Systematic Movements in Haptic Search: Spirals, Zigzags, and Parallel Sweeps

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Abstract—Movement strategies were investigated in a one-handed haptic search task in which blindfolded-sighted participants used either one or five fingers to find a landmark on an unstructured tactile map. Search theory predicts that systematic strategies, such as spirals, zigzags, and parallel sweeps, should be more prevalent when the searcher's detection radius is small (one finger) and less common when the detection radius is large (five fingers). As predicted, systematic strategies were more common in one-finger than five-finger search. Participants were able to exploit the larger detection radius during five-finger search to detect targets with any of their fingers, and in one-finger search used more systematic strategies. For the most part, participants' fingers moved together during five-finger search, expanding and moving quickly when looking for search targets/distractors, and contracting and moving slowly when examining search targets/distractors. There was no evidence of fingers being used as spatial anchors or other independent finger movements in five-finger search. While targets could be found with any fingers, examination was primarily accomplished using the index and middle fingers. Overall, these results indicate that untrained sighted participants will use optimal systematic strategies during haptic search, and this behavior is appropriately modulated by detection radius.

Index Terms—Haptics, perceptual search, systematic, search theory, exploratory procedures

1 Introduction

Motor and perceptual systems are often conceptualized as separate output and input channels, the motor system responsible for planning and controlling action, and the perceptual system responsible for processing sensory information. However, the visual and haptic perceptual systems rely on movements of the eyes and limbs, respectively, to gather sensory information. In haptic perception, stereotyped hand movements, referred to as exploratory procedures (EPs), are used in an optimal fashion to extract information from three-dimensional (3-D) objects [1]. For example, lateral motion is used to extract texture, enclosure to examine global shape and volume, and unsupported holding to determine object weight. EPs enable haptic perceptual tasks to be efficiently completed using hand movements specific to the perceptual goals.

The exploratory procedures used with 3-D objects result in near-perfect performance in extracting object attributes and object identification [1]. In contrast, individuals are generally poor at identifying objects in two-dimensional (2-D) raised-line depictions [2], [3]. This may be due in part to the use of ineffective exploration strategies. For example, untrained blindfolded-sighted participants often use one finger to explore raised-line drawings [4], even though using multiple fingers provides better performance on a large variety of 2-D haptic tasks, including search, distance comparison, and straight-line movement [5]. This implies that while haptic perception of 3-D objects is associated with appropriate hand movements, 2-D tactile displays are explored suboptimally.

Another example of poor 2-D haptic performance is the underuse of systematic patterns when exploring 2-D tactile displays, e.g., raised-line/textured tactile graphics and tactile maps. With these materials, systematic movements are known to provide individuals with visual impairments better perceptual outcomes than non-systematic (i.e., random) exploration [6]. However, it is believed that systematic haptic strategies do not emerge spontaneously among the majority of people [7]. Therefore, children and adults with visual impairments are taught to explore 2-D tactile materials using systematic hand movements, such as parallel up-down scanning movements [8].

The current research examines the incidence of systematic strategies in 2-D haptic search among untrained individuals, and how this behavior is affected by the hand's detection radius. This work is an extension of [9], and includes previously unreported analyses of finger-movement dynamics during five-finger search. Before presenting empirical results, the next section provides a background on systematic search in the context of search theory and in practice.

2 Background on Systematic Search

2.1 Search Theory

This section applies search theory, the application of mathematics to search problems, to investigate the

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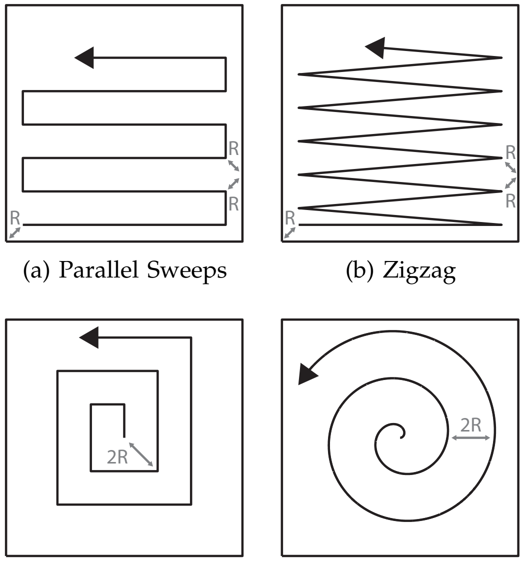
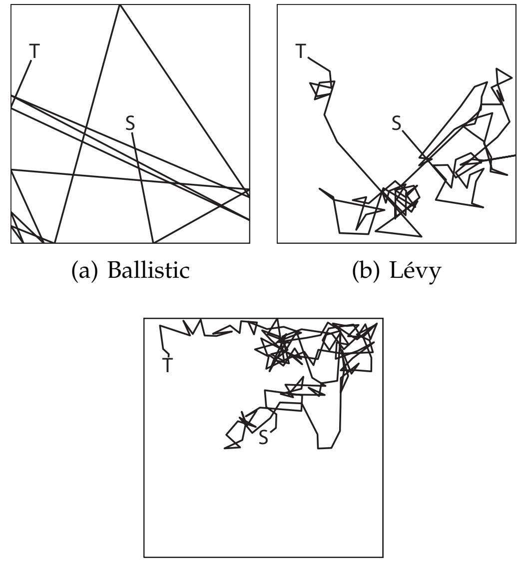


(a) Parallel Sweeps (b) Zigzag

(c) Expanding Square (d) Archimedes Spiral

Fig. 1: Example systematic strategies for searching a square area with detection radius R. Trajectories are specified such that a target in any location will be detected, while minimizing path length.



(a) Ballistic (b) Lévy

(c) Brownian

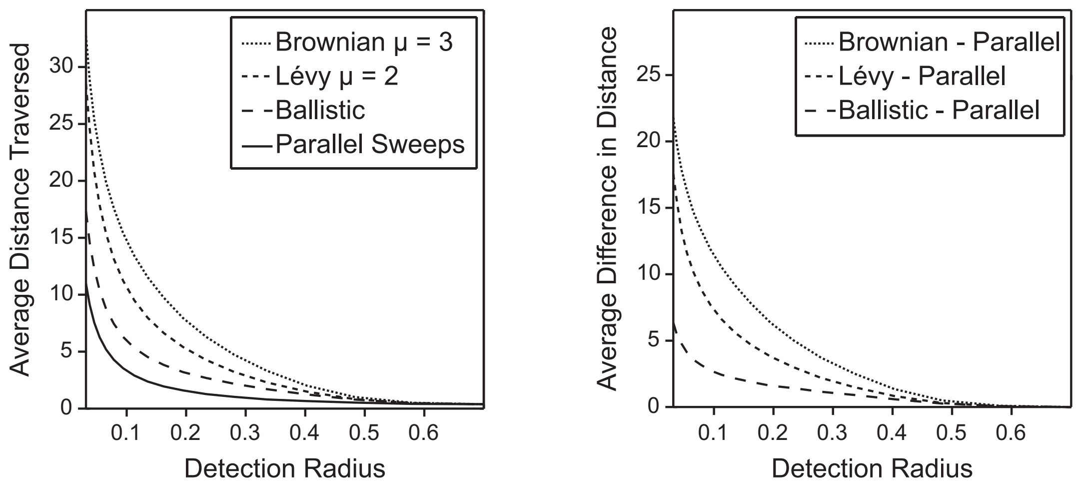
Fig. 2: Example random search strategies, starting in the center of the square search area (marked "S"), ending when the target is found in the upper left (marked "T").

