figure 1. (a) The object used for haptic exploration. (b) The haptic feature (button) that was placed on the object. (c) A foldout of the object surface. Three arrows are one point where the finger starting point was located. Dashed lines indicate seams of the foldout. A, B, and C are the three button locations used during the experiment. This foldout schematic is used for the rest of this paper.

In this paper, we report our first observation of haptic exploration strategy with a single-digit when participants were asked to find a small haptic feature on a 3D object. While we report the qualitative analysis of the strategy used in trials in which the target location was unknown (first trial after the target location was changed), we focused on the quantitative analysis of strategies used to relocate the haptic feature on the second and third trials in this paper. We demonstrate a scanning strategy used during the first trial, and two distinct strategies used by participants to relocate a haptic feature: landmarks used on the object, and development of feed-forward model of the object.

2 METHODS

2.1 Experimental Environment

The object used for the haptic exploration is shown in Fig. 1. It was a hollow rectangular prism with rounded edges. The angle between each face was sixty degrees with each face measuring 8.9 cm high and 5.1 cm wide. The object was made of hard plastic and covered with a 0.13 mm thick layer of silicone covered by a layer of masking tape. Masking tape was chosen as the surface layer material due to its relatively low coefficient of friction that allowed the exploration behavior to be smooth and natural. The masking tape was thin enough so that overlaps and edges of the tape layer could not be detected by tactile exploration.

The haptic feature that participants were asked to find was a button as shown in Fig. 1(b), which was a square with 0.76 cm on a side and 0.56 mm thick. There were three assigned target locations for button placement, one on each face of the object. A foldout view of the object is shown in Fig. 1(c) with target locations indicated. Target A was located 0.25 cm from the nearest vertical edge and 4.8 cm from the top of the object. Target B was located 0.25 cm from the nearest vertical edge and 1.9 cm from the top of the object. Location C was placed equidistant from two edges and 7.1 cm from the top of the object, on the face opposite from the participant's body. The buttons were attached to the object at the target location using masking tape, which created a cohesive object of one texture. Target locations were chosen to provide coverage along all 3 faces of the object and the full height.
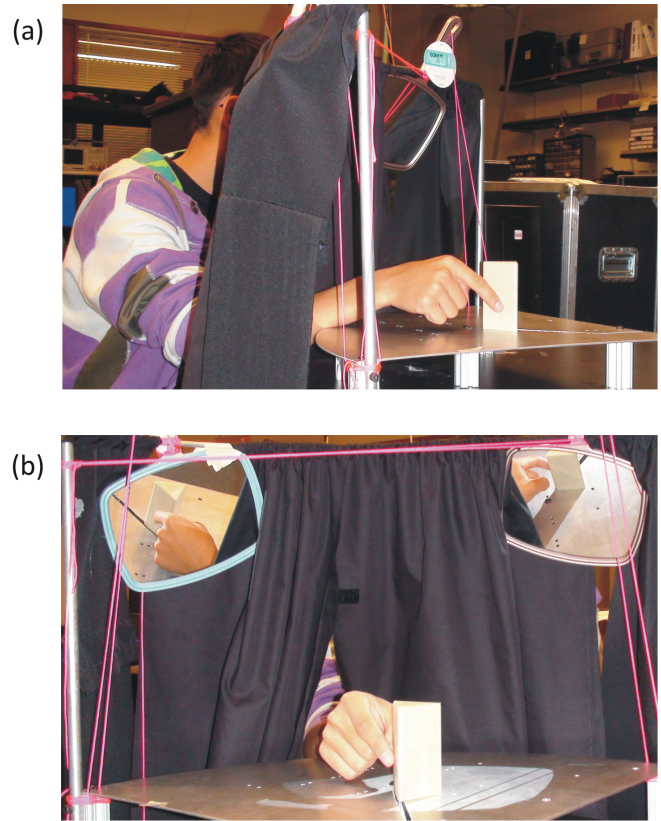

Figure 2. The experimental environment. (a) side view and (b) front view.

