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Detection Radius Modulates Systematic Strategies in Unstructured Haptic Search

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***Abstract*— Movement strategies were investigated in a one-handed haptic search task where 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 parallel sweeps and spirals, should be more prevalent when the searcher's detection radius is small (one finger) than when the detection radius is large (five fingers). Movement patterns were classified as either non-systematic or systematic. As predicted by search theory, systematic strategies were more common in one-finger than five-finger searches. Overall, these results indicate that systematic haptic search strategies are used and modulated by detection radius for untrained sighted participants.**

I. BACKGROUND

The current research examines the prevalence of systematic strategies during haptic search for a landmark on an unstructured tactile map. Exploratory movements have been detailed for the perception of three-dimensional objects [1], but less work has been done on the use of optimal hand movements on two-dimensional displays. Generally, when searching for a target in an enclosed space, the searcher can adopt either a systematic or a random movement strategy. Systematic strategies include movement patterns such as spirals, parallel sweeps, and expanding squares (Figure 1) [2]. The relative benefits of systematic versus random search strategies have been most thoroughly examined in the fields of animal ecology and operations research. The current study's haptic search task is analogous to what is referred to in ecology as destructive foraging, 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.

Alternatives to systematic strategies include random walks, which are characterized as sequential steps in random directions of lengths ℓ_j drawn from a distribution $P(\ell_j) \sim \ell_j^{-\mu}$, $\ell_j > \ell_{\text{min}}$, continuing until the target is within the searcher's detection radius. For animals, the detection radius is typically range of sight, hearing, or olfaction; while in haptic search the detection radius is the area within the hand's immediate contact area. When $\mu \to 1$, the movement pattern is called ballistic, the searcher turns a random direction and continues straight until hitting a target or barrier. 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 process is Brownian (Figure 2) [3], [4].

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 [5], [3], [6], [7]. Higher efficiency can be attributed to better avoidance of previously searched ground. This efficiency benefit decreases with increasing detection radius, as shown by Monte Carlo simulations in Figure 3. When the detection radius is large, the benefits associated with a systematic strategy may be small enough that the searcher elects a random strategy that requires less memory and motor planning.

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 [6]. Instead, several reports indicate that animals forage for resources following a Lévy walk with $\mu \approx 2$, which is optimal for sparse revisitable (non-exhaustible or replenishing) targets [5], [4]. Given that systematic search strategies are uncommonly observed in (non-human) animals, the current research examines their use by humans. Systematic search strategies have been used in operations research beginning in WWII, with the allies' search for German U-boats in the Bay of Biscay [8], [9], and are currently used for the planning of large-scale human movements in military maneuvers, search and rescue operations, and aerial monitoring [10]. 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.

Systematic strategies are rarely observed in human perceptual processes with an unstructured stimulus, and this study, to my knowledge, is the first to show that this behavior is modulated by detection radius. Human visual search does not typically produce a systematic scan pattern, and is better described as jumps between locations with high salience [11], [12] or probability of containing the target [13]. The exception is when the stimulus is structured in a grid or concentric circles so that serially searching features induces reading-like patterns [14] or spirals [15], respectively. Haptic search can also follow reading-like movements when the stimulus is structured as a grid [16]. Research on unstructured haptic search, which has been previously conducted

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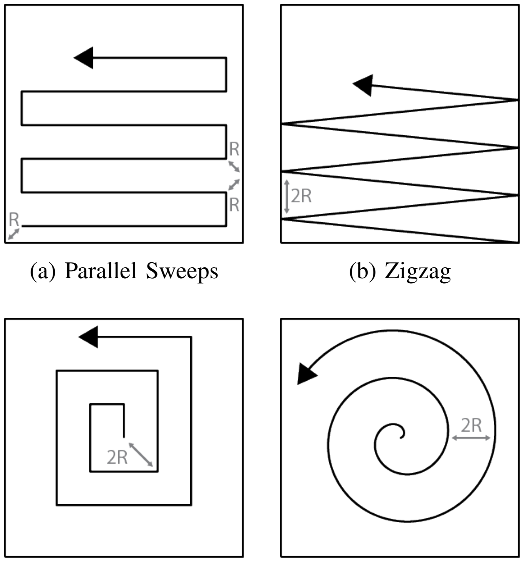
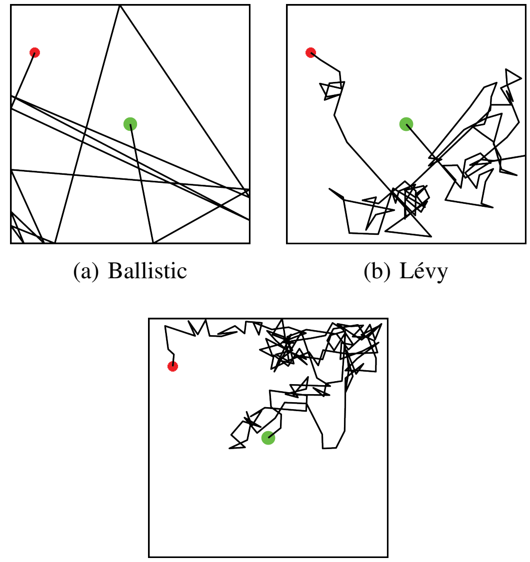