relative benefits of systematic and random search, and develops predictions for haptic search. When searching for a target, the searcher can adopt either a systematic or a random movement strategy. These strategies are mutually exclusive and exhaustive. Random and systematic movement strategies can be differentiated based on the predictability of the searcher's position. In a random movement strategy, only the probability distribution of the searcher's position, and not its exact position, can be predicted over time. In contrast, the exact position of a searcher can be predicted if the searcher is using a systematic strategy, and the systematic trajectory may be explicitly represented using an equation [10]. Systematic strategies include movement patterns such as spirals, zigzags, parallel sweeps, and expanding squares (Fig. 1), among others [10], [11].

The relative benefits of systematic and random search have been most thoroughly examined in the fields of animal ecology and operations research. The current study's haptic search task involves searching for a target in an enclosed space, which is analogous to destructive foraging in ecology, where resources are non-revisitable because they are consumed upon discovery. Technically, the locations of consumed resources *can* be revisited, but these visits are no longer beneficial. During haptic search of a static display, there is no value in the participants revisiting "resources," which in a perceptual search context are the distractors and target. Once a distractor is examined and identified as not the target, assuming that identification is not fallible, there is no benefit in reexamining the distractor.

Alternatives to systematic strategies include random walks, which are characterized as sequential steps in random directions of lengths ℓ_j drawn from a distribution $P(\ell_j) \sim \ell_j^{-\mu}$, $\ell_j > \ell_{\min}$. A walk continues until the target is within the searcher's detection radius, the area around the searcher in which the target can be detected. For animals the detection radius is typically range of sight, hearing, or olfaction; in operations research the detection radius may be the range of ultrasound or infrared receivers; and in haptic search the detection radius is the area within the hand's immediate contact (which is larger when using five fingers than one finger). When $\mu \to 1$, the random movement pattern is called ballistic, the searcher turns a random direction and continues straight until hitting a barrier or a resource (target or distractor). When $1 < \mu \leq 3$ the step length distribution is heavy tailed and the movement process is called a Lévy walk, where clusters of short steps are connected by long steps. When $\mu > 3$, the movement is Brownian (Fig. 2) [12], [13].

Note that when used in the context of search theory, the term "ballistic" has a distinct meaning from its definition in vision science. Eye movements over a stationary scene alternate between fixations, when gaze is held on a fixed point in the visual field, and rapid movements between fixations called saccades. When used in the context of search theory, ballistic refers to movement step lengths; while ballistic eye movements refer to the pre-planned nature of saccades. Specifically, during a saccade to a visual target, the eye cannot divert if the target is moved until the saccade is complete [16]. During non-visual



(a) Average Distance Traversed

(b) Average Difference in Traversed Distances

Fig. 3: Search movement simulations for detection radii 0.03 - 0.70 in a square search area (side length = 1), for a randomly located target. The only systematic strategy shown is parallel sweeps, but other systematic strategies produce similar results. Random strategy simulations began in the search area's center, and were simulated $\ell_j = \ell_{\min} u_j^{1/(1-\mu)}$, where $u \sim \mathrm{unif}(0,1)$, and $\ell_{\min} = 0.05$ [14], [12], [15]. Simulations were executed until the searcher was within the given detection radius of the target. Traversed distances, from start position to target, were averaged across 100,000 simulations.

search (e.g., haptic, animal, human operations, etc.), the searcher can detect the search target within its detection radius at any time and location along the movement trajectory and immediately change course.

The most efficient strategy in the case of non-revisitable resources (destructive foraging) is a systematic strategy, followed by ballistic movements, then a Lévy walk, and finally Brownian motion (Fig. 3a) [17], [12], [18], [19]. Higher efficiency can be attributed to better avoidance of previously searched ground. This can be seen in Fig. 2; the ballistic movement (Fig. 2a) contains relatively few areas of "intensive search," where exploration is concentrated and overlapping in an area [20]. The Lévy walk (Fig. 2b) contains more intensive search than ballistic movement, especially during periods of short steps. Brownian motion (Fig. 2c), which is comprised of only short steps, contains almost exclusively intensive search.

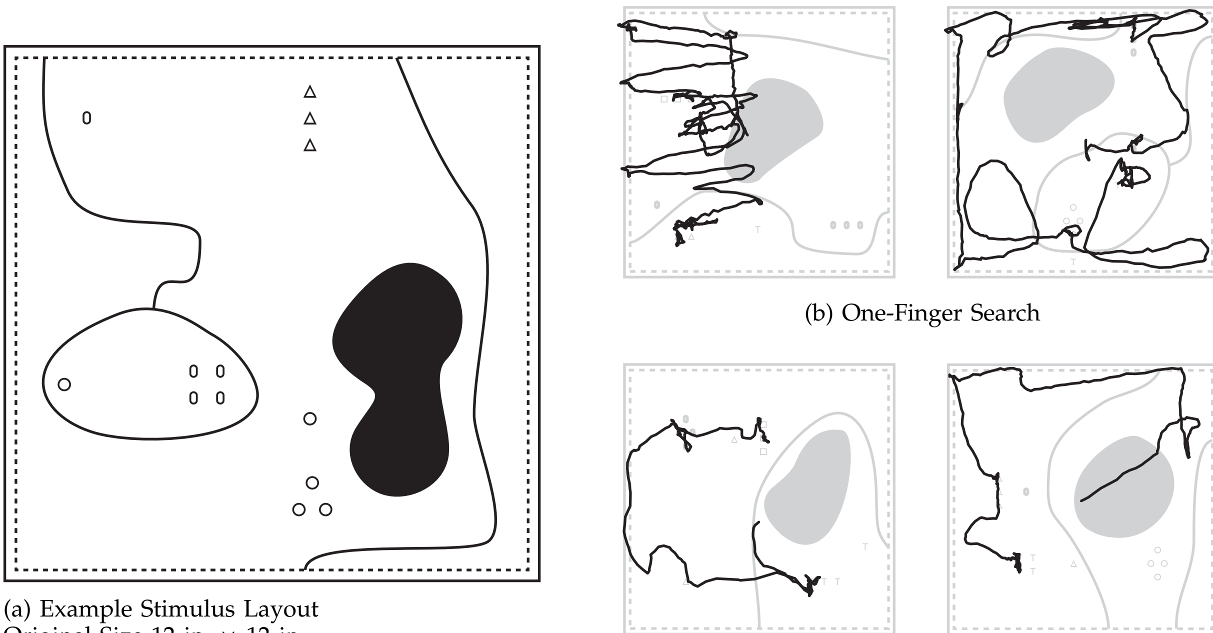
Systematic search's efficiency benefit decreases with increasing detection radius, as shown by Monte Carlo simulations in Fig. 3b. When the detection radius is large, the benefit associated with a systematic strategy may be small enough that the searcher elects a random strategy that requires less memory and motor planning.