The experimental environment is shown in Fig. 2. The object was firmly secured on a large metal plate with a screw. A curtain was placed between the participant and the object to occlude vision. The participants sat at a comfortable height and distance from the object.

2.2 Experimental Protocol

Fifteen (9 male and 6 female) individuals participated in the experiment. Of the 15 participants, 14 were right-handed and 1 was left-handed. All participants used their dominant hand in the exploration task.

Prior to experimentation, the object was shown to participants, and they were allowed to feel the button on the object to familiarize themselves with the feature to identify before beginning the exploring task. The button was placed in a location other than the pre-set locations A, B, or C during the exploration and then moved before the first trial. Participants were also warned that other bumps or discontinuities might be on the surface of the object. Finally, participants were blind folded to prevent peeking at the object or button placement.

Participants were instructed to locate a button on one of the three sides as quickly as possible, using only one fingerpad to explore during the trial. There were a total of 18 trials in a session. Participants explored with two finger conditions (index fingerpad only and thumb fingerpad only) and three target locations (A, B, and C; see Fig. 1), over three successive trials for each of these 6 conditions. During the successive trials, participants were made aware that they would receive the same target location three times in a row before the target location changed. The order of target location presentation and the finger conditions were randomized for different participants.
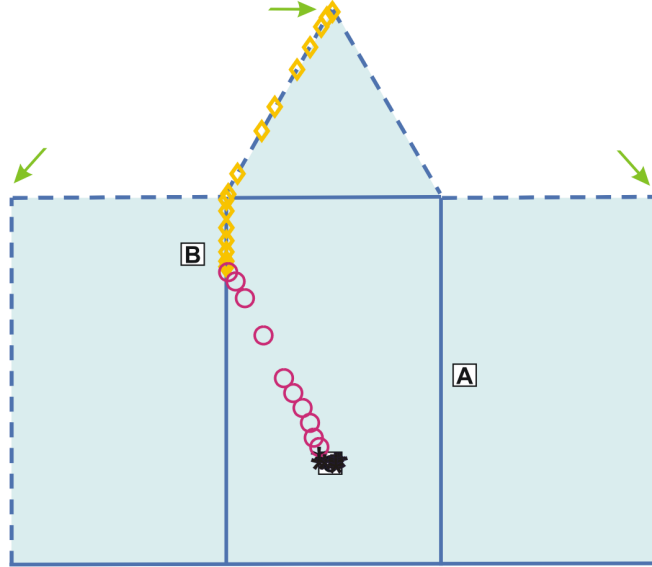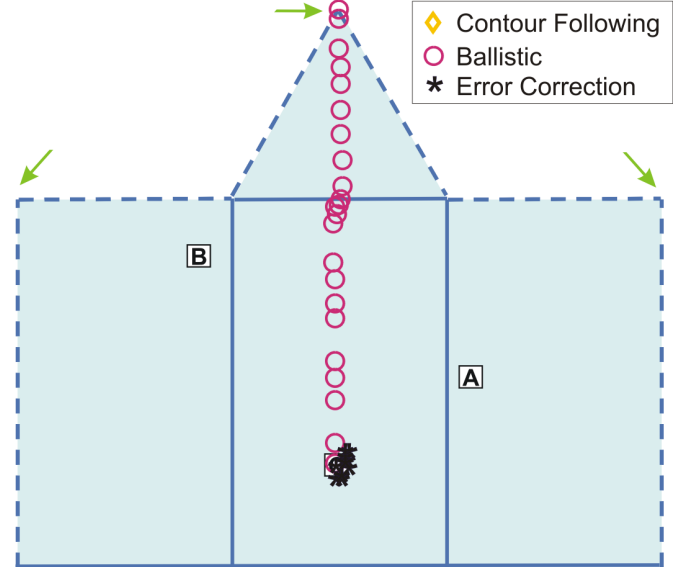
Figure 3. Example paths of search behaviors. Finger location is indicated at each 1/15 s. The left panel shows an example path of a participant utilizing the landmark strategy to relocate the target, whereas the right panel shows the path during the direct strategy.