(a) Parallel Sweeps (b) Zigzag

(c) Expanding Square (d) Archimedes Spiral

Fig. 1: Example optimal systematic strategies for a square search area with detection radius R.


(a) Ballistic (b) Lévy

(c) Brownian

Fig. 2: Example random search strategies, starting in the center of the search space (green circle), ending when the target is found in the upper left (red circle).

without a sole focus on systematic strategies, has sometimes observed participants using systematic parallel sweeps [17], [18], but other studies have only observed movements that follow straight lines or complex patterns (i.e., random movements) [19], [20]. Of interest in the current study is whether humans will spontaneously use systematic search strategies without extensive experience or training on an unstructured tactile display. Furthermore, if this behavior is more common with a smaller detection radius, as would be predicted based on search efficiency.

II. METHODS

A. Participants

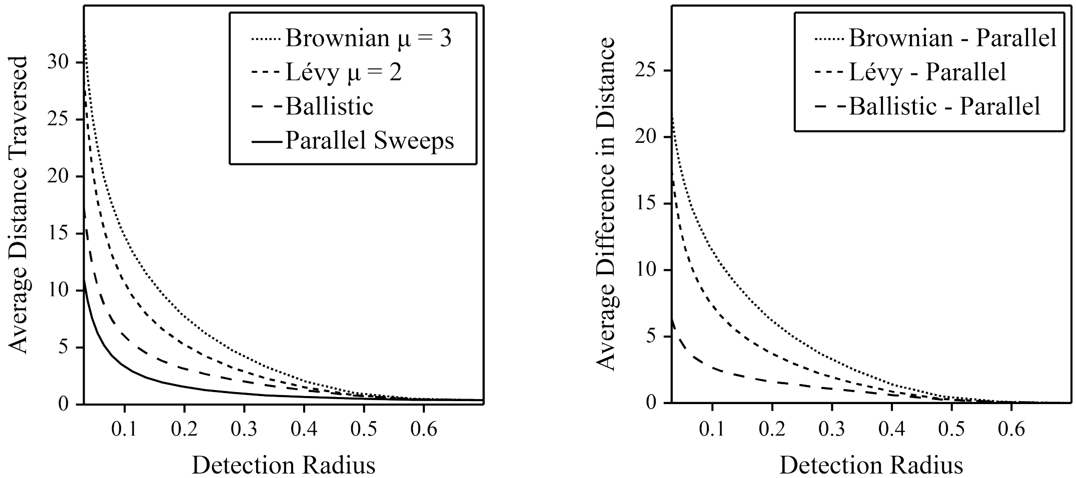
Nine right-handed sighted adults participated in this research; seven were female, and the average age was 27.2 years ($SD = 6.1$ years). The protocol was approved by the University of California, Berkeley's Committee for Protection of Human Subjects, and informed consent was obtained from all participants prior to their participation. Because the participants were sighted, unlike individuals with visual impairments, they did not have focused training on exploring tactile materials. Such training often includes instructions on using systematic strategies, as these are not automatically adopted by blind/low-vision individuals [21], [22].

B. Stimuli

The stimuli were taken from the Tactile Map Open Stimulus Set (TMOSS), which consists of 7 groups of 8 maps in total [23], 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. The purpose of using one group of stimuli for all one-finger trials, and a separate group for all five-finger trials, not randomizing group assignment between participants, was in providing the opportunity to visualize spatial distributions of explorations. This necessitated averaging finger locations across participants to provide enough data for two-dimensional density estimation (sometimes called "heat maps"). However, the TMOSS maps were developed such that map parameters, including distances, angles, and symbol types, numbers, and configurations were controlled to be the same across map groups. An example map layout is shown in Figure 4.

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 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.