2.2 Systematic Search in Practice

Surprisingly, even though a systematic search strategy would be the most efficient approach during foraging when targets are non-revisitable, are scattered, and have locations that are not known a priori, there are few examples of animals using systematic search [18]. Instead, several reports indicate that animals forage for resources following a Lévy walk with $\mu \approx 2$, which is the optimal strategy for sparse revisitable (non-exhaustible or replenishing) targets [17], [13].

While systematic search strategies are uncommonly observed in (non-human) animals, they are frequently used by humans for large-scale search operations. Systematic strategies were first developed in WWII, with the allies' search for German U-boats in the Bay of Biscay [21], [22], and are currently used for the planning of large-scale human movements in military maneuvers, search and rescue operations, and aerial monitoring [11]. However, the use of systematic strategies in these applications was not automatic, only initially emerging under the pressures of war, and are orchestrated through substantial research and planning.

The slow and labored adoption of systematic strategies in operations research is consistent with the notion that systematic movements are not immediately obvious to individuals exploring tactile materials [7]. It also reinforces the importance of training individuals with visual impairments to use systematic haptic exploration strategies [8]. However, consistent spontaneous adoption of systematic movements in untrained participants can emerge in haptic search when the stimulus is structured as a grid, which elicits zigzags or parallel sweeps as the hand serially examines features in rows or columns [23]. Research on unstructured haptic search, which has been previously conducted without a sole focus on systematic strategies, has sometimes observed participants using systematic parallel sweeps [24], [25], but other



(a) Example Stimulus Layout
Original Size 12 in. × 12 in.

(b) One-Finger Search

(c) Five-Finger Search

Fig. 4: Example stimulus layout and index-finger trackings. Lines and areas in black (a) and gray (b and c) are raised and recessed/textured. Black lines (b and c) show index-finger trajectories.

studies have only observed movements that follow straight lines or complex patterns (i.e., ballistic or other random walk movements) [26], [27]. Of interest in the current study is whether untrained humans will spontaneously use systematic search strategies on an unstructured tactile display. Furthermore, if this behavior is more common with a smaller detection radius (fewer number of fingers), as predicted by search theory (developed in this section, Fig. 3).

3 METHODS

3.1 Participants

Nine right-handed sighted adults participated in this research; two were male, and the average age was 27.2 years ($SD = 6.1$ years). The protocol was approved by the local institutional review board, and informed consent was obtained from all participants prior to their participation. Because the participants were sighted and not visually impaired, they were not trained to explore tactile materials using systematic strategies [8].

3.2 Stimuli

Tactile maps were used as stimuli, which are popular for investigating 2-D tactile perception due to being inherently two-dimensional, controllability, ease of participant understanding, and relevance to real-world applications [28], [29]. Tactile maps are similar to visual maps, in which the lines have been raised and areas textured to make them accessible to touch. The current study's stimuli were taken from the Tactile Map Open Stimulus Set (TMOSS), which consists of 7 groups of 8 maps [30], and were manufactured from laser cutting/etching clear acrylic. One group of TMOSS maps (group 3) was used for one-finger trials, and a separate TMOSS group (group 4) was used for five-finger trials. TMOSS maps were designed so that map parameters, including distances, angles, and symbol types, numbers, and configurations were the same across map groups. Importantly, the target symbol clusters on the one-finger and five-finger maps were distributed similarly in space. An example map layout is shown in Fig. 4.

The purpose of using one group of stimuli for all one-finger trials and a separate group for all five-finger trials, and not randomizing group assignment between participants, was so that spatial data could be averaged over participants. Creation of two-dimensional density estimates (a.k.a "heat maps") necessitated averaging finger positions across participants for the same condition on the same stimulus. Pilot research indicated that at least eight participants were needed per stimulus using the same finger condition to produce stable density estimates.

Each tactile map represented a fictitious park, and contained 13 point symbols: circles, squares, ovals, Ts, or triangles, to represent the locations of features, such as trash cans and picnic benches. Solid lines on the maps represented walking paths, and a recessed textured area on each map represented a lake. All maps were surrounded by a dotted line, 0.635 cm (0.25 in) from the map edge, to indicate the map border.

On every map, there were three clusters of symbols, each configured as a square, diamond, vertical line, horizontal line, or triangle shaped arrangement of a single symbol type, e.g., a square-shaped cluster of triangles. These clusters served as landmarks that could be unambiguously referenced as search targets. Non-target symbols (loose and in clusters) were search distractors, while other map features (e.g., paths) were largely ignored (based on Sec. 4.2 results).

3.3 Procedure

Participants were blindfolded and sat at a clear table on which stimuli were placed (Fig. 5). The participants were trained to recognize map symbols and clusters before beginning the main study. During the training, four of the participants were randomly selected to use their right index finger, and their other fingers were bent into and taped to their palm. The other five participants used all fingers on their right hand during training. The training consisted of presenting a participant with each type of map symbol and each shape of landmark (symbol cluster). Then, the participant was tested on naming the five symbols, e.g., "oval," and the five cluster shapes, e.g., "a square cluster (of ovals)." These were presented in random order, and each participant successfully named the five symbols and five cluster shapes with no mistakes on their first try. The participants were allowed to freely explore three practice maps, and also execute mock trials on these maps to ensure that they understood the task.

During the main experiment, the participants completed 16 trials. In each trial, a map was placed on the table in front of the participant. The maps were in random order, with the constraint that one-finger and five-finger maps alternated. Before starting one-finger trials the participant's other fingers were taped to the palm, and before starting five-finger trials the tape was removed. Then, the participant's right index finger was placed at approximately the middle of the map, avoiding contact with any path or point symbols. The participant was asked to hold his/her hand in that position without moving until he/she was asked a question to search for a specific symbol cluster on the map and a beep indicated it was time to start moving, e.g., "Please locate the cluster of squares and say 'here,' ⟨beep⟩." The participant was instructed to complete trials as quickly as possible, and once he/she had found the target to stop moving his/her hand, say "here," and remove his/her hand from the map. Following completion of the experimental procedures, participants were asked if they used any strategies during one- and five-finger search.