At the start of each trial, the experimenter placed the participant's fingerpad to the top corner of the object nearest to their body (the start point indicated in Fig. 1). An audio cue was used to signal the start of the exploration to the participant, and the end of searching was indicated verbally by the participant by reporting the target as "found."

The exploration trials were recorded with a video camera at a rate of 30 frames per second. Mirrors were used (see Fig. 2) to allow for visualization of all sides of the object in the video recording. Video recordings were examined by one of two of the experimenters to determine overall search strategy, as well as to record manually relevant fingerpad locations onto our 2D representation of the object surface (see Fig. 1). Approximately 6% of trials were analyzed by two experimenters, yielding inter-rater reliability in the form of Pearson's R of 0.99 for time measures (search time and contour following time) and 0.99 for the distance between transition points and target location.

Statistical analysis consisting of analysis of variance (ANOVA), the general linear model, and Tukey and Student's t-tests, which were all performed using Minitab statistical software.

3   RESULTS

3.1   Novel Target Location Search Methods

During haptic exploration (the first trials), the mean search time participants used to locate the target was 49.8 s (STD = 58.9 s). All participants utilized exhaustive "scanning" behavior over the faces of the object, followed by confirmation of the target location, a strategy termed here as the "scanning strategy." In 3% of trials, participants began with an initial "guess" of the target location, effectively initiating the scanning strategy at a point on the object other than the trial start point (see arrows on Fig. 1). A 3 factor ANOVA was used to examine the effects of participant, digit (thumb or index finger), and target location (A, B, C) on search time. No statistically significant effect was seen by participant ($p = 0.41$), digit ($p = 0.77$), or target location ($p = 0.78$). A 3 factor ANOVA examining the effects of participant, digit, and target location on the number of false positives did not

find statistically significant effects of digit ($p = 0.95$) or target location ($p = 0.46$), but did find an effect of participant ($p = 0.05$).

3.2   Relocalization Methods

Interestingly, behaviors during second and third trials (relocalization of a known target position) could all be categorized into one of two search strategies, which we have termed "landmark" and "direct." The landmark strategy consisted of three distinct phases of search behavior: (1) contour following along the edges of the object, (2) a quick ballistic movement from an edge toward the area of the target location, and (3) error correction and confirmation of the target location. Conversely, the direct strategy consisted of two distinct phases of search behavior: (1) a quick ballistic movement from the initial start position directly to the area of the target location, and (2) error correction and confirmation of the target location. Ballistic motion consisted of single open-loop movements, whether or not the fingerpad was touching the object. Fig. 3 shows two example paths taken by a participant to reach target location C using the landmark and direct strategies.

Overall, participants used the landmark strategy in 42% of trials and the direct strategy in 58% of trials. Although most participants utilized both strategies at least once, strategy choice varied by participant, with some showing a strong preference for one or the other. A 4 factor ANOVA was used to examine the effects of participant, digit (thumb or index finger), target location (A, B, C), and trial (second or third) on the strategy chosen. There was a statistically significant effect of participant ($p < 0.001$) and digit ($p = 0.02$), but not target location ($p = 0.46$) or trial ($p = 0.32$). A *post hoc* proportion test (two-sided) showed that the landmark strategy was utilized significantly ($p = 0.032$) more often by the index finger than by the thumb.

A 4 factor ANOVA found a statistically significant effect of participant ($p = 0.02$) and target location ($p = 0.01$) on search time, but no effect of digit or trial (second or third). *Post hoc* Tukey t-tests (two-sided) found that trials to relocate target C were significantly longer than trials locating targets A and B ($p = 0.008$). Given the obvious differences in the two strategies, we

