

# Target search and inspection strategies in haptic search

Anna Metzger, Matteo Toscani, Matteo Valsecchi and Knut Drewing

**Abstract**—Haptic search is a common everyday task, usually consisting of two processes: target search and target analysis. During target search we need to know where our fingers are in space, remember the already completed path and the outline of the remaining space. During target analysis we need to understand whether the detected potential target is the desired one. Here we characterized dynamics of exploratory movements in these two processes. In our experiments participants searched for a particular configuration of symbols on a rectangular tactile display. We observed that participants preferentially moved the hand parallel to the edges of the tactile display during target search, which possibly eased orientation within the search space. After a potential target was detected by any of the fingers, there was higher probability that subsequent exploration was performed by the index or the middle finger. At the same time, these fingers dramatically slowed down. Being in contact with the potential target, the index and the middle finger moved within a smaller area than the other fingers, which rather seemed to move away to leave them space. These results suggest that the middle and the index finger are specialized for fine analysis in haptic search.

**Index Terms**—Human exploratory behavior, haptics, perception, search

## I. INTRODUCTION

ACTIVE touch is essential in many common everyday situations. For example, when appreciating specific “haptic” properties of an object such as its softness, weight, temperature or roughness, active touch provides more reliable information than the other senses. In some further situations, other senses, e.g. vision, are not available at all, for instance when searching for the keys in the bag. Lederman & Klatzky (1987) intensively investigated the exploratory behavior used to perceive specific haptic features and showed that humans tend to perform highly stereotypical movements (exploratory procedures, EPs), to perceive different haptic properties of objects: For instance, enclosing the object in the hand to judge its global shape or following the contour of the object to perceive its exact shape [1]. The authors also showed that these property-specific EPs are optimal (most accurate or fastest) as compared to other EPs [1]. Further it was shown that parameters of exploratory procedures (e.g. indentation force in the exploration of softness) are adjusted to ensure the most effective way to accomplish a task [2], [3]. In contrast, how the

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hand and fingers move during haptic search has not yet been characterized in detail. Morash (2016) suggested that haptic search consists of two alternating processes: target search and target inspection [4]. Here, we want to investigate exploratory behavior in these two processes for naturalistic five-finger search. More precisely we aim to study how different fingers are utilized during target inspection in order to identify specialized fingers and to characterize movement strategies of the hand during target search. This work is an extension of [5], in which we only reported the data from the process of target inspection obtained in Experiment 1. Here we include more trials in the analyses of Experiment 1 and we include a second experiment, dedicated to investigate more in detail the process of target search. We will start with an overview about previous findings on target inspection and target search.

### A. Target inspection

Grunwald et al. (2014) analyzed movements in object exploration with respect to exploration pauses [6]. They found that the exploring hand frequently stops for a time between 67 ms and 330 ms (depending on the exploration task), suggesting that haptic exploration might consist of alternating fast movements and exploration pauses, similar to saccadic eye movements and fixations in human vision. Indeed, in the animal domain Catania & Remple (2004) showed that star-nosed moles, with their specialized somatosensory organ consisting of several appendages surrounding the nostrils, perform rapid movements similar to saccades in vision [7]. Further, the authors observed that the mole detected the prey equally likely with any of the appendages, but it used for the identification of the prey consistently a specific pair of appendages. Similarly, for humans performing haptic search, Morash (2016) observed that, while participants detected search targets with each of the fingers equally likely, the middle and the index finger stayed significantly longer in contact with targets and distractors than the thumb, ring and little fingers [4]. Consistent with this result, average finger speed was significantly lower during the contact with the potential target only if the contacting finger was the middle or the index finger. The author suggests that haptic search is characterized by a serial process consisting of a search process, in which any finger is involved, and an identification process, mostly involving the index and the middle finger. However, the hypothesis that the index and the middle fingers are preferred for the analysis of relevant items in haptic search has not been empirically tested in that previous study because the dynamics of finger usage have not been addressed. Thus, it remains unclear whether after

encountering a potential target people actually switch from the usage of other fingers to inspect the target with the middle or index finger. Previous data can alternatively be explained by the assumption that any finger is used for target identification, but people for some reason spend more time on identification when incidentally middle or index finger contacted the target first.

In Experiment 1 we explicitly test the hypothesis that index and middle fingers are specialized for target inspection while target search can be accomplished with all fingers. If this hypothesis is true, the specialized fingers should be characterized by a relatively high probability of touching a potential target after it was initially encountered by any of the other fingers. Thus, we analyzed how the probability of each finger to touch a potential target evolves over time, given that the target is first encountered by a certain finger. Potential differences in the utilization of the different fingers would be also reflected in the speed and in the extension of movement trajectories of the fingers depending on whether the finger touches the target or not. In the case the fine analysis of a search item is performed with a specialized finger, we expect that the speed of this finger would decrease and it would perform short exploratory movements during target contact, as opposed to relatively high speed and rather long searching movements when not in contact with the target. Such differences are not expected for a non-specialized finger.

### B. Target search

When searching for a target within a certain space, it is necessary to keep in mind the outline of the available space and to have information about the current and past positions of the fingers relative to it, thus it is necessary to build up a representation of the search space in order to be able to perform haptic search. In general, the spatial properties of a stimulus usually cannot be perceived “at a glance” with the sense of touch but, instead, the arm, hand and fingers need to be moved over the stimulus. To build up a representation of the spatial properties of the stimulus it is necessary to combine the obtained proprioceptive and tactile information and integrate it across time. Though this seems a rather difficult task, people quickly and accurately recognize known [8], [9] and novel, complex 3D objects [10] by touch when vision is excluded. However, recognizing 2D line-drawings of known objects by following them with one finger seems to be very difficult [8], indicating that a spatial representation of a stimulus built up from the path of the moving finger might be imprecise and inaccurate. There is evidence from studies investigating haptic perception of orientation, that haptic perception of space is indeed distorted with respect to e.g. perceived parallelity [11] or curvature [12] and that distortions in perceived angles are not geometrically consistent with perceived length [13]. There is also an anisotropy for precision in orientation perception: Cardinal stimulus orientations can be discriminated better than oblique orientations [14] (for review see [15]). Also, reproduction of oblique orientations is less precise than reproduction of cardinal orientations [16]. Given this level of uncertainty in haptic spatial perception, it is

interesting to investigate how participants orient themselves when performing haptic search. Previous studies addressing exploratory movements in the process of target search on a 2D plane focused on categorizing exploratory movements by eye to define search strategies. For instance, Van Polanen, Bergmann Tiest & Kappers (2011) and Plaisier, Bergmann Tiest & Kappers (2008) differentiated between parallel and serial search strategy, depending on which movement category prevailed: In parallel search, participants mostly performed hand sweeps or circular hand movements over the 2D display, while in serial search scribbling movements and item-wise exploration were more common [17], [18]. The choice of a certain search strategy seems to depend on the difficulty of the search task and the salience of the target. Namely, a parallel search strategy was mostly used for easy searches (e.g. pop-out targets or displays with little number of distractors), whereas a more serial strategy was used for difficult searches (e.g. display with many or pop-out distractors) [17]. Further, the spontaneous use of search strategies during haptic search for landmarks on an unstructured 2D tactile map also depends on the size of the hand area used for the search: systematic search strategies such as spirals, zigzags or parallel sweeps were more prominent in one-finger search as compared to five-finger search [4], [19]. In five-finger search such systematic patterns could be so far detected (by visual inspection) only in a little number of trials, leaving five-finger movements thus largely uncharacterized. Participants may also perform particular movements to orient themselves within the search space. For instance, they might prefer movements in cardinal orientations because these orientations can be perceived and reproduced more precisely. However other factors might play a role, for instance participants could prefer to perform low-cost movements in terms of execution or motor planning. Goble et al. (2007) showed that in a free-stroke task, participants who were instructed to make straight strokes in the horizontal plane in all possible directions, movements along the diagonal were preferred. These movements were shown to minimize the cost for motor planning, because only one joint (elbow or shoulder) was actively moved while the motion at the other joint was largely passive minimizing regulation of interaction torque by muscular force [20]. Here we investigated which movements were preferred by participants in haptic search.