Below the clear table and tactile map a video camera was positioned (Canon Vixia HF R21, with a Canon 3.28-megapixel full HD CMOS image sensor). It pointed upwards and was focused to the depth plane of the tactile map. The camera's field of view was filled by the tactile map (30.5 cm x 30.5 cm) plus some additional space on each side (roughly 8 cm). The video camera recorded at a 1920 x 1080 resolution at 30 Hz (29.97 frames per second). Above the table was a white shelf that provided the video a white backdrop. Video clips of each trial were cropped so that they began when the participant initiated movement and ended when movement stopped, so that there was no footage of a stationary hand.

Fig. 5: Experimental setup.

3.4 Finger Tracking

Each trial's video was run through a finger-tracking algorithm [31] to determine the position of the index and all five fingers in one- and five-finger search, respectively. This algorithm applied a ridge-detection transform to each video frame, after which fingertip positions could be picked out using value thresholding. Example finger trajectories are shown in Fig. 4. The algorithm did not disambiguate contact and non-contact, due to the participant lifting his/her hand from the stimulus. Anecdotally, participants did not appear to lift their fingers from the stimulus. However, future research may investigate this phenomenon, and address possible approaches to handling missing position data.

3.5 Analyses

3.5.1 Systematic Strategies

Index-finger trajectories were analyzed for systematic movements through visual inspection. Trajectories were printed on a blank background, and identified only by a random code to disguise the trajectory's associated map, condition, and participant. Two coders inspected each trajectory for zigzags, parallel sweeps, and spirals, the author and a coder with no knowledge of the study procedures or hypotheses. No other systematic strategies, e.g., expanding squares, were observed. Coder percent agreement and Cohen's Kappa [32] were used to establish that the systematic strategies were clearly apparent and reliably coded.

Participants' use of systematic strategies was modeled using a mixed effects logistic regression, with fixed effects of condition (one-finger, five-finger) and systematic strategy type (spiral, zigzag/parallel-sweeps), and random effect of participant. A general linear model (e.g., an ANOVA) was not possible due to non-Normality (participant averages were sums over only eight trials and positively skewed). All subsequent analyses satisfied general linear model assumptions. A previous study that used the same stimuli and same search task, but a different group of sighted participants and without finger tracking, found that five-finger search was significantly faster than one-finger search [5]. To rule out the possibility that more systematic strategies occurred in one-finger search simply due to longer search times, one-finger search trajectories were truncated to be no longer than the average five-finger search time in the current study (the latter part of a trajectory eliminated). These truncated trajectories were recoded and reanalyzed.

3.5.2 Spatial Densities

It could be argued that one- and five-finger search differ in ways beyond detection radius, and these differences are those driving systematic-strategy effects. For example, differences in what and where participants touched the stimuli, and the speeds of their hand movements, could be the cause of differential systematic-strategy appearance. To examine whether one- and five-finger search were associated with different spatial foci, distributions of participants' index-finger positions were visualized as spatial densities ("heat maps"). Positions were averaged across participants for each map using kernel density estimation, with a Normal kernel, bandwidth chosen using the Normal reference distribution, about 3 cm [33, p. 130].

3.5.3 Index-Finger Speeds

To examine whether one- and five-finger search were associated with different hand-movement speeds, index-finger speeds were calculated for each frame indexed by i using the centered differencing formula (second-order Taylor method): $\mathbf{r}'_i \approx (\mathbf{r}_{i+1} - \mathbf{r}_{i-1})/(2\Delta t)$, where $\mathbf{r}_i = (x_i, y_i)^{\mathrm{T}}$ represented position and $\Delta t = 33$ ms was the time between position samples. Participants' average index-finger speeds during contact and non-contact with search targets/distractors (with any finger) were compared using a repeated-measures ANOVA with main effects of symbol contact (contact, non-contact) and condition (one-finger, five-finger). For this and future analyses, contact was defined as the finger being within 0.5 cm of any part of a symbol (not just the center). Additionally, this and all subsequent ANOVAs are reported with the generalized eta-squared (η^2_G) measure of effect size [34]. Distributions were examined to confirm Normality. Assumptions of sphericity were tested using Mauchly's test, and violations of sphericity were dealt with using the Greenhouse-Geisser correction to degrees of freedom.

3.5.4 Dynamics of Five-Finger Search

Several analyses were carried out to investigate finger-movement dynamics during five-finger search. Of particular interest was how the fingers worked together to provide a larger detection radius during five-finger search. Finger independence and speed were analyzed to examine whether the fingers moved independently or as a single unit. Hand speed and spread (separation of the fingers) were analyzed to reveal how these changed depending on contact with search targets/distractors. Finally, analyses revealed which fingers in five-finger search were used on search targets/distractors for detection and examination/identification.

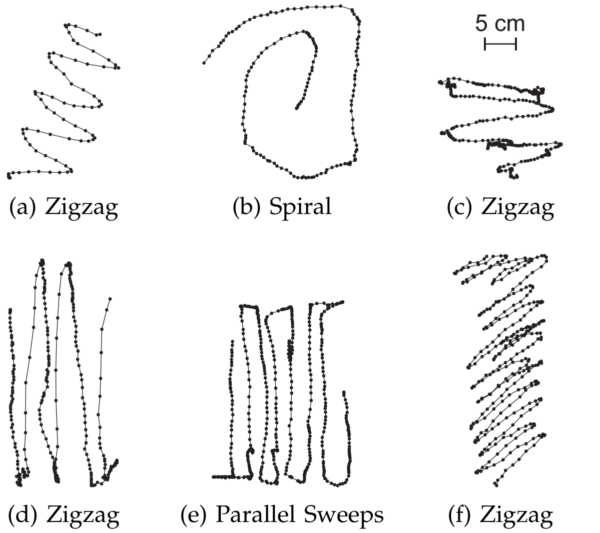
3.5.4.1 Finger Independence: Participants' average positional coefficients of determination (r^2) values were computed for every pair of fingers. In general, r^2 values reflected the proportion of a finger's positional (f_1) variance explained by a linear relationship with another finger's position (f_2): $f_1 = \alpha + \beta f_2$ (presumably the estimate of β would equal 1). The r^2 values were compared using a repeated-measures ANOVA with main effects of finger pair (thumb-index, thumb-middle, etc., for 10 pairs) and position axis (x, y).

3.5.4.2 Speeds Across the Fingers: Participants' average finger speeds were calculated as in Sec. 3.5.3 and were compared using a repeated-measures ANOVA with main effect of finger (thumb, index, middle, ring, little).