Target A

Target B

- ○ Index, Trial 2
- ○ Index, Trial 3
- ◇ Thumb, Trial 2
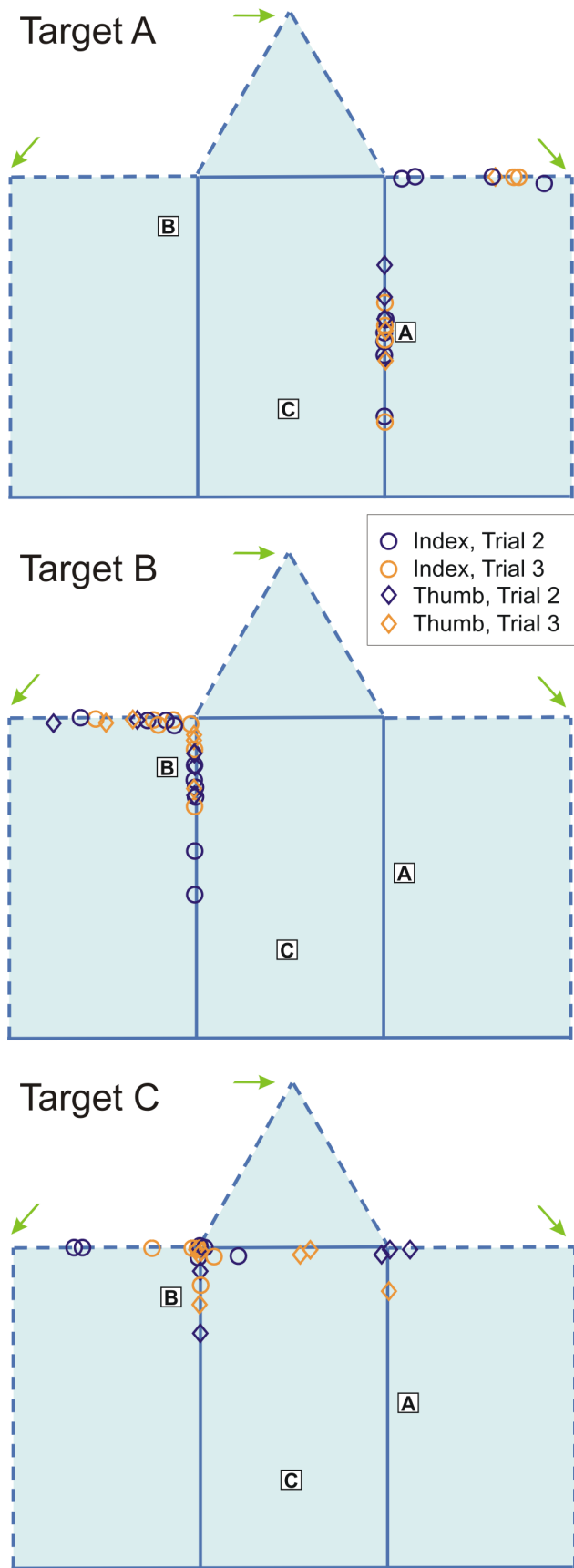- ◇ Thumb, Trial 3

Target C

Figure 4. Transition points. Symbols mark the transitions between contour following and ballistic movement for the landmark strategy.

examined the possible association of strategy choice with search time. The search time was 4.4 s (STD = 4.4 s) for the landmark strategy and 3.4 s (STD = 3.0s) for the direct strategy. Although there was a trend for longer search times for the landmark strategy relative to the direct strategy, a two sample Student's t-test (two-sided) did not find a statistically significant effect ($p = 0.07$).

Sometimes participants changed their strategy choice between the second and third trials of a single target location, leading us to question whether this change in strategy was expressed in a reduction in the search time between the two tasks. Search times for each trial were normalized by the mean search times of each participant to compute the normalized search time. For each participant/target combination, the difference between the second and third trial normalized search time was computed. Regardless of the choice to change strategies, normalized search times tended to decrease between the second and third trials; however, a two sample Student's t-test (two-sided) did not show a difference between the instances of strategy change and those in which the strategy remained constant ($p = 0.58$). A 3 factor ANOVA was used to determine the effects of subject, digit, and target location on whether or not there was a strategy change, finding a significant effect of digit ($p = 0.01$) and target location ($p = 0.04$). P*ost hoc* proportion tests (two-sided) showed that a change in strategy between trials 2 and 3 was significantly more likely during use of the index finger relative to the thumb ($p = 0.01$), and when the target was at location C relative to location B ($p = 0.01$). When strategy change between trials 2 and 3 occurred, 63% of the time it represented a switch between landmark strategy for trial 2 changing to direct strategy for trial 3, whereas 37% of the time the converse was true.