Most importantly, the target symbol clusters on the one-finger and five-finger maps were *not* differently distributed. The average location of symbol-cluster centers, relative to the bottom left of the map, towards the right on one-finger maps was 10.29 cm ($SD = 6.50$ cm) and on five-finger maps was 15.42 cm ($SD = 6.59$ cm), $t(14) = -1.57$, $p = 0.139$; and upwards on one-finger maps was 13.06 cm ($SD = 7.89$ cm) and on five-finger maps was 11.68 cm ($SD = 7.12$ cm), $t(14) = 0.37$, $p = 0.719$. The average distance of symbol-cluster centers from the center of the map on one-finger maps was 10.76 cm ($SD = 2.36$ cm) and on five-finger maps was 9.44 cm ($SD = 2.60$ cm), $t(14) = 1.06$, $p = 0.306$.



(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 $\ell_j = \ell_{\min} \mathrm{u}_j^{1/(1-\mu)}$, where $\mathrm{u} \sim \mathrm{unif}(0, 1)$, and $\ell_{\min} = 0.05$ was equivalent to a 1.5 cm finger movement [24], [3], [25]. 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.

The two groups of maps also had the same distribution of target symbols (3 Ts, 1 circle, 2 triangles, 2 squares, and 0 ovals) and target cluster shapes (2 vertical lines, 1 diamond, 2 triangles, 2 squares, and 1 horizontal line).

C. Procedure

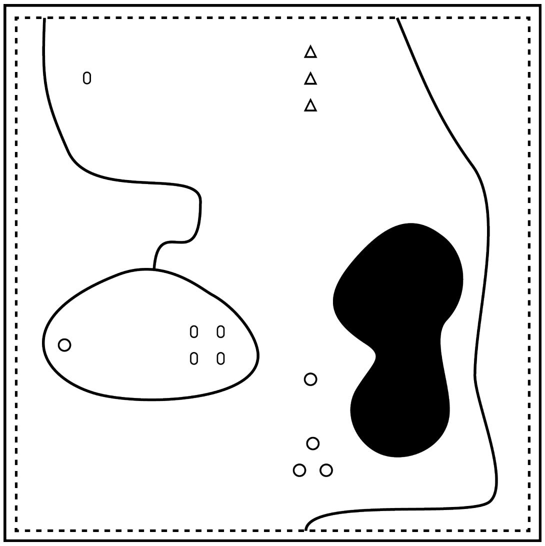
Participants were blindfolded and sat at a clear table on which stimuli were placed. The participants were trained how to recognize map symbols and clusters before beginning the main study. During the training, four of the participants were randomly selected to use their right index finger, and their other fingers were bent over 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 landmark to stop moving his/her hand, say "here," and remove his/her hand from the map.

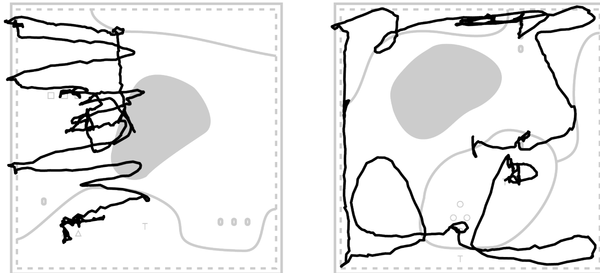
Below the clear table and tactile map a video camera was positioned (Canon Vixia HF R21, with a Canon 3.28-megapixel full HD CMOS image sensor). It pointed upwards and was focused to the depth plane of the tactile map. The camera's field of view was filled by the tactile map (30.5 cm x 30.5 cm) plus some additional space on each side (roughly 8 cm). The video camera recorded at a 1920 x 1080 resolution at 29.97 frames per second (commonly referred to as 30 Hz). 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 the movement completely stopped, so that there was no footage of a stationary hand.

D. Finger Tracking

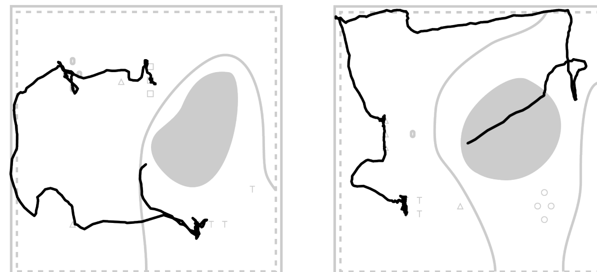
Each trial's video was run through a finger-tracking algorithm [26]. This algorithm applied a ridge-detection transform to each video frame, after which fingertip locations could be picked out using value thresholding. Example finger paths are shown in Figure 4. The algorithm did not disambiguate contact 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,



(a) Example Stimulus Layout
Original Size 12 inches × 12 inches



(b) One-Finger Search



(c) Five-Finger Search

Fig. 4: Example stimulus layout and index-finger trackings. Lines and areas in black (left) and gray (right) are raised and recessed/textured, respectively.

and address possible approaches to handling “missing” non-contact location data.

E. Analysis

1) Spatial Distributions: It was