3.5.4.3 Hand Speed Variation: Index-finger speeds were used as a proxy for hand speeds (validity of this is discussed in the Results). Participants' average index-finger speeds were calculated as in Sec. 3.5.3 for periods of contact and non-contact with search targets/distractors with each finger, and compared using a repeated-measures ANOVA with main effects of contact (contact, non-contact) and contacting finger (thumb, index, middle, ring, little).

3.5.4.4 Detection Radius Variation: Hand spread, defined as distance between thumb and little-finger positions, was computed for periods of overall (i.e., any finger) contact and non-contact with search targets/distractors, and compared using a paired t-test. Participants' average hand spreads during contact and non-contact with search targets/distractors for each finger were compared using a repeated-measures ANOVA with main effects of contact (contact, non-contact) and contacting finger (thumb, index, middle, ring, little).

3.5.4.5 Target Detection Across Fingers: If using more fingers effectively enlarged the hand's detection radius, detection of the search target should have been



(a) Zigzag (b) Spiral (c) Zigzag

(d) Zigzag (e) Parallel Sweeps (f) Zigzag

Fig. 6: Example systematic strategies observed in the current study. Trajectories are to shown scale, and positions (dots) were sampled every 33 ms.

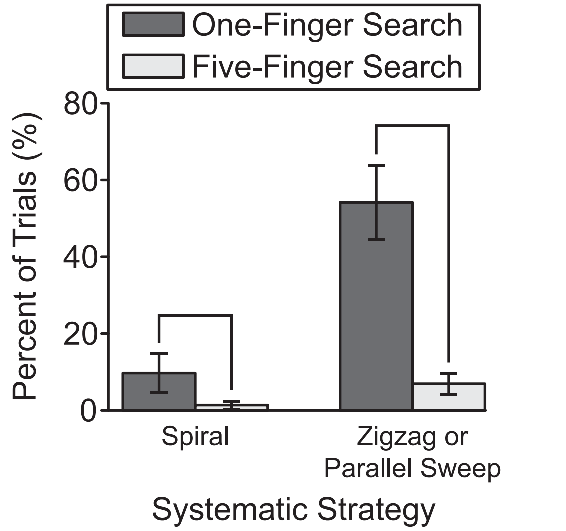


Fig. 7: Participants' average use of systematic strategies (%, with SEs). Strategy and condition effects, but not the interaction, were significant ($p < 0.001$).

possible with any of the exploring fingers. To examine this prediction, the percentages of trials in which first contact with the search target was made by each finger were compared using a repeated-measures ANOVA with a main effect of finger (thumb, index, middle, ring, little).

First contact was defined as a finger being within 0.5 cm of the target (any part of the target, not just the center) with the fingers remaining within 0.5 cm of the target, with no more than a 20 sample (0.67 s) departure until the end of the trial. Changing these time and distance thresholds, within reasonable limits, did not change results. The departure allowed the participant to briefly move his/her hand away from the target symbol-cluster to look for nearby symbols that might belong to the target.

3.5.4.6 Target/Distractor Time Across Fingers: To investigate which fingers were preferred for examining search targets/distractors, participants' average percentages of time in contact with search targets/distractors was calculated overall (i.e., with any finger) and for each finger. Participants' average percentages of time in contact with search targets/distractors for each finger were compared using a repeated-measures ANOVA with main effect of finger (thumb, index, middle, ring, little).

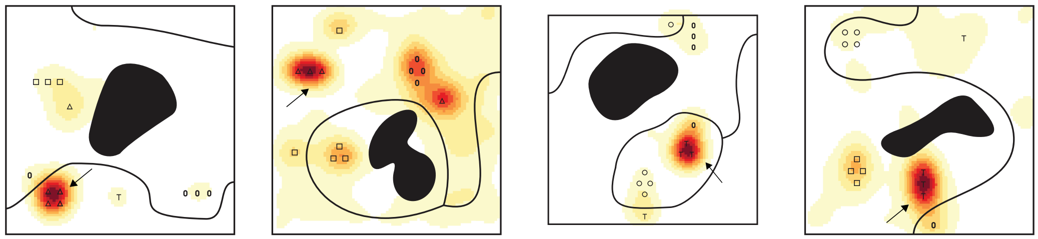
4 Results

4.1 Systematic Strategies

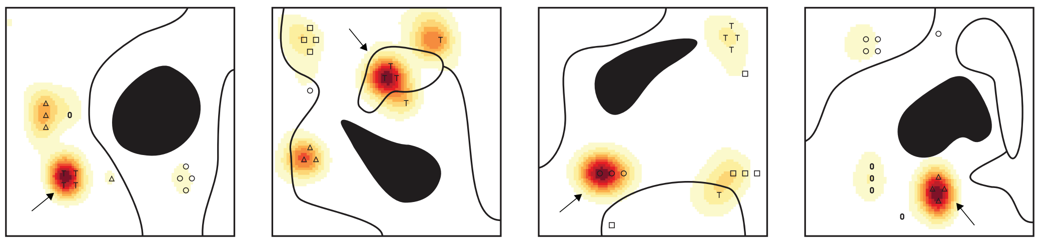
Participants' index-finger scan paths included zigzags, parallel sweeps, and spirals (Fig. 6). No other systematic strategies were observed. Trajectories that lacked systematic patterns were random. The inter-rater reliability indicated that the systematic strategies were readily apparent, based on percent agreement and Cohen's Kappa. Agreement was for zigzags 98.6%, $\kappa = 0.96$; for parallel sweeps 97.9%, $\kappa = 0.87$; and for spirals 99.3%, $\kappa = 0.93$. Typical disagreements between coders were over whether a trajectory contained a zigzag, parallels sweeps, or combination, as these patterns could be very similar. For example, trajectories in Figs. 6c and 6d contain elements of both zigzags and parallel sweeps. Therefore, the codes for zigzags and parallel sweeps were combined into the code zigzag/parallel-sweeps, with agreement 98.6%, $\kappa = 0.97$.

A mixed-effects logistic regression was used to examine the effects of strategy type (zigzag/parallel-sweeps, spiral) and condition (one-finger, five-finger) on occurrence of systematic strategies (Fig. 7). Likelihood ratio tests executed during forward model selection revealed a significant effect of strategy type $\chi^2(1) = 34.47$, $p < 0.001$, a significant effect of condition $\chi^2(1) = 51.12$, $p < 0.001$, and a non-significant interaction $\chi^2(1) = 0.62$, $p = 0.43$. Order of added effects did not change results. The use of spirals ($est = -2.62$, $SE = 0.48$, $p < 0.001$) and five fingers ($est = -2.97$, $SE = 0.52$, $p < 0.001$) both reduced the occurrence of systematic strategies.