For the trials in which the participant utilized the landmark strategy, the location of their transition from contour following to ballistic movement was noted as a "transition point." These transition point locations are shown in Fig. 4 as a function of target location. Transition points show interesting clustering based on the target location.

For each trial utilizing the landmark strategy, the 2D Euclidian distance between each transition point and the corresponding target location, and the percent of total search time spent contour following were calculated. A 4 factor ANOVA found no significant effects of participant ($p = 0.42$), digit ($p = 0.24$), target location ($p = 0.96$), or trial ($p = 0.25$) on the normalized contour following time. A 4 factor ANOVA found no significant effects of participant ($p = 0.07$), digit ($p = 0.24$), or trial ($p = 0.41$) on the distance between the transition point and target location, but found a significant effect of target location ($p < 0.001$). Two *post hoc* Tukey's Simultaneous t-tests (two-sided) showed that the distance between transition points and target C were significantly greater ($p < 0.001$) than those for targets A and B.

4 DISCUSSION

4.1 A Peek at First Trial Exploration Strategy

In this preliminary study, we chose to concentrate on the second and third trials because the first trial, when the target location was unknown, typically took very long to complete (MEAN = 49.8 s) and consisted of exhaustive scanning the areas of interest. There was also large variation in the search times during first trials, with some trials taking as long as 387 s. It was even difficult to build a visualization technique for our results, so Fig. 5 shows a cartoon illustration of typical search behaviors. Analysis via ANOVA showed that this variation in search time was not a function of digit or target location.

All participants utilized exhaustive back and forth movement over the faces of the object, followed by confirmation of the target location (scanning strategy). Figure 5 shows two variations of the
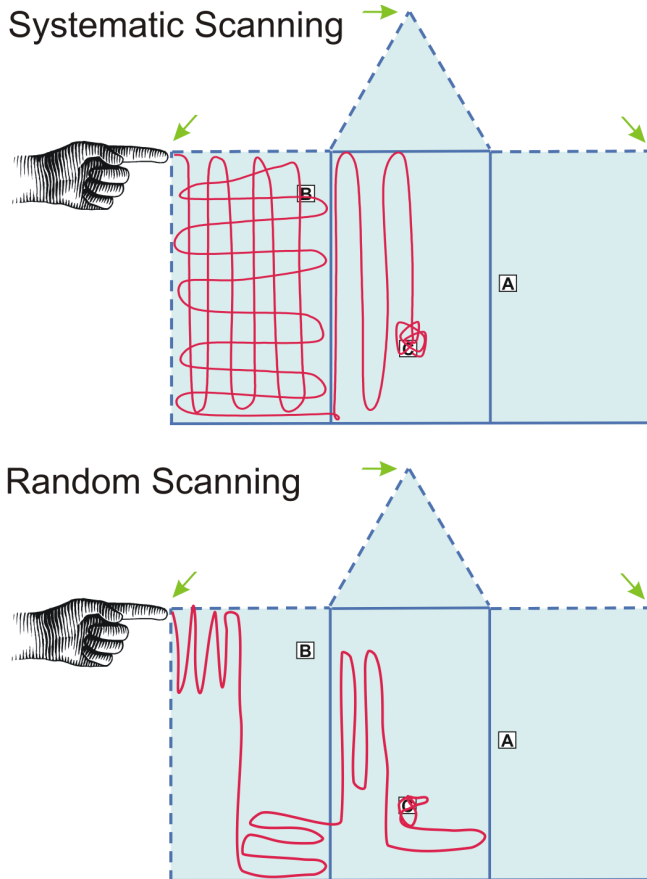
Systematic Scanning

Random Scanning

Figure 5. A cartoon illustration of the stereotypical search methods used during the first trial for participants. Here is an example case using button location C.

scanning strategy typical of the range of behaviors: systematic and more random. Exploration trials consisted of scanning behavior with varying degrees of this randomness. More systematic scanning generally consisted of meticulous back and forth motion across each entire face of the object before moving to a new face, whereas more "random" scanning was characterized by similar motions over smaller sections of the object. The data from these first trials contain rich information about how humans explore to find a haptic feature for the first time, and we plan to analyze them more quantitatively in the future.