In Experiment 2 we aimed to quantitatively analyse exploratory movements in haptic five-finger search to uncover possible strategies applied during target search. More precisely, we analysed whether some movement orientation is preferred over others and how this preference depends on the orientation of the search space. In Experiment 1 we presented the rectangular haptic search stimulus parallel to the frontal and median plane of a participant’s body. In Experiment 2 we recruited two more participant groups; for one the search stimulus was rotated 30° clockwise and for the other group 30° counter-clockwise. Our hypothesis was that participants prefer to move parallel to the edges of the haptic search map, thus we expected preferred directions of motion at 90° and 180° in Experiment 1, 30° and 120° when the stimulus is presented 30° rotated counter clockwise, and at 60° and 150° when the stimulus is rotated 30° clockwise in Experiment 2.

In contrast, some movement orientations might be preferred because of e.g. low muscular cost or better discrimination and reproduction. Humans learn to optimize movements to reduce metabolic costs (e.g. [21]), thus some characteristics of movements must be due to this optimization. For instance the choice of human reaching and pointing movements is consistent with the minimization of energy costs of final postures and arm trajectories [22], [23]. It is also plausible that some movements are preferred just because they can be performed most accurately and thus maximize the information gain when exploring any stimulus. If movement preferences are due to such stimulus-independent factors, no influence of stimulus orientation is expected on the orientation of movements. Additionally, we repeated the main analyses of Experiment 1 on the data of Experiment 2 to test whether our conclusions made on the different roles of the fingers during target inspection are robust.

## II. METHODS

In both experiments participants performed speeded search on a rectangular 2D tactile display for a certain arrangement of symbols (e.g. a square of circles). During this process the position of all fingers was tracked and we analysed movement parameters for both processes, target search and target inspection.

### A. Participants

Nine students (6 females) participated in Experiment 1. In Experiment 2, there were 14 participants (9 female), half of them participated in the condition in which the stimulus was rotated 30° clockwise and the other half participated in the condition in which the stimulus was rotated 30° counter clockwise. All participants were volunteers, naïve to the purpose of the experiment and were reimbursed for their participation (8€/h). All participants were right-handed and did not report any sensory or motor impairment at the right hand. The study was approved by the local ethics committee LEK FB06 at Giessen University and was in line with the declaration of Helsinki from 2008. Written informed consent was obtained from each participant.

### B. Stimuli

We designed 20 different search stimuli similar to the ones described in [4]. These haptic search maps were rectangular boards 19cm long (y-axis), 29cm wide (x-axis) and 2mm thick with raised line symbols (line thickness 1 mm and line height 0.2mm) serving as targets and distractors (example in Fig. 1B). Each map contained in total 13 symbols. Some of these symbols were arranged into clusters (3 in each map). There were five different symbols: oval, square, circle, triangle and 'T', and five different clusters forming a higher order symbol: horizontal line, vertical line and triangle (consisting of 3 symbols), and diamond and square (consisting of 4 symbols) (Fig. 1C). All symbols were 7mm long (y-axis). The width (x-axis) of the oval was 5mm and that of the 'T' was 6mm, for the other symbols the width was the same as the length. The

distance between symbol centers in each cluster was 15mm. Within the map the symbols and symbol clusters were arranged at randomly chosen coordinates with the restriction that the borders of search items (single symbols and clusters) were at least 15mm apart and at least 20mm away from the edge of the map. Only symbol clusters were chosen as targets. Clusters and cluster symbols could repeat, but each combination of cluster and symbol was unique. Also single symbols in each map were unique. The stimuli were generated in OpenSCAD and printed with a 3D printer (Object30Pro, Stratasys, material VeroClear, nominal resolution 600 to 1600 dpi).

### C. Apparatus

Participants sat at a table in front of a monitor (120 Hz Samsung SyncMaster 2230R7 22-in., spatial resolution 1680 x 1050 pixels, Fig. 1A) in a lighted room. The head was stabilized by a chin rest. In Experiment 1 the search stimuli were placed in front of the participants in a way that the center of the search map was located approximately 30cm away from the body on the y-axis (Fig. 1A) and aligned with the body midline on the x-axis. The edges of the search map were parallel to the median and frontal plane of the body. In Experiment 2, the search stimuli were rotated from this parallel position 30° clockwise in one condition and 30° counter clockwise in the other condition (Fig. 2). The search targets were presented on the monitor in black on a gray background and viewed from 40 cm viewing distance. The search maps were stabilized at the corners with four holders of the same height as the stimuli; both holders and stimuli were 3D printed. The holders were attached to the table with double sided tape (Fig.1A) and also used for calibration of the motion capture system. For this purpose, each holder contained in the middle a small cone (calibration bump, base radius 1.5mm, height 0.75mm above the holder surface). The view on the search map and the moving hand was prevented by a sheet of paper (blind) attached at the bottom of the chin rest. The experiment was controlled by a computer program in MATLAB (MathWorks, Natick, MA, USA).

The position of each finger of the right hand in 3D space was tracked at 50 Hz<sup>1</sup> with the Zebris ultrasound system (Zebris Medical GmbH, Isny). The nominal resolution of the system is under 0.1 mm and the nominal accuracy, at the measurement distance used in the setup (around 35cm), is under 1 mm. The Zebris motion capture system was placed at the left side of the desk. The markers (five in total) were attached to the fingernails of the five fingers.

### D. Procedure

In both Experiments in the beginning of the experimental session for each participant we calibrated the measured finger positions with respect to the four corners of the search map in the parallel position. For this purpose, participants were

<sup>1</sup>Please note in [5] the sampling rate was wrongly assumed to be at 100Hz, thus the absolute values concerning exploration speed are scaled by factor 2. However, the different scale neither changes the shape of the speed curves nor the relative differences in speed between the fingers. Therefore, our main conclusion are not affected by this.

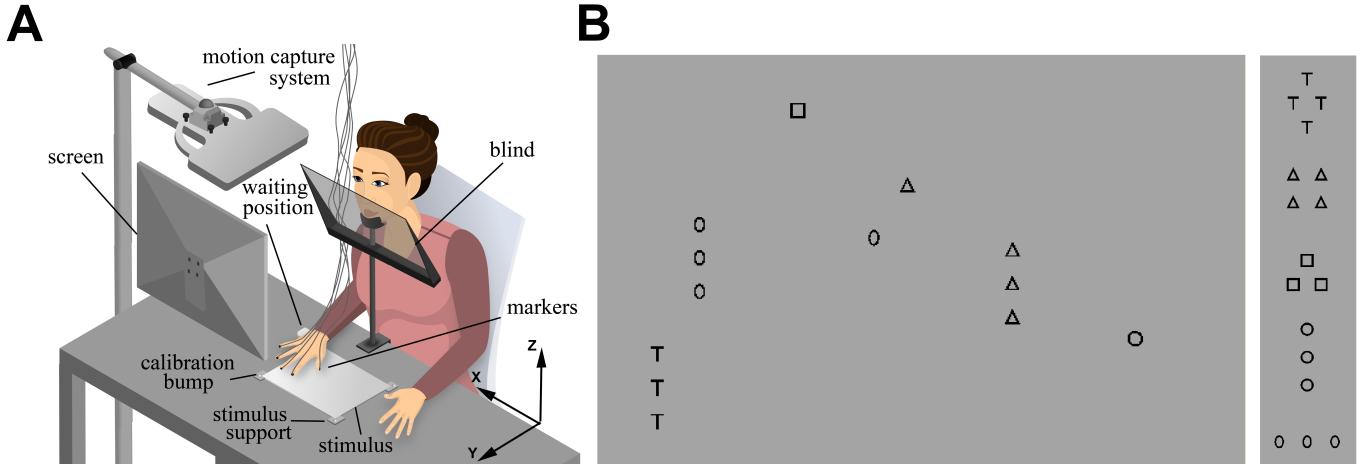


Fig. 1. A) Experimental setup. B) On the left, an example haptic search map template. The symbols outlined in black were elevated by 0.2mm above the surface. On the right, symbols ('T', triangle, square, circle, oval, from top to bottom) and symbol clusters (diamond, square, triangle, vertical line, horizontal line from top to bottom) used in the experiment. Each cluster could consist of each symbol.

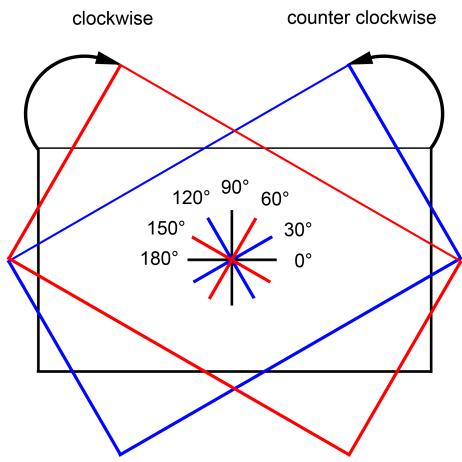


Fig. 2. Schematic of the haptic search stimulus orientation. In Experiment 1 the stimulus was presented parallel to the body (black). In Experiment 2 for one group of participants the stimulus was rotated 30° clockwise (red), and for another group of participants it was rotated 30° counter-clockwise (blue). For each orientation the inner star in the same colour indicates the orientation of the edges of the stimulus.

instructed to position the index finger of their right hand sequentially on each of the four calibration bumps in a way that the marker attached on top of the finger was right above the bump. Then they pressed a keyboard button and the position was recorded for 3s. The recorded positions were averaged over the 3s for each corner and used to define a projective transformation to map touched positions onto the horizontal stimulus plane. Only the index finger was calibrated, assuming that the same calibration applies to the other fingers. After the calibration participants were presented in every trial with a haptic search map. They were instructed to search as quick as possible for a cluster of symbols which was shown on the monitor, and to press a keyboard button as soon as they found it. In each haptic search map (20) each cluster (3) was once presented as the target, resulting in 60 trials. The order of the trials was randomized. The stimuli

were placed by the experimenter who sat at the right side of the participant. The stimulus number was displayed in the right corner of the monitor invisible for the participant. Before each trial, participants were instructed to place the middle finger at the waiting position (a little 3D printed finger holder, 3x2cm, same height as the search maps containing a central cylindrical cavity) located at the bottom edge of the search map, 5 cm away from its right edge in the parallel position. At the end of the trial we drew an outline of the hand with spread fingers. The experimental session was on average completed within 1h.

#### E. Data Analysis

We preprocessed the data in Experiment 1 to individuate the time points at which participants touched search items by computing for every participant, every trial and each finger pad, the intersection area with every symbol (single symbols and symbols in target and distracter clusters). An example of finger traces in one trial is shown in Figure 3A and the corresponding intersection area plot for each finger in Figure 3B. The finger pad was approximated by a square oriented parallel to the haptic search map. The circle and triangle symbols were approximated by squares and the 'T' and oval symbols by rectangles. For the approximation of finger pads we used the average finger diameter measured from the drawn hand contours across fingers and participants, ceiled to the next integer, resulting in a generous finger diameter of 17mm. We used equally sized squares to approximate all fingers, to prevent the results to be driven merely by the differences in the anatomy of the fingers. In order to individuate single touches of the symbols, we used similar criteria as in [4]. Specifically, the finger was considered in contact with a symbol as long as the intersection area between finger and symbol was above a certain threshold ( $4 \text{ mm}^2$ ) and did not drop below it for longer than 0.67s. We chose a smaller threshold than in [4] because we considered each of the symbols (not the clusters as a whole) as individual search items. Using these criteria, for further analysis, the intersection area per symbol, per time

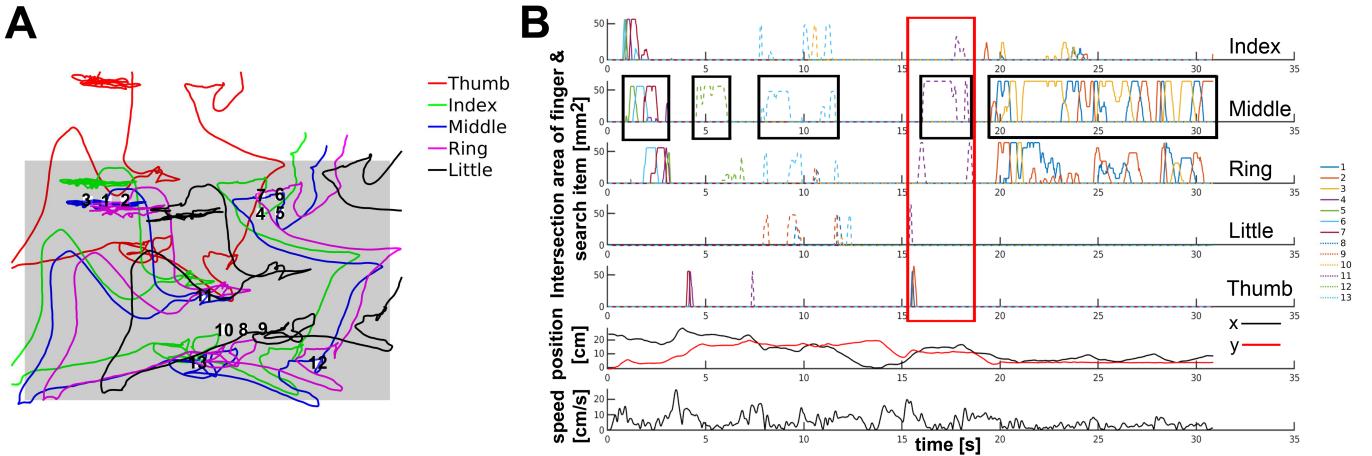


Fig. 3. A) Example of finger movements in one trial. B) Intersection area for each finger and target, x- and y-position and speed over time for the same trial as in A. Different colours indicate different search items 1-13. The location of these search items is shown in A. An example of an episode with contact of an individual item across fingers, as used to compute touch probability profiles is indicated for the search item 11 (purple dotted) by a red frame. Examples of episodes with contact of one finger with any search item, as used for the analysis of movement parameters are indicated for the middle finger by black frames.

point and per finger was discretized in touch (1) or no touch (0).

To compute touch probability profiles we aggregated episodes in which one single symbol within a cluster (search item) was explored with one or more fingers without loosing contact for longer than 2s (example in Fig. 3B, framed red). For larger intervals, we assumed that the symbol was revisited. In order to aggregate these episodes, we imposed to each of them the same time scale by normalizing time for each duration. For this purpose we chose an arbitrary size of 100 samples in arbitrary time units and up- or downsampled each episode to this size by nearest neighbor interpolation (*interp1* function in MATLAB). Average touch probability profiles were computed separately for episodes beginning with different fingers. This analysis potentially indicates which finger is used after the encounter of a potential target, suggesting its involvement in fine analysis. For statistical analyses, we focused on the final portion of the exploration time and averaged probability across the last 30%. Then, we run a two-way repeated measures ANOVA on the average probability of exploration, with first finger and exploring finger as fixed factors. We expect a significant main effect of the exploring finger, if the hypothesis is true that some finger is used more likely than other fingers to explore a potential target after detection with another finger. Given a significant main effect of the exploring finger we performed multiple post-hoc comparisons to identify the finger which most likely explored potential targets after they were detected with another finger.

In order to analyze movement parameters, we individuated for every finger episodes in which it was exploring search items (i.e. contact with any of the search item did not stop for longer than 0.67ms (framed black in Fig. 3B). We aligned these episodes by the onset of touch and computed for 1s temporal windows around it from the two dimensional trajectories of each of the finger pads the speed  $S$  at the time point  $i$  as follows:

$$S_i = |xy_i - xy_{i-1}| / (t_i - t_{i-1}) \quad (1)$$

With  $xy_i$  being the finger pad position at the time point  $i$ ,  $xy_{i-1}$  at the previous time sample and  $t_i - t_{i-1} = 20\text{ms}$ . The so computed speed profiles were averaged for each of the fingers separately. Individual baseline average speed profiles were computed by virtually repositioning each search item of a map in each trial to randomly chosen coordinates and computing when these virtual search items were touched. Thus, we could gain an insight on the speed pattern independent of the actual contact with potential targets. We think that this baseline best reflects the random component of our analyses. To compute the speed and acceleration profiles we search in every trace of each finger for contacts with search items. In general, if finger speed varies during exploration, as is expected from a trajectory of biological motion, the probability of crossing the boundary between any two areas increases with finger speed. This selection bias manifests itself in the increased speed at the time of boundary crossing. In particular, in our experiment participants performed a search task, in which long (space occupying) quick movements between search items and rather slow, time consuming movements concentrated within search items are typical. By randomly sampling in space (as we do when searching for contacts with potential targets) it is more likely to hit the quick part of the movement (outside of potential targets) but by looking at a time window around this moment it is more likely to get the slow part of the movement (on a potential target). Thus we expect that around the onsets of the exploration of search items the speed would be by definition higher than in the time windows around it just by the structure of the data and the way we identified the contacts with potential targets. For more explanation on the baseline see Supplemental Material. Thus to investigate the speed profiles related to the contact of potential targets it is important to look at differences to the baseline. Statistical analyses on the speed profiles focused

on a 300ms time window before and after the touch onset. The choice for this time window is based on the finding that participants make pauses of up to 330ms in haptic explorations of unknown relief stimuli ([6]), likely related to processing of the input, similar to fixations in visual perception. Average differences between the speed and baseline speed in each time window were computed for each participant and each finger independently, yielding two relative average speed values (i.e. before and after touch onset) per finger for each participant. In order to test for differences between time windows and fingers, we performed a two-way repeated measures ANOVA on relative average speed with time window and finger as fixed factors. If some finger is specialized on target inspection we expect an interaction between these factors, indicating that only some finger slows down to analyze a potential target. To individuate such fingers we compared for each finger the speed before and after touch onset with additional post-hoc *t*-tests corrected for 5 comparisons. We conducted analogous analyses on acceleration profiles, with acceleration  $A$  being computed at the time point  $i$  as follows:

$$A_i = (S_i - S_{i-1}) / (t_i - t_{i-1}) \quad (2)$$

To analyze the extension of movement trajectories in the cases the finger was in touch with a symbol or not we used a box-counting algorithm which computes the number of boxes of a size of 1mm, corresponding to tactile spatial acuity [24] necessary to cover a given piece (60ms) of the movement trajectory (cf. [25]). We then compared the average number of boxes during contact and no contact of search items using a *t*-test for different fingers separately. We expect that only specialized fingers would perform fine analysis movements, which are concentrated in a small area, when being in contact with potential targets and long ranging search movements otherwise.

To test whether there was a preferred moving orientation during target search, we first excluded from the movement data the samples in which either the index or/and the middle finger were in contact with one of the search items, as they were shown to be mostly involved in fine target inspection in Experiment 1. On the remaining traces we calculated the orientation of the movement for each participant, each trial, each finger position and each time point for Experiment 1 and 2. The data was first cleaned by removing samples in which a velocity of more than 150 cm/s was detected, considering them to be artefacts. On average  $< 0.001$  data was excluded by this procedure. Afterwards the traces of the fingers were smoothed using a 220ms moving average filter. The movement direction  $\alpha$  for each participant, each trial, each finger and each time point  $i$  was then computed as the inverse tangent from the cleaned and smoothed  $x$ - and  $y$ -positions in the time points  $i$  and  $i+1$  as follows:

$$\alpha_i = \arctan((y_{i+1} - y_i) / (x_{i+1} - x_i)) \quad (3)$$

We transformed the resulting angular data into axial data, as each direction is equivalent to the opposite direction (e.g. upward motion along the  $90^\circ$  direction is equivalent to downward motion along the  $-90^\circ$  direction). Given that finger positions

were highly correlated (correlation of horizontal and vertical positions between each couple of fingers ranged between Pearson's  $r = 0.871$ , to  $r = 0.999$ ) consistent with previous findings [4] we performed the analysis only on the orientation of the middle finger. Our hypothesis was that participants would move parallel to the edges of the stimulus resulting in four peaks in the circular distribution of movement orientations  $90^\circ$  apart from each other for any orientation of the search map. Under our hypothesis, the four expected distribution modes in our data would collapse into one when distributions are folded to a quarter of the full range along the directions at which the distributions are mirror symmetrical:  $45^\circ - 135^\circ$  and  $-135^\circ - 45^\circ$  for the condition in which the search map was parallel to the frontal body plane;  $-15^\circ - 165^\circ$  and  $-105^\circ - 75^\circ$  for the counter clockwise rotated search map and  $-75^\circ - 105^\circ$  and  $-165^\circ - 15^\circ$  for the clockwise rotated search map. If participants move parallel to the edges of the stimulus the resulting angular distributions should peak at the corresponding rotation angle  $\beta \in [30^\circ, 0^\circ, -30^\circ]$  depending on the orientation of the search map (rotated counter clockwise, not rotated, rotated clockwise, respectively) when collapsed to the  $90^\circ$  range and at  $\beta * 4$  after the remapping to the full range. Thus fulfilling the assumption of unimodality for statistical testing. We computed for every participant and trial the circular mean of the movement orientation distribution. To test for the statistical significance of the preference to move parallel to the edges of the stimulus we performed a Rayleigh test for non-uniformity of circular data [26]. We also tested whether empirical average movement orientations are consistent with the predicted ones. For this purpose we used the V-test [27], a variant of the Reyleigh test. A significant result in the V-test means that angles are not distributed uniformly around the circle but have a defined mean. We performed the Reyleigh and the V-test for every participant separately (across trials) and also on the average movement orientations (across participants). Finally, we tested whether movement preferences depend on the orientation of the search stimulus using the Watson-Williams multi-sample test for equal means an analog to the one-way ANOVA test for circular data [27]. For all statistics we used the Circular Statistics Toolbox of MATLAB [28]. For visualization, moving directions in every trial were partitioned into predefined bins of  $3.6^\circ$  between  $0^\circ$  and  $180^\circ$ , and we calculated the relative frequency in each bin. Then we averaged the relative count in each bin over trials for each participant and then over participants.

### III. RESULTS

#### A. Experiment 1

Figure 4 shows the probability of each finger to touch a potential target after it was first encountered by a certain finger in an average exploration. Each panel represents one first touching finger, the different lines represent probabilities of touch for each finger afterwards. The duration of an average search item exploration was 2.56s. Essentially, irrespective of which finger touched first, the middle and the index fingers seem to have a relatively high probability of following, as their probability curves exhibit a peak at the end of the exploration time in all the panels.

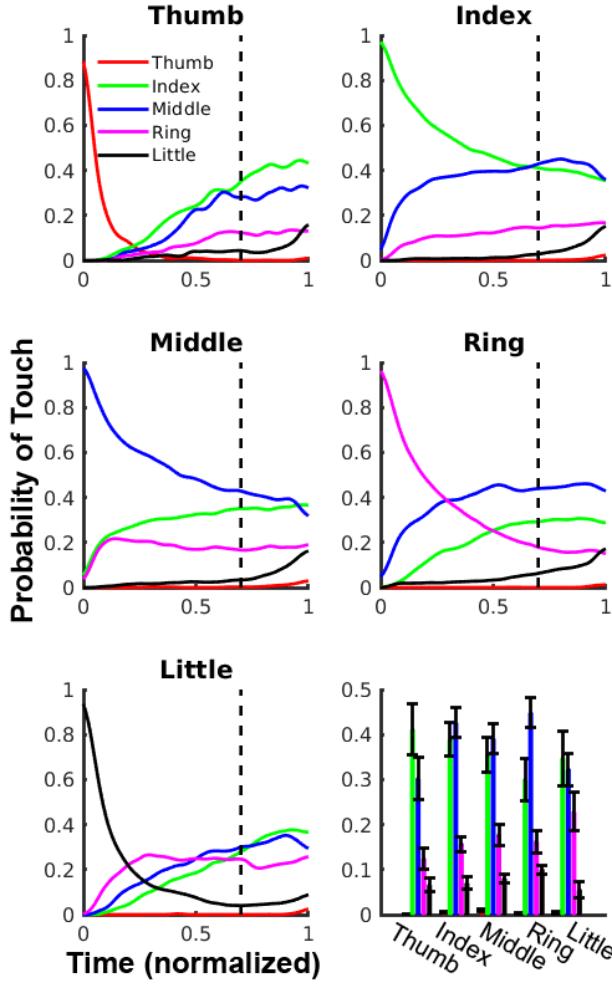


Fig. 4. Probability that each of the fingers (different colors) touches a potential target (y-axis) over time (x-axis), after it was first encountered by a certain finger (panels 1–5). Probabilities are averaged across participants. In order to aggregate the data, the time scale was normalized. The curves are smoothed with a Gaussian window of  $\sigma = 10\%$  normalized units. Average duration of the exploration of one search item was 2.56s. In the last panel the average probability to touch a potential target (y-axis) after it was encountered by a certain finger (as indicated on the x-axis) in the last 30% of the exploration is plotted for each finger (different colors). Error bars represent the standard error.

The two-way repeated measures ANOVA on the average probability of the last 30% of the exploration (dotted line in Fig. 4), with first finger and exploring finger as fixed factors revealed a main effect of exploring finger,  $F(4,32) = 32.66, p < 0.001$ , a main effect of first finger,  $F(4,32) = 6.01, p = 0.001$ , and a significant interaction  $F(16,128) = 5.18, p < 0.001$ . This suggests that exploration with some fingers tends to follow the first touch more often than exploration with other fingers. Multiple post-hoc comparisons Bonferroni-Holm corrected (10 comparisons for each first finger) confirmed the pattern shown in Fig. 4 - last panel. The index and the middle finger were more likely to touch a potential target than all the other fingers after the detection of the item with most of the fingers (all  $p <$

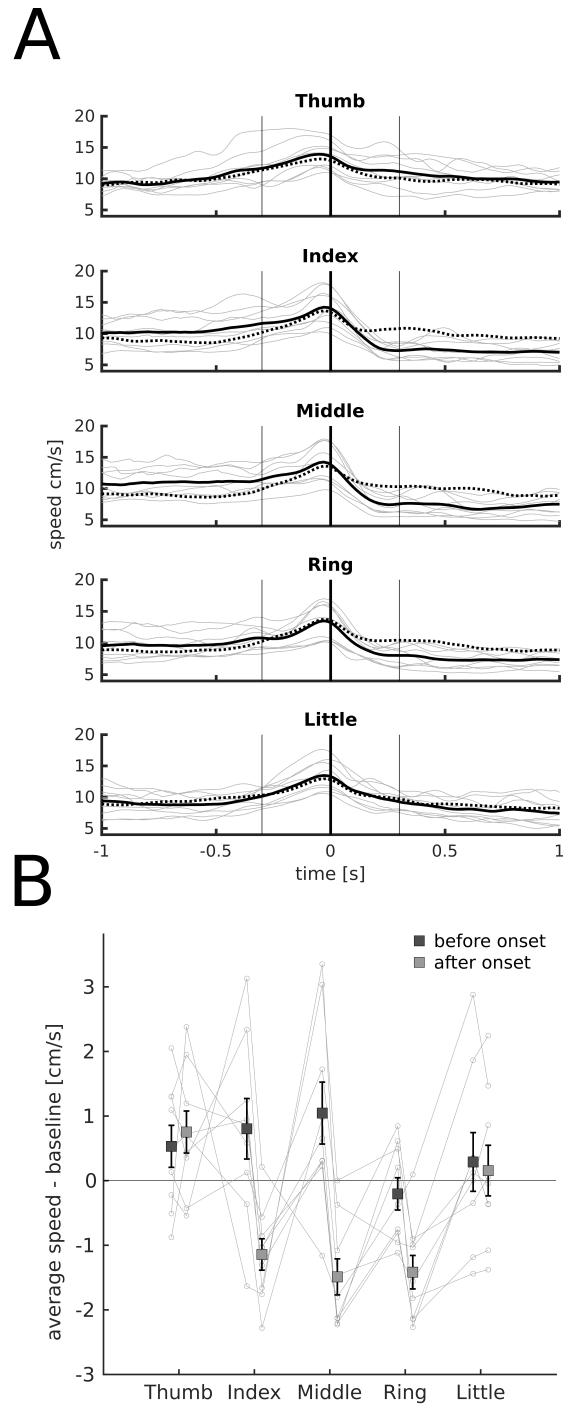


Fig. 5. A) Speed over time, before and after each of the fingers encountered a potential target. Continuous black lines represent the average speed across observers over time, individual data is plotted in gray and the dashed lines represent the baselines. A peak in speed around the onset of target contact (in the average speed and the baseline) is expected in a biological movement (see Data Analysis). Thick vertical lines indicate the onset of touch and the thin lines indicate the time windows (300ms before and after touch onset) used for statistical analyses. B) Average speed within 300ms before and 300ms after touch onset for each finger. Error bars represent the standard error.

$< 0.05$ , besides index and middle vs. ring after little and index vs. ring after ring,  $t(8) = 1.15, p = 0.565$ ,  $t(8) = 2.40, p = 0.13$ ,  $t(8) = 1.99, p = 0.163$ , respectively). The ring finger more likely followed most of the other fingers in exploration than

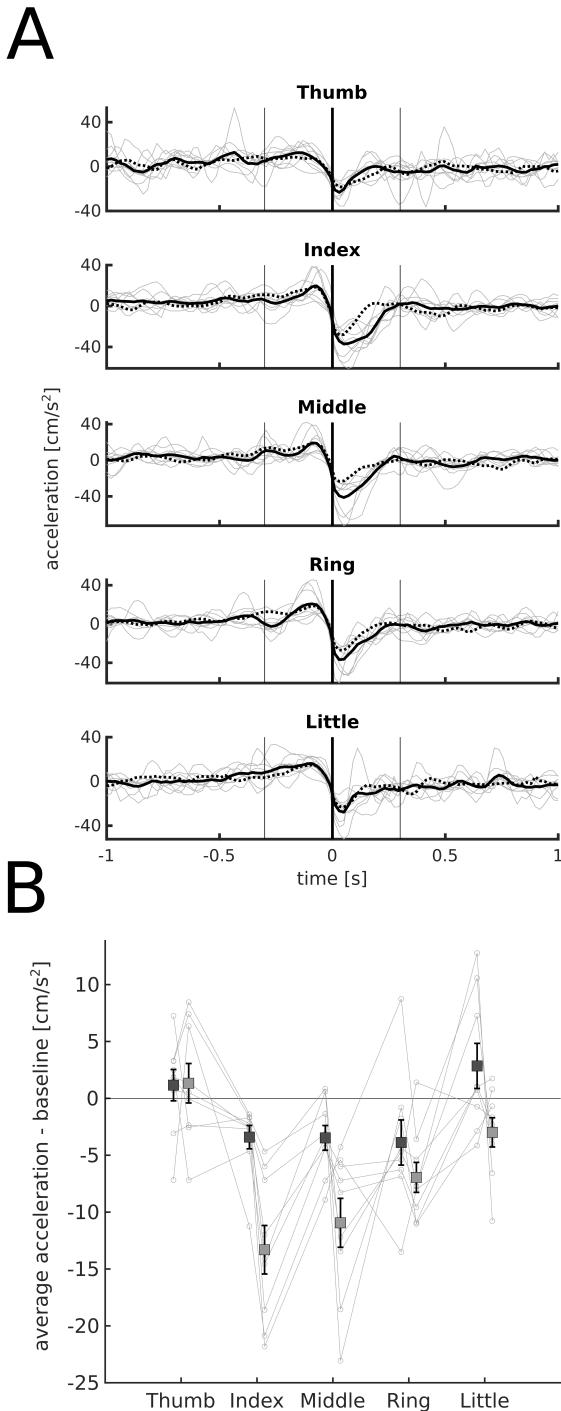


Fig. 6. **A)** Acceleration over time, before and after each finger encountered a potential target. Continuous black lines represent the average speed across observers over time, individual data is plotted in gray and the dashed lines represent the baselines. Thick vertical lines indicate the onset of touch and the thin lines indicate the time windows (300ms before and after touch onset) used for statistical analyses. **B)** Average acceleration within 300ms before and 300ms after touch onset for each finger. Error bars represent the standard error.

the little finger and the thumb (all  $p < 0.05$ , besides ring vs. little after thumb and ring,  $t(8) = 2.60, p = 0.063, t(8) = 2.40, p = 0.13$ , respectively) and the little finger followed the thumb more likely in exploration (all  $p < 0.05$ , besides after little,

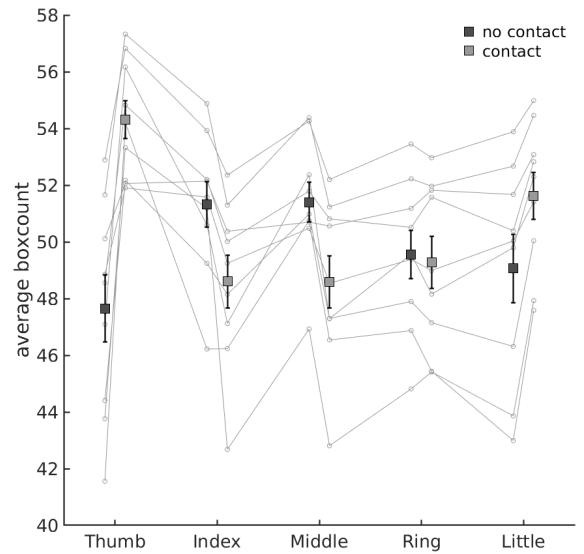


Fig. 7. Average box-count (y-axis) for the different fingers (x-axis), for the time the finger was in contact with any of the search items (light gray symbols) and the time it was not (dark symbols). Error bars represent the standard error.

$t(8) = -2.86, p = 0.084$ ). Overall, these results indicate that the middle and the index finger tend to touch a potential target more likely than the other fingers after it was encountered with any other finger.

Figures 5A and 6A depict the average speed and acceleration profiles around the time points, when each finger encountered any of the potential targets. On average the fingers stayed for 1.51s in touch with potential targets. The speed and acceleration profiles for the thumb and little finger are essentially the same during actual touch and the baseline (touch of virtual search items). Conversely, the index and the middle finger move faster than the baseline before they encounter a search item and dramatically decelerate and start to move slow once they are in contact with a potential target. This is confirmed by statistical analyses on the average speed and acceleration in the surround of the touch onset (Fig.5B and 6B). Also the ring finger decelerates and moves slower after it contacts a potential target, but the difference between the speed and acceleration before and after touch onset are smaller than for the index and middle finger.

We conducted two-way repeated measures ANOVA, on average speed and average acceleration, separately. We found a significant interaction between time window and finger on average speed,  $F(4,32) = 11.44, p < 0.001$ , and at the edge of significance for average acceleration,  $F(4,32) = 2.47, p = 0.065$ , indicating that for some fingers the speed and acceleration changed due to the contact with a potential target. Because the differences between fingers change between the two time windows (before onset and after onset), we performed separate one-way repeated measures ANOVAs for the two time windows.

The ANOVA failed to reveal a significant difference in the average speed between fingers for the before onset time window,  $F(4,32) = 1.21, p = 0.324$ . Conversely, for the after onset window the average speed significantly differed between

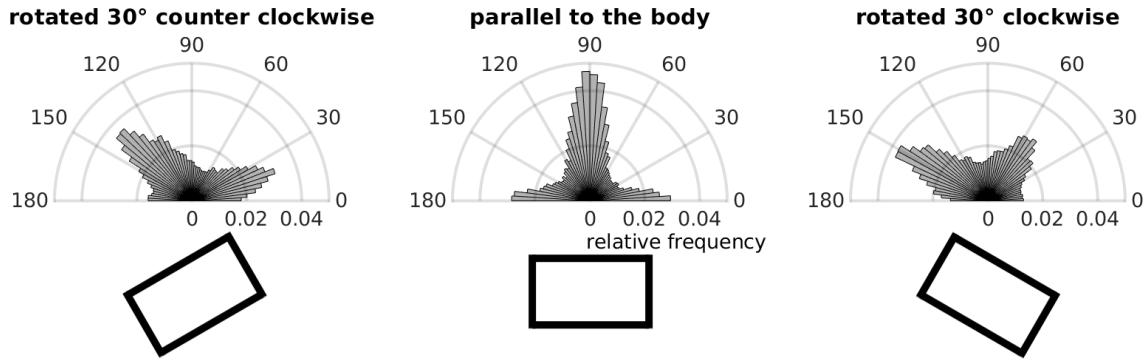


Fig. 8. Average movement direction histograms. For each orientation of the haptic search map as indicated below the histograms, the average relative frequencies are plotted for each movement direction bin of  $3.6^\circ$  between  $0^\circ$  and  $180^\circ$ . Movement directions along the same axis are collapsed.