Participants were significantly faster at five-finger search than one-finger search, $t(8) = 2.59$, $p = 0.032$. Average time to complete a one-finger search was 24.39 s ($SE = 3.70$ s), and to complete a five-finger search was 14.98 s ($SE = 1.61$ s). On average, five-finger search was almost 10 s, or 40% faster than one-finger search. This 40% reduction is identical to that measured in a previous study that used the same stimuli (with TMOSS groups randomly assigned to finger conditions for each participant), with a different group of sighted participants and without finger tracking [5]. However, trial length cannot ex-



(a) One-Finger Search, Index Finger



(b) Five-Finger Search, Index Finger

Fig. 8: Two-dimensional kernel density estimates of finger positions, averaged across participants. Target clusters are marked with arrows. Black lines are raised, and the large black areas are recessed and textured. Darker red color indicates greater density values.

plain the greater number of systematic strategies in one-finger than five-finger search. Analyzing truncated one-finger searches, which were no longer than the average five-finger search time, eliminated five zigzags/parallel-sweeps and no spirals, and produced similar modeling results: a significant effect of strategy type $\chi^2(1) = 27.21$, $p < 0.001$, a significant effect of condition $\chi^2(1) = 40.05$, $p < 0.001$, and a non-significant interaction $\chi^2(1) = 0.25$, $p = 0.620$.

The use of systematic strategies observed in the current study was consistent with predictions based on search efficiency. The average distance between participants' thumb and little-finger positions during five-finger search was 9.03 cm (SE = 0.60 cm). In contrast, the diameter of the index finger is approximately 2 cm. Therefore, the relative ratios of radius to stimulus width/height was for the fingertip (radius 1 cm) approximately 0.03, and for the hand (radius 4.5 cm) approximately 0.15. Referring to these values in the simulation results shown in Fig. 3a, the relative benefit of using a systematic strategy over a random strategy was for the current participants 2.71-3.65 times greater in one-finger than five-finger search (Table 1). This greater efficiency benefit of systematic strategies in one-finer than five-finger search (Fig. 3) produced the prediction that systematic strategies should be more prevalent in one-finger search, and this was confirmed empirically (Fig. 7).

When asked about search strategies, participants 1, 3, 4, and 8 reported that they were not aware of any strategies that they used to complete the search tasks. Participant 2 indicated that he would break the stimulus into areas, either quadrants or using stimulus features, and search these areas sequentially.

TABLE 1: Computed difference in distances traversed for simulated strategies (Fig. 3a).

	Average Difference in Distances for Random and Parallel Sweeps		
Random Strategy	One-Finger Radius = 0.03	Five-Finger Radius = 0.15	Ratio One / Five
Ballistic	6.62	1.98	3.35
Lévy	18.55	5.08	3.65
Brownian	22.55	8.32	2.71

Participants 5, 7, and 9 indicated that they used a border- or path-tracing strategy during one-finger search. These approaches would be ineffective because search targets/distractors never coincided with borders/paths. Noticing that border- and path-tracing strategies were fruitless, participants 5 and 9 reported that they abandoned this approach and switched to using zigzags/parallel-sweeps (5 and 9) or spirals (5 only) for later one-finger search trials. Participants 6 and 9 indicated that they used all five fingers to detect targets/distractors during five-finger search.

4.2 Spatial Densities

The spatial densities associated with a random selection of four one-finger and four five-finger search stimuli are shown in Fig. 8. The highest densities of finger positions were located on target clusters. A lower, but apparent increase in density was also associated with distractors: other clusters and loose symbols. There were no apparent effects of map borders, paths, or lakes on finger positions, consistent with non-symbol features being ignored by participants. Spatial densities appeared more diffuse (e.g., Fig. 8a example 2) in one-finger than five-finger search.

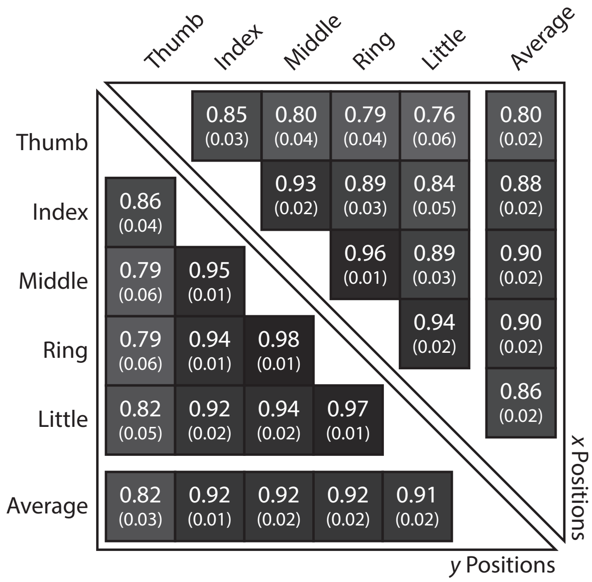


Fig. 9: Average positional r^2 values (with SEs) between pairs of fingers. x positions are in the upper right, y positions are in the lower left. Darker shading indicates larger r^2 values.

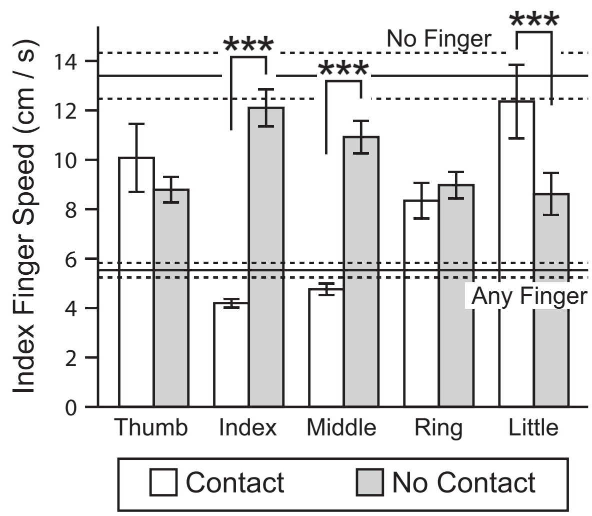


Fig. 10: Average hand speeds during contact and non-contact with search targets/distractors depending on contacting finger (cm/s, with SEs). Top line shows speed for no finger contact, bottom line for any finger contact (with SEs dashed). $^{***}p < 0.001$.

4.3 Index-Finger Speeds

Participants' average index-finger speeds in one- and five-finger search during contact and non-contact with search targets/distractors (Table 2) were analyzed using a Greenhouse-Geisser repeated-measures ANOVA, which revealed a significant main effect of contact $F(1, 8) = 185.15$, $p < 0.001$, $\eta_G^2 = 0.82$, a non-significant effect of condition $F(1, 8) < 0.001$, $p = 0.996$, $\eta_G^2 < 0.001$, and a non-significant interaction $F(1, 8) = 3.16$, $p = 0.114$, $\eta_G^2 = 0.03$.