4.2 Landmark Selection during Relocalization

When the landmark strategy was chosen during relocalization (trials 2 and 3), participants utilized haptic features to guide the finger to a specific landmark location before leaping to the target. We are interested in identifying which haptic features and landmarks were used to place the fingerpad as fast as possible to the target, and why such landmarks were chosen.

Lederman and Klatzky noted contour following, also referred to as dynamic edge following, as one of several fundamental exploratory procedures (e.g., [11]). Likewise, for the 15 participants studied here, the contour following (phase 1 of landmark strategy) was along the edges or corners of the object. These edges and corners provide certainty of location on 3D objects. Corners localize the fingerpad to a specific location in space, whereas edges reduce 3D variability to 1D. Movements along the faces of the object are inherently uncertain in 2D. Therefore, it is intuitive that we use these edge and corner haptic

cues to reduce the uncertainty of fingerpad position. In fact, it has been shown previously that corners are specially implicated as anchor points for haptic localization [12].

However, participants chose to use the direct strategy slightly more on average than the landmark strategy. Moreover, Fig. 4 shows clusters of transition points on the edge next to the target locations A and B, but not for C. We hypothesize that this is due to the fact that targets A and B are 'close enough' to the edge that this strategy effectively reduces the uncertainty of the fingerpad location with respect to the target location. There are several possible reasons for the lack of transition points on the long edge of the face containing target C (see Figure 4). It is possible that the distance between the edge and the target C was too long to use the edge as a reliable landmark source, or conversely that the target was located so low that the vertical directional uncertainty would be great enough as to make the edge following technique less useful. It is also possible that following the long vertical edge may slow down the search enough to make it worth risking a lengthier error correction phase. Future studies should test different target locations to isolate (or to observe the interaction of) these causes. Regardless of the precise cause, the choices that participants made suggest a strong relationship between learning, uncertainty, and strategy that bears elucidation in future work in developing a computational model for such a search behavior.

Finally, biomechanics may also affect the relocation behavior. Participants in this study used the landmark strategy with their index fingers more often than with their thumbs. This may have been caused by the higher tactile sensitivity of the index fingerpad, due to practice effects or inherently increased sensitivity. In other words, sensory information from the index finger may reduce uncertainty more than sensory information from the thumb, making the landmark strategy more useful for the index finger. However, recent comparison of single digit curvature change thresholds did not show a significant difference in sensitivity between the index finger and thumb [13]. Another possibility is that the structure of the hand made it easier to follow an edge with the index finger than with the thumb given the ergonomic conditions of the experiment.

4.3 Two Distinct Relocalization Strategies

It is important to note that there were two and only two strategies used by all participants for relocalization (second and third) trials. In addition, there were three distinct phases comprising the two strategies: (1) contour (edge/corner) following to reach a landmark, (2) a quick ballistic movement from a landmark or starting point toward the area of the target location, and (3) error correction and confirmation of the target location. Excluding the exhaustive scanning strategy found in the first trial, are there only three approaches for relocating a haptic feature on the surface of a 3D object?

For the most part, the scanning strategy was only present in the first trial when the target location was unknown. However, a few exceptions occurred when the direct or landmark strategy failed, and the scanning strategy was redeployed during the second or third trial. In these cases the participant appeared to miss the target following the ballistic phase, failing to transition smoothly into the error correction phase. Out of the 180 relocation trials, there were a total of 9 such trials that resulted in having the sweeping phase and much longer trial time than the rest (MEAN = 15.8 s).

Our future work will incorporate multi-digit trials, which may provide information about more complex modes of search that were not available to these participants during single digit search.