the fingers,  $F(4,32) = 11.77, p < 0.001$ . However, for average acceleration we found a significant difference between the fingers for the before onset time window,  $F(4,32) = 6.41, p < 0.001$  as well as for the after onset time window,  $F(4,32) = 9.29, p < 0.001$ . To identify for which finger speed and acceleration changed due to the contact with a potential target we post-hoc compared the speed and acceleration for every finger before and after they encountered a potential target. We found that the index,  $t(8) = 5.72, p < 0.001$ , middle,  $t(8) = 7.71, p < 0.001$  and ring finger  $t(8) = 3.51, p = 0.008$  moved significantly slower after they encountered a potential target. The index finger also decelerated after the onset of contact as compared to the time before the onset,  $t(8) = 5.23, p < 0.001$ , and there was a trend for the middle finger,  $t(8) = 2.43, p = 0.041$  (corrected for 5 comparisons  $\alpha = 0.01$ ).

Figure 7 depicts the average box-count for the phases of contact and no contact with any of the search items for the different fingers separately. The box-count was significantly lower for the index  $t(8) = -3.35, p = 0.01$ , and the middle finger,  $t(8) = -5.15, p < 0.001$  in the case these fingers were in contact with a search item, reflecting shorter movements when in contact with the target than when not being in contact. For the little finger and the thumb, the box-count was significantly higher when a search item was contacted: little finger,  $t(8) = 5.96, p < 0.001$ ; thumb:  $t(8) = 5.79, p < 0.001$ . For the ring finger no significant difference in the extension of movement trajectories between the contact and no contact phases could be shown,  $t(8) = -0.91, p = 0.389$ . These results suggest that target inspection was performed with the index and the middle finger, while contact with the other fingers likely was mostly detected while these fingers moved accidentally over the search items or moved away to leave space to the middle and index finger.

### B. Experiment 2

We replicated almost exactly all the findings of Experiment 1 on the data of Experiment 2 (see Results of the replication in Supplemental Material).

Figure 8 shows the average relative frequencies of movement directions in haptic search, for the three different orientations of the haptic search maps: parallel to the body, rotated  $30^\circ$  counter-clockwise and rotated  $30^\circ$  clockwise from the parallel orientation. In all conditions participants more frequently

moved the hand parallel to the edges of the stimulus than in other directions. This resulted in frequency peaks around  $90^\circ$  and  $0^\circ/180^\circ$  when the search stimulus was positioned parallel to the body of the participant, approximately around  $30^\circ$  and  $120^\circ$  when the stimulus was rotated  $30^\circ$  counter clockwise and around  $60^\circ$  and  $150^\circ$  when the stimulus was rotated  $30^\circ$  clockwise (Fig. 8).

Figure 9 depict individual movement direction histograms for each orientation of the haptic search stimulus. When the haptic search stimulus was presented parallel to the body or rotated  $30^\circ$  counter clockwise most of the participants seemed to prefer movements parallel to the horizontal as well as parallel to its vertical edge. However, when the stimulus was rotated  $30^\circ$  clockwise there was more inter-individual variance. Here most of the participants expressed a clear preference for movement orientated either parallel to the horizontal stimulus edge or parallel to its vertical edge.

The Rayleigh test for non-uniformity on trial-wise average movement directions was significant in all conditions for all participants (all  $p < 0.05$ ), confirming that some movement directions were more frequent than others for each participant. Further the V-test, testing the hypothesis that a distribution is non-uniform and has a certain mean revealed that empirical means of movement direction distributions do not deviate from the predicted ones in all conditions for all participants (all  $p < 0.005$ ), confirming that participants as predicted preferred to move parallel to the edges of the stimulus. The distribution of average movement directions across participants were also non-uniform as confirmed by the Rayleigh test in every condition  $z = 6.12, p < 0.001$ , for the counter-clockwise rotated search map;  $z = 8.10, p < 0.001$  for the parallel orientation of the search map and  $z = 4.96, p = 0.003$  for the clockwise rotated search map. Movement directions did not deviate from predicted ones in every condition also on average across participants as confirmed by the V-test: mean  $78.09^\circ$  vs. predicted  $120^\circ$ ,  $V = 4.87, p = 0.005$ , for the counter clockwise rotation; mean  $-7.44^\circ$  vs. predicted  $0^\circ$ ,  $V = 8.47, p < 0.001$ , for the parallel orientation of the search map and mean  $-120.48^\circ$  vs. predicted  $-120^\circ$ ,  $V = 5.89, p < 0.001$ . We further used the Watson-Williams test to compare the means between the different search map orientation conditions. The test revealed a significant difference,  $F(2,20) = 74.34, p <$

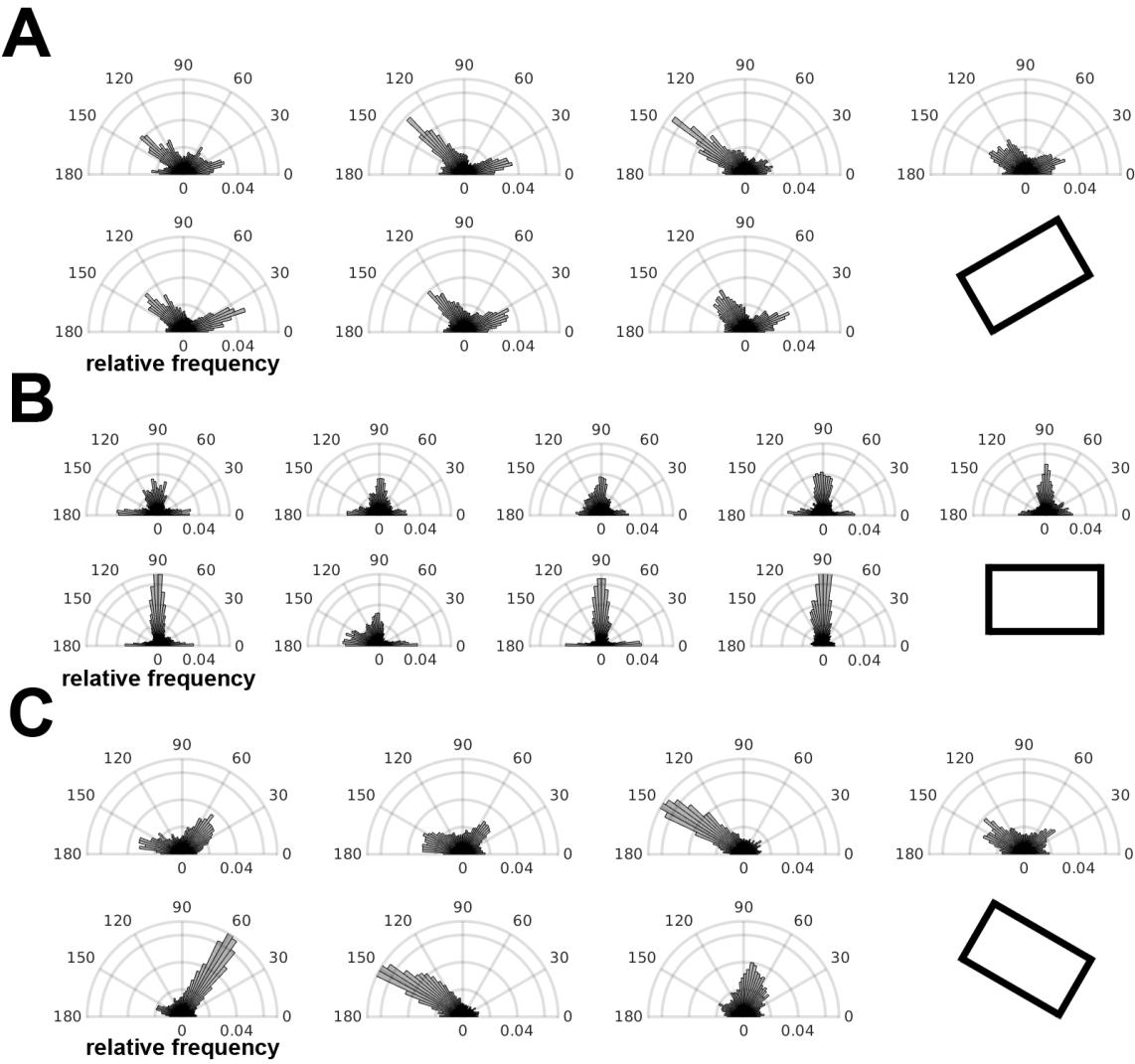


Fig. 9. Individual movement direction histograms for haptic search maps rotated 30° counter clockwise, oriented parallel to the frontal body plane and rotated 30° clockwise in A-C respectively. For each participant the average relative frequencies are plotted for each movement direction bin of 3.6° between 0° and 180°. Movement directions along the same axis are collapsed. The orientation of the search map is indicated in the right left corner.

0.001, confirming our hypothesis that movement preferences depend on the orientation of the search map.

#### IV. DISCUSSION

In Experiment 1 we addressed the role of different fingers in the process of target inspection in haptic search. Thus we investigated the dynamics of haptic search behaviour in proximity to potential targets. We found that when a search item was encountered by any of the fingers, it was subsequently likely to be explored by the index or the middle finger, suggesting their specialization for fine analysis. Consistent with this hypothesis, the middle and the index fingers dramatically slowed down after encountering potential targets. For the middle and the index finger, we found higher speed before contact onset. Also this is consistent with our hypothesis, as only for specialized fingers we would expect that quick search movements or movements towards the item detected by an other finger would precede the contact. For not specialized fingers contacts with search items would rather occur accidentally

(e.g. while another search item in the proximity is explored) or would relate to detection, by which the movement speed would be either slow or high before contact, similar as in the baseline. Finally, a box-count analysis revealed that the index and the middle finger moved in a smaller area than the other fingers when encountering a potential target, enforcing the idea of their special role in fine exploration. In fact, within the same time window, when the other fingers encounter a target, their trajectories cover a larger area, which may indicate that they move away from the potential target in order to leave space to the index and the middle fingers. By replicating these results also on the data of Experiment 2, we show that our findings are robust, which strengthens our conclusion that the index and middle finger play a special role in the fine analysis of planar objects.

Together, these results strongly corroborate the hypothesis of [4]: when any of the fingers encounters a potential target, this is subsequently explored by the index or/and the middle finger. These fingers quickly decelerate to keep contact with

the target for relatively long time, while the other fingers move away. Such a dynamic pattern is consistent with what is considered a saccade behavior in the star-nosed mole [7]. Specifically, that the mole detects the target (prey) with any of the appendages and then performs rapid, saccadic-like movements with the star to bring the foveal appendages to the target for fine inspection. However, whereas the star-nosed mole could move its appendixes independently, the finger movements happen to be correlated [4]. This is also confirmed in our analyses: correlation of horizontal and vertical positions between each couple of fingers ranged between Pearson's  $r = 0.871$ , to  $r = 0.999$ . Thus, it might be doubted that specialization of the fingers is useful. However, Overvliet, et al., (2007) showed that reaction times in haptic search increased when participants were forced to use multiple fingers (index, middle and ring) as a unit as compared to one finger, indicating longer processing times for each search item [29] and consistent with the finding that critical shape information cannot be processed simultaneously across fingers [30].

We propose here that the index and the middle fingers are specialized for fine analysis. While the present study did not have any measure of identification performance to support this idea, such evidence is reported in the literature. For example, it was reported that tactile sensitivity varies across the hand [31], [32], being minimal at the palm and best for the index and the middle finger.

Higher discrimination performance usually correlates with the area of cortical representation. For instance, Catania & Remple (2004) reported that the number of contacts of each of the appendix with potential targets correlated with its cortical representation in the primary sensory cortex of the star-nosed mole, suggesting that the appendixes who are more involved in fine exploration are specialized for fine analysis [7]. In humans, tactile discrimination thresholds correlate with imaging measurements of cortical finger representations within primary somatosensory cortex [33]. Furthermore, there is evidence that the cortical representation for the index and for the middle finger is relatively large as compared to the other fingers (e.g. [34]). There are also reports of a particularly large cortical representation of the thumb (e.g. [34], [35]), although the thumb seems hardly involved in target analysis in haptic search on a 2D display. However, the enlarged representation of the thumb is likely due to the fact that the thumb is usually involved in object manipulation tasks in 3D.

In Experiment 2 we analysed whether some movement orientation is preferred over others during target search. We found that participants preferred to move the hand parallel to the edges of the search space across different search stimulus orientations (parallel,  $30^\circ$  clockwise and  $30^\circ$  counter clockwise rotated). A previous study had detected typical systematic movements such as zigzags, spirals or parallel sweeps for five-finger search only in a minority of trials by visual inspection [4]. Our results, however, suggest that in five-finger haptic search participants apply a strategy, i.e. moving the hand parallel to the edges of the search space, which does not clearly fall in any of the above mentioned categories, but possibly helps orienting them within the search space.

It is also possible that the strategy of participants was to

move parallel to the search items, most of which were oriented parallel to the edges of the stimulus. However, we observed that participants most clearly moved parallel to the edges at the edges where no search items were located by the design of the stimuli. Thus we believe that this movement strategy is rather designated to refresh the representation of the outline of the search map in order to improve orientation within the map than to improve the detection of potential targets. Based on the data of this experiment we can not rule out other possibilities, but we aim to address this question in future.

We found more inter-individual variability in the condition in which the stimulus was rotated  $30^\circ$  clockwise. In this condition most of participants expressed a clear preference to move only parallel to one of the stimulus edges. This might be because this rotation of objects handled in a 2D plane at the table is less common in everyday life. For instance when writing the majority of right-handers slant the paper in the opposite direction (counter clockwise [36]). Thus it can be that with a less common position of the stimulus a less complex strategy (orient relative to only one stimulus axis) is applied. This speculation is consistent with numerically highest response times in this condition (15.42s vs. 14.44s with  $30^\circ$  counter clockwise rotation and 12.95s with placement parallel to the median and frontal body plane). However, the effect of rotation on response times was not significant in the between group comparison ( $F(2,20) = 0.8$ ,  $p = 0.463$ ).

Taken together, by inspecting the dynamics of basic movement features in haptic search, we provided evidence that haptic search involves a two phases process of target search and target analysis similar to vision: peripheral detection and saccade for high resolution processing. For target inspection, participants tend to use the middle and index finger to perform detailed analysis. In the phase of target search participants often move parallel to the edges of the search space, possibly to orient themselves for efficiently scanning the search space. Previous research associated search strategies mostly with restrictions of available hand area (i.e. one-finger search [4]), whereas our results suggest that also in five-finger search exploratory movements are strategic.

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