TABLE 2: Average index-finger speeds during contact and non-contact with search targets/distractors with any finger (cm/s, with SEs).

Condition	Contact	No Contact
One-Finger	4.82 (0.31)	14.11 (1.00)
Five-Finger	5.53 (0.30)	13.40 (0.93)

4.4 Dynamics of Five-Finger Search

4.4.1 Finger Independence

Participants' average positional coefficients of determination (r^2) values in x and y for each finger pair (Fig. 9) were analyzed using a Greenhouse-Geisser repeated-measures ANOVA, which revealed a significant main effect of finger pair $F(1.65, 13.18) = 17.40$, $p < 0.001$, $\eta_G^2 = 0.31$, a non-significant main effect of position axis $F(1, 8) = 2.25$, $p = 0.172$, $\eta_G^2 = 0.02$, and a non-significant interaction $F(1.87, 14.92) = 0.73$, $p = 0.490$, $\eta_G^2 = 0.01$. Post-hoc contrasts were computed to compare pairs of fingers, e.g., the eight r^2 values for the thumb to the eight for the little finger, with p-values adjusted by Bonferroni method. The only significant contrasts were for thumb-index ($M = -0.09$, $SE = 0.01$, adjusted $p < 0.001$), thumb-middle ($M = -0.1$, $SE = 0.01$, adjusted $p < 0.001$), thumb-ring ($M = -0.1$, $SE = 0.01$, adjusted $p < 0.001$), and thumb-little ($M = -0.08$, $SE = 0.01$, adjusted $p < 0.001$). The thumb had lower r^2 values than all other fingers.

The amount of variance attributable to the finger-tracking algorithm was calculated as the ratio of finger-tracking variance (reported in [31]) to observed total positional variance: ranging from 0.0050 to 0.0097 across fingers in x, and 0.0037 to 0.0046 in y.

4.4.2 Speeds Across the Fingers

Participants' average finger speeds (Table 3) were analyzed using a Greenhouse-Geisser repeated-measures ANOVA, which revealed a non-significant main effect of finger $F(1.34, 10.73) = 1.27$, $p = 0.301$, $\eta_G^2 = 0.01$.

TABLE 3: Average finger speeds (cm/s, with SEs).

Thumb	Index	Middle	Ring	Little
10.31 (0.67)	10.32 (0.34)	10.67 (0.62)	10.55 (0.55)	10.17 (0.50)

4.4.3 Hand Speed Variation

Index-finger speed was used as a proxy for hand speed based on previous results (Sec. 4.4.1) that revealed a high dependence between fingers' positions. Participants' average index-finger speeds

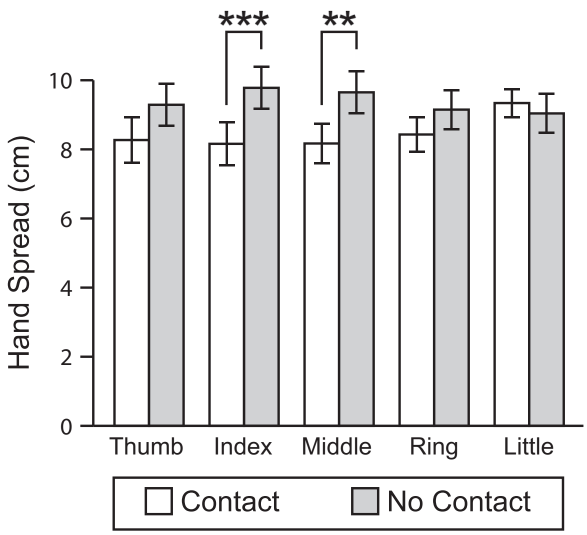


Fig. 11: Average hand spreads during finger contact and non-contact with targets/distractors (cm, with SEs). $^{**}p < 0.01$, $^{***}p < 0.001$.

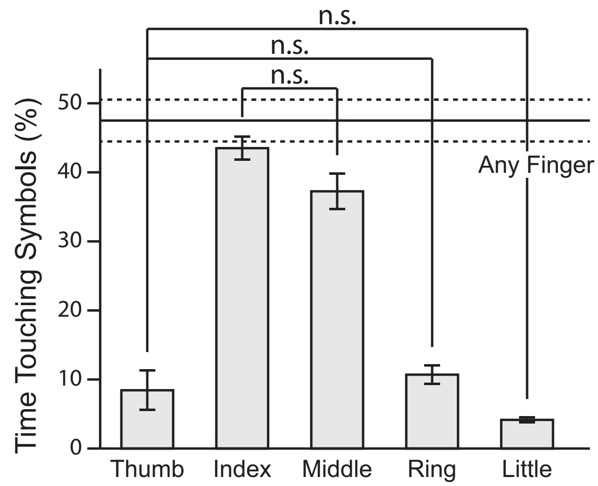


Fig. 12: Average target/distractor (symbol) contact (%, with SEs). Line shows average contact for any finger (SEs dashed). n.s. $p \geq 0.067$, all other pairwise comparisons $p < 0.048$.

during contact and non-contact with search targets/distractors for each finger (Fig. 10) were analyzed with a Greenhouse-Geisser repeated-measures ANOVA, which revealed a significant main effect of contact $F(1, 8) = 66.48$, $p < 0.001$, $\eta^2_G = 0.13$, a significant main effect of contacting finger $F(2.10, 16.81) = 6.60$, $p = 0.002$, $\eta^2_G = 0.13$, and a significant interaction $F(2.27, 18.18) = 24.42$, $p < 0.001$, $\eta^2_G = 0.44$. Post-hoc Tukey HSD tests indicated that index-finger speeds were significantly affected by contact with search targets/distractors for the index finger $p < 0.001$, middle finger $p < 0.001$, and little finger $p < 0.001$ (thumb $p = 0.433$, ring finger $p = 0.988$). The hand moved significantly faster when search targets/distractors were touched by the little finger, and significantly slower when search targets/distractors were touched by the index and middle fingers. These two results are likely one in the same, as spatial separation between the index and middle fingers with the little finger would cause their contact with search targets/distractors to be mutually exclusive.

4.4.4 Detection Radius Variation

Participants' average hand spreads (thumb to little-finger distances) during contact (for any finger) with a search target/distractor was 8.37 cm ($SE = 0.62$ cm), and during symbol non-contact was 10.26 cm ($SE = 0.76$ cm), which were significantly different $t(8) = -3.05$, $p = 0.016$.