4.4 Feedforward Movement using a 3D Model of the Object

The paradigm employed here bears similarity to that used in studies of raised line drawings (e.g., [14]), but differs in the main task, which is localization/relocalization rather than identification. Identification of raised-line drawings requires spatial integration of information coming from the fingertip, while relocalization does not. Thus, strategies like ballistic motion become possible. The fact that we consistently see the ballistic movement phase during the second and third trials is strong evidence that there is a model of the object being formed in the nervous system. While there was no statistically significant difference in search times between the second and third trials, it is possible that continued reduction in search time might be observed if the experiment continued for several more trials. This finding would suggest that the 3D object model is not fully formed during initial trials, but is still being constructed in subsequent trials.

For this reason, we expected shorter search times for those trials utilizing the direct strategy than for those utilizing the landmark strategy. However, no significant association was seen between strategy choice and normalized search time. Furthermore, for individuals who changed strategy between subsequent trials, there was no gain in performance. It is possible that the direct strategy results in longer error correction and confirmation of the target location, even if the fingerpad gets close to the target faster than when using the landmark strategy. It will be interesting to investigate whether the use of the landmark strategy is more effective for refinement of the internal model of the 3D object.

4.5 Future Directions

The current experiment is our first step in quantitatively exposing some of the fascinating behaviors individuals utilize for haptic exploration; however, there are still many areas to explore based on this work. Our future work includes the formation of a computational model of human haptic exploration. Based on object knowledge uncertainty, such a model would supply discrete phases and strategies used by humans that could one day be used by a robot.

Specific further research directions would explore the effects of multiple digits, varying object characteristics and stability, object position in relation to the participant, varying the performance goals of the participant, and learning and uncertainty on strategy selection.

It is unclear how the simultaneous use of multiple digits could affect search strategy. Previous work has shown a decrease in sensitivity for change in curvature for use of the index finger and thumb as compared to their use as single digits [13]. However, in our preliminary work (not reported here), we noticed that some individuals performing a search with the thumb and index finger simultaneously tended to search only with the index finger, using the thumb as an anchor to a known position (often on a corner) on the object. This strategy reduces uncertainty of the thumb to one location in space, which in turn reduces the uncertainty of the index finger location to a set position in relation to the thumb. However, use of available digits as anchors may have limited utility in speeding relocation: previous work in haptic path and distance judgments has shown that the use of an anchor often does not improve performance [15]. We are interested in understanding which situations elicit individuals to use anchoring for multi-digit search rather than searching with all available fingerpads.

Obviously the size, shape, surface characteristics, and stability of an object and a target feature affect human 3D exploration of that object. We would like to understand how these characteristics and the landmarks they supply affect search strategy choice. For example, if an object's surface has a high coefficient of friction, are individuals less likely to employ the landmark strategy for search due to the increased time and force necessary for edge following in that environment?

In this preliminary study, we have ascertained search behaviors for three targets, each located at differing heights and faces of the object. Unfortunately, the differences in search behavior for target C relative to the other two are confounded by these multiple differences. Our future work will not only explore multiple target locations, but will also investigate the effects of changing the object location in relation to the participant. This will prevent individuals from relying on the use of proprioception of their hand and arm to locate the target in relation to their body, but will force individuals to reference the target to features on the object, providing even more information about which landmarks are most crucial.

In the current experiment, participants were asked to find the target as quickly as possible. No penalty was incurred for mislabeling the target. We plan to explore participant goals and the interactions of speed and accuracy, to elucidate the objectives behind search strategy selection. Likewise, assessing the uncertainty of participants as a function of strategy selection is a critical next step in understanding why and when we use particular search strategies. For example, in order to control the amount of uncertainty reduction obtainable from an edge, future work could explore start points that are not touching the object. The position of the object could then be varied; if such variation was small relative to the target size, an edge may not be useful to a trained participant. However, if the variation was large relative to target size, participants may require the use of an edge or corner.

These studies will reveal how strategy selection depends on the strength of the individual's internal model of the 3D object. This information is vital for the formation of a computational model of strategy selection for human object exploration, which may be a step toward improved robotic control.

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