Dynamics of exploration in haptic search*

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Abstract— **Haptic search is a common every day task. Here we characterize the movement dynamics in haptic search. Participants searched for a particular configuration of symbols on a tactile display. We compared the exploratory behavior of the fingers in proximity to potential targets: when any of the fingers encountered a potential target, there was higher probability that subsequent exploration was performed by the index or the middle finger. At the same time, the middle and the index fingers dramatically slowed down. Being in contact with the potential target, the index and the middle finger moved in around a smaller area than the other fingers, which rather seemed to move away to leave them space. Our results corroborate a previous hypothesis [1] that haptic search consists of two phases: a process of target search using all fingers, and a target analysis using the middle and the index finger, which might be specialized for fine analysis.**

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. The exploratory behavior used to perceive specific haptic features has been intensively investigated, showing that humans tend to perform highly stereotypical movements (*exploratory procedures*, EPs [2]), 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 [2]. These property specific EPs were shown to be optimal (most accurate or fastest) as compared to other EPs [2]. 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 [3][4]. In contrast, how the hand and fingers move during haptic search has not yet been characterized in detail. Here, we aim to investigate the exploratory behavior of different fingers in haptic search in order to identify fingers specialized for target inspection.

It was analyzed how the hand and fingers move during haptic search in an unstructured 3D display in order to identify stereotypical *search procedures* [5] similar to the *exploratory procedures* [2]. Participants explored with a single hand (dressed in a haptic glove) a wooden panel consisting of bricks with different upper shape (e.g. half of a sphere or cylinder), searching for a certain combination of such bricks. Consistent with optimal exploration of object shape, participants performed the EPs of enclosure and contour following [2]. The search could be characterized by the alternation of three representative *search procedures*: 1. execution of one EP (contour following or enclosure) by one finger, 2. parallel execution of the same exploratory procedure with different fingers and 3. mixture of different exploratory procedures (contour following + enclosure). However, these exploratory movement characteristics focus mostly on target exploration and neglect the actual target search process.

Target search process in haptic search seems to involve systematic movement patterns, which can be categorized as parallel or serial search [6][7]. Parallel search, is characterized by one or two hand sweeps or a circular hand movement over the 3D display, while several scribbling movements and item-wise exploration indicated serial search. The choice of a certain search category was shown to depend on the difficulty of the search task and the salience of the target. Namely, parallel search strategy was mostly used for easy search (e.g. pop out targets or display with little number of distractors) and a more serial strategy for difficult search (e.g. display with many or pop-out distractors) [6]. Further it was shown that 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 [1][8]: systematic search strategies such as spirals, zigzags or parallel sweeps were more prominent in one-finger search as compared to five-finger search. In five-finger search such systematic patterns could be detected by visual inspection only in a little number of trials, leaving it thus largely uncharacterized. Further on, search strategies characterize mostly the target search process in particular cases, while characteristics are missing of haptic search as a whole - including target search and target inspection, particularly regarding the roles of different fingers.

Movements in object exploration were analyzed with respect to exploration pauses [9]. It was 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 it was shown that star-nosed moles, with their specialized somatosensory organ consisting of several appendages surrounding the nostrils, perform rapid movements similar to saccades in vision [10]. Further, detection of the prey was observed to happen equally likely with any of the appendages, whereas the identification of the prey was consistently performed with a specific pair of appendages. Similarly, for humans performing haptic search, it was observed that, while the search targets could be

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detected 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 [1]. 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 phase, in which any finger is involved, and an identification phase, 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 is not empirically tested because the dynamics are not 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.

Here 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.

II. METHODS

A. Participants

Nine students (naïve to the purpose of the experiment, 6 females) volunteered to participate in the experiment. They 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 haptic search maps similar to the ones described in [1]. These 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 and setup

Participants sat at a table in front of a monitor (120 Hz Samsung SyncMaster 2230R7 22-in., spatial resolution 1680×1050 pixels; Fig. 1A) in a lighted room. The head was stabilized by a chin rest. The haptic search maps were placed in front of the participants in a way that vertically the center of the search map was located approximately 30cm away from the body and horizontally it was approximately aligned with the body midline. 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 which were also 3D printed as the stimuli. The holders were attached to the table with double sided tape (Fig.1A) and also used for calibration. For this purpose, each holder contained in the middle a small cone (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 attached at the bottom of the chinrest. 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 100 Hz 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

For each participant we calibrated in the beginning of the experimental session the measured finger positions with respect to the four corners of the search map. For this purpose, participants were instructed to position the index finger sequentially on each of the four calibration cones in a way that the marker attached on top of the finger was right above the cone. 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