Participants' average hand spreads during symbol contact and non-contact with search targets/distractors for each finger (Fig. 11) were analyzed using a Greenhouse-Geisser repeated-measures ANOVA, which revealed a significant main effect of contact $F(1, 8) = 7.58$, $p = 0.025$, $\eta^2_G = 0.07$, a non-significant main effect of contacting finger $F(1.60, 12.77) = 2.31$, $p = 0.145$, $\eta^2_G = 0.01$, and a significant interaction $F(1.44, 11.50) = 5.52$, $p = 0.028$, $\eta^2_G = 0.04$. Post-hoc Tukey HSD tests indicated that hand spread was significantly affected by contact with search targets/distractors for the index $p < 0.001$, and middle fingers $p = 0.002$ (all other fingers $p > 0.124$).

4.4.5 Target Detection Across Fingers

Participants' average percentages of trials in which first contact with the search target was made by each finger (Table 4) were analyzed using a Greenhouse-Geisser repeated-measures ANOVA, which did not find a significant main effect of finger $F(4, 32) = 1.72$, $p = 0.169$. Note that there were no trials of one- or five-finger search in which the participant made contact with the search target and did not immediately then examine and identify the target. In other words, there was no evidence that target detection was fallible in the current study as there were no instances in which a participant found the target and ignored it or misidentified it as a distractor.

TABLE 4: Average percentages of first contact with targets (%, with SEs).

Thumb	Index	Middle	Ring	Little
18.06 (6.94)	33.33 (6.25)	12.50 (4.17)	15.28 (5.01)	20.83 (4.66)

4.4.6 Target/Distractor Time Across Fingers

Participants' average percentages of time in contact with search targets/distractors for each finger (Fig. 12) were analyzed with a Greenhouse-Geisser repeated measures ANOVA, which revealed a significant main effect of finger $F(4, 32) = 115.51$, $\eta_G^2 = 0.88$, $p < 0.001$. Post-hoc Tukey HSD tests revealed that time percentages varied between every finger pair (all $p < 0.048$) except for index and middle fingers $p = 0.067$, thumb and ring finger $p = 0.879$, and thumb and little finger $p = 0.377$.

5 Discussion

This report demonstrates that untrained humans spontaneously use systematic search strategies: spirals, zigzags, and parallel sweeps, during one-handed haptic search on an unstructured 2-D tactile display. Differences in five-finger and one-finger search patterns aligned with search theory (developed in Sec. 2.1 and Fig. 3): systematic search was more common with a smaller detection radius (Fig. 7). When the detection radius is large, the efficiency benefits from systematic search are reduced, and the searcher may reasonably opt for a random strategy that has lower memory and motor planning costs. Thereby, this report demonstrates that untrained individuals will use optimal hand movements not only when exploring 3-D objects [1], but also with 2-D tactile displays.

A larger detection radius provided the current study's participants with a 40% reduction in search times. This is consistent with previous findings [5]. Reduced search times from a larger detection radius are unlikely to extend to structured search, in which targets and distractors are structured, e.g., in rows and columns. In structured search, the searcher knows where targets/distractors are located and does not need to search for their locations. Therefore, using more fingers does not necessarily reduce search times in structured search [35]. Similarly, with knowledge of where targets/distractors are located provided through vision, there is no need to execute systematic movements to search for them [24].

An alternative explanation for systematic movements is that these arise naturally from the mechanics of the arm, e.g., opening and closing the elbow resulting in zigzags. However, this explanation cannot account for movement trajectories that are unlikely to be symptoms of the arm's mechanics, including zigzags/parallel-sweeps oriented vertically and spirals. However, preference for zigzags and parallel sweeps over spirals may be related to the higher motoric demands of spirals. Most importantly, arm mechanics cannot account for the differential use of systematic strategies in one- and five-finger search.

Systematic strategy differences in one- and five-finger search were also not explained by different spatial foci, nor hand-speed differences. Search targets/distractors were the main spatial focus in both one-finger and five finger search. One-finger search did appear more diffuse than five-finger search (Fig. 8), likely because it involved a more thorough exploration of the search area. Hand-movement speeds were also similar in one- and five-finger search. For both, the hand moved quickly when searching for search targets/distractors and slowly when identifying/examining them (Table 2). This mixture of slow examination and fast relocation has been observed in structured haptic search [35].

During five-finger search, the fingers' positions were highly correlated (Fig. 9). While thumb positions were less correlated with the other fingers' positions, the thumb did not move slower than the other fingers(Table 3). This implies that the thumb's lower positional correlations were not due to spatial anchoring (using a finger as a stationary spatial reference while other fingers move), which would have reduced the thumb's average movement speeds. High positional correlations and similar movement speeds among the fingers are consistent with the fingers moving as a single unit.

During five-finger search, target detection occurred across the fingers in similar proportions (Table 4), while examination of search targets/distractors was accomplished primarily by the index and middle fingers (Fig. 12). When the index and middle fingers were not touching search targets/distractors, the fingers spread out to expand the hand's detection radius (Fig. 11), and the hand moved relatively quickly (Fig. 10). Once a search target/distractor was found, the fingers contracted and focused the index and middle fingers for identification. The expansions and contractions of the hand may account for imperfect positional correlations ($r^2 \neq 1$). The thumb may have had lower r^2 values than the other fingers due to it moving larger distances, back and forth from the other fingers, during hand expansion and contraction. The fact that participants expanded their hands when searching, and detected search targets equally across their fingers is consistent with participants exploiting the larger detection radius of five-finger search.

Search theory provides additional predictions about haptic search, beyond those examined in the current report. Specifically, the incidence of systematic movements should be related to the *ratio* of detection radius to search area. For a very larger search area, participants should use systematic strategies even when searching with five fingers, as long as the detection radius to search area ratio is relatively small. Additionally, the incidence of systematic movements should be inversely proportional to motor-planning costs, with systematic strategies being more common when planning and executing these movements is easy, and vice versa. Motor-planning costs could be reduced with training, or possibly increased in an unfamiliar force field. A larger minimum distance ($\ell_{\min}$), possibly due to movement amplification in a force field, would reduce the benefits and occurence of systematic search. Lastly, the layout of systematic trajectories, such as the spacing between parallel sweeps, should be affected by detection radius (Fig. 1).

In the current study, two of the nine participants reported that they used systematic strategies during one-finger search, and two reported that they used all of their fingers to detect search targets in five-finger search. It's possible that the other participants were aware that they used systematic strategies and exploited the larger detection radius associated with five fingers, but could not articulate or did not realize the significance of these strategies. Alternatively, exploratory movements may be adopted automatically at a non-conscious level, similar to the use of exploratory procedures on 3-D objects [36]. No matter the mechanism through which systematic strategies arise, the current report indicates that their presence is consistent with optimal behavior.

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