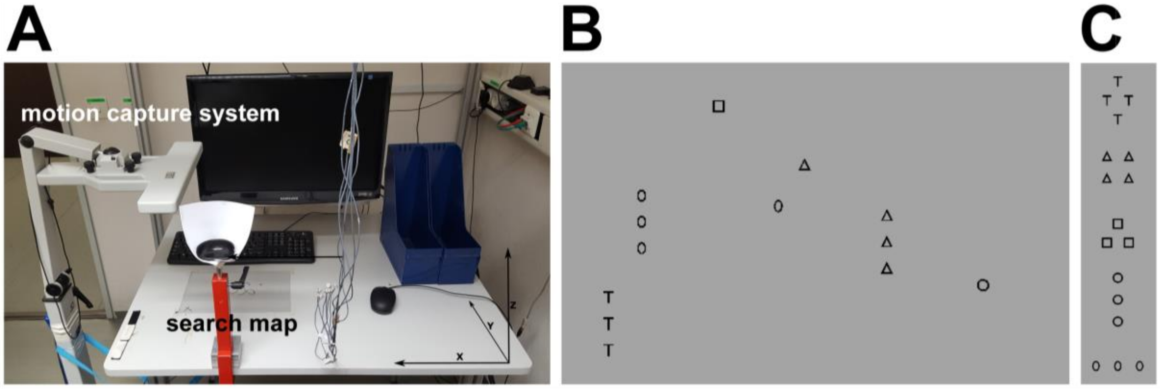

Figure 1. A) Experimental setup. B) An example haptic search map template. The symbols outlined in black were elevated by 0.2mm above the surface. C) Symbols ('T', triangle, square, circle oval, from top to bottom) and symbol clusters (diamond, square, triangle, vertical line, horizontal line from top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

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 into a little 3D printed finger holder (3x2cm, same height as the search maps) containing a central cylindrical cavity and located at the bottom edge of the search map, 5 cm away from its right edge (Fig. 1A). 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*

To individuate the time points at which participants touched search items we computed for every participant, every trial and each finger pad, the intersection area with every symbol (single symbols and symbols in target and distracter clusters). 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 [1]. 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 mm^2) and did not drop below it for longer than 0.67s. We chose a smaller threshold 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 point and per finger was discretized in touch (1) or no touch (0). We additionally individuated *touch episodes,* which could consist of several single touches with different fingers of the same symbol which were no longer apart from each other than 1s, reflecting one encounter or exploration of the symbol. For larger intervals, we assumed that the symbol was revisited and we treated this data as a different touch episode.

In order to aggregate individual touch episodes, we imposed to each of them the same time scale by normalizing time for each duration. Average touch probability profiles were computed separately for touch 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.

To compute speed profiles, we collapsed individual touches for each finger over all symbols to individuate the times the finger was in touch with any of the symbols (we called this *touch phase*). For each *touch phase* and a certain temporal window around it we computed from the two dimensional trajectories of each of the finger pads the speed S at the time point i as follows:

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

With xy_i being the finger pad position at the time point i, xy_{i-1} at the previous time sample and $t_i - t_{i-1} = 10$ms. We aggregated the speed profiles over individual touch phases for each of the fingers separately. To do so, we imposed to each of the touch phases the same time scale by normalizing time for each duration. Thus, the temporal windows before and after the touch phase were defined according to each individual touch phase duration, as the same time as the touch phase duration. A baseline average speed profile was 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. Statistical analyses on the speed profiles focused on a 50ms time window before and after the touch onset. Average speed was computed for each time window within each individual speed profile, then averaged across trials, yielding two average speed values (i.e. before and after touch onset) per finger for each participant. In order to test for differences between time windows (before and after touch onset) and fingers, we performed a two-way repeated measures ANOVA on average speed with *time window* and *finger* as fixed factors. We conducted analogous analyses on acceleration profiles, with acceleration A being computed at the time point i as follows:

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

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 [11] necessary to cover a given piece (60ms) of the movement trajectory (cf. [12]). We then compared the average number of boxes during contact and no contact of search items using a *t*-test for different fingers separately.

III. RESULTS

Figure 2 shows the probability of each finger to touch a potential target after it was first encountered by a certain finger in an average touch episode. Each panel represents one first touching finger, the different lines represent probabilities of touch for each finger afterwards. The duration of an average touch episode was 0.86s. Essentially, irrespectively 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.

For statistical analyses, we focused on the final portion of the exploration time and averaged probability across the last 30% of the touch episode (Fig. 2). Then, we run a two-way repeated measures ANOVA on the average probability of exploration, with *first finger* and *exploring finger* as fixed factors. The ANOVA revealed a main effect of *exploring finger*, $F(4,32) = 20.05$, $p < 0.001$, no significant main effect of *first finger*, $F(4,32) = 2.468$, $p = 0.065$, and no significant interaction $F(16,128) = 1.297$, $p = 0.209$. This suggests that exploration with some fingers tends to follow the first touch more often than exploration with other fingers independent of which finger had touched the target first. Since there was no significant effect of *first finger*, we averaged probabilities across this factor, and performed multiple post-hoc comparisons to test the differences between the individual fingers. Bonferroni corrected (with 10 comparisons, corrected alpha = 0.005) t-tests, revealed that probability of touch for the thumb is significantly less than for the index and for the middle. The probability of touch for the ring and the little fingers are significantly smaller than for the middle finger, and the probability for the little finger is less than for the index finger. Overall, these results indicate that the middle and the index finger tend to touch a potential target after it was encountered with any other finger.

Figure 3 depicts the average speed profile in a touch phase, when each finger is encountering any of the potential targets. The average duration of touch phases was 1.26s. The speed profile for the thumb and little finger is essentially the same during actual touch and the baseline. Conversely, when the other fingers encounter a search item they dramatically slow down. This is confirmed by statistical analyses on the average speed and acceleration in the surround of the touch onset (Fig. 4).

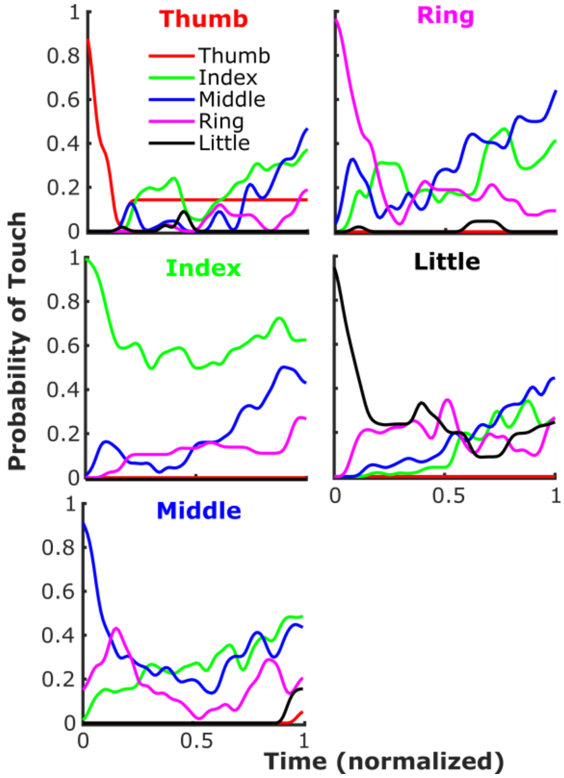

Figure 2. Probability that each of the fingers touches a potential target (y-axis) over time (x-axis), after it was first encounters by a certain finger (different panels). Probabilities are averaged across subjects. In order to aggregate the data, the time scale was normalized. The curves are and smoothed with a gaussian window of sigma= 10% normalized units. Average duration of a touch episodes was 0.86s.

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*, $F(4,32) = 9.976$, $p < 0.001$, and a significant main effect of *time window*, $F(1,8) = 220.153$, $p < 0.001$, but no main effect of *finger*, $F(4,32) = 2.537$, $p = 0.059$. Analyses on *average acceleration* revealed an analogous pattern of results: significant interaction, $F(4,32) = 11.312$, $p < 0.001$, main effect of *time window*, $F(1,8) = 83.394$, $p < 0.001$ and no main effect of *finger*, $F(4,32) = 1.5$, $p = 0.226$. Because the differences between fingers change between the two time windows (before onset and after onset), as revealed by significant interaction for both the ANOVAs, 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, $F(4,32) = 1.293$, $p = 0.293$. Conversely, for the after onset window the average speed significantly differed between the fingers, $F(4,32) = 4.189$, $p = 0.008$. The same is true for *average acceleration*: for the before onset time window we could not find any significant difference between the fingers, $F(4,32) = 1.827$, $p = 0.148$, but for the after onset time window, *average acceleration* significantly differed between the fingers, $F(4,32) = 12.52$, $p < 0.001$. These results indicate that when some specialized finger encounters a potential target, it quickly slows down to identify it as a target or a distractor, whereas other fingers keep their initial speed. Instead, when searching for potential targets, every finger moves at a similar speed (search phase).

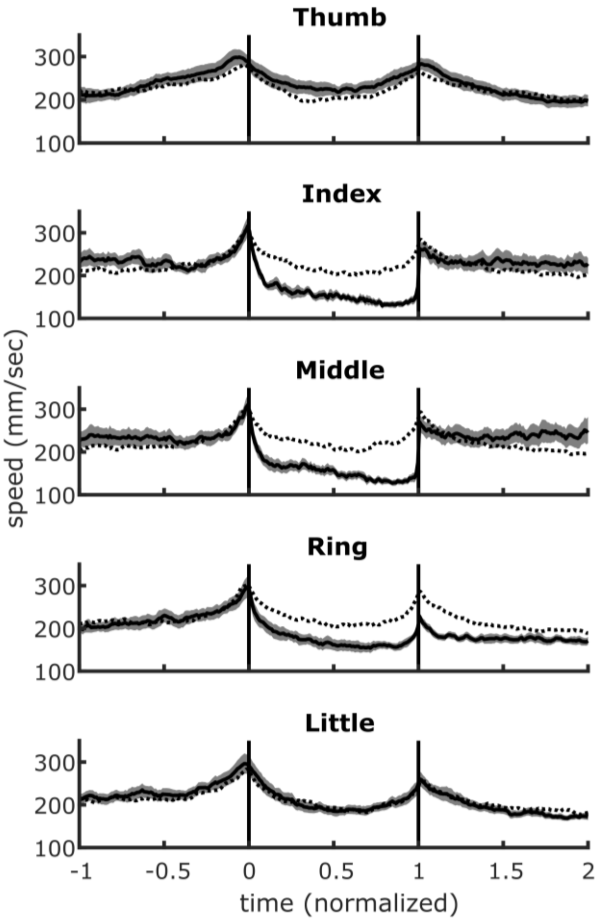

Figure 3. Speed over time, before, during and after each of the fingers encountered any of the potential targets. For each panel: normalized time on x-axis, speed on the y-axis. In each panel, the continuous black line represents the average speed across observers over time, with its standard error in gray. The dashed line represents the baseline. Vertical lines are the touch onset and offset. The average duration of touch phases was 1.26s.

Figure 5 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 $t(8) = -2.93$, $p = 0.019$, and the middle finger, $t(8) = -4.05$, $p = 0.004$ 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, $t(8) = 6.13$, $p < 0.001$; 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, $t(8) = 0.41$, $p = 0.696$. 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.

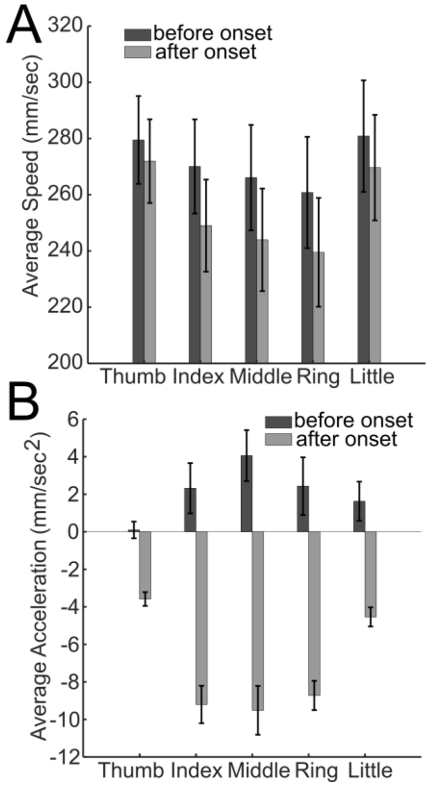

Figure 4. A) Average speed (y-axis) for the different fingers (x-axis), for the time window before the touch onset (dark bars) or after (light gray bars). B) Average acceleration (y-axis) for the different fingers (x-axis), for the time window before the touch onset (dark bars) or after (light gray bars).

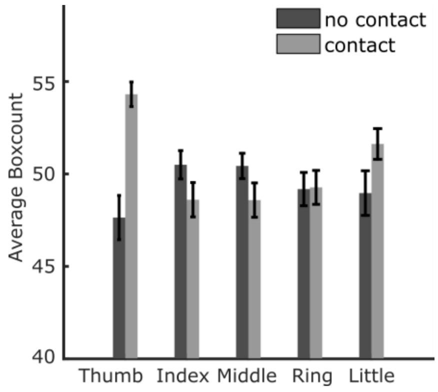

Figure 5. Average box-count (y-axis) for the different fingers (x-axis), for the time the finger was in contact with any of the search items (light gray bars) and the time it was not (dark bars).

IV. DISCUSSION

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. 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.

Together, these results strongly corroborate the hypothesis of [1]: 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 [10] is considered a foveation behavior in the star-nosed mole. 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 [1]. 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, it was shown 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 [13] and consistent with the finding that critical shape information cannot be processed simultaneously across fingers [14].

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 [15] [16], being minimal at the palm and best for the index and the middle finger.

Higher discrimination performance usually coincides with cortical representation. For instance, [10] 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. In humans, tactile discrimination thresholds correlate with imaging measurements of cortical finger representations within primary somatosensory cortex [17]. 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. [18]). There are also reports of a particularly large cortical representation of the thumb (e.g. [18],[19]), 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.

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 foveation for high resolution processing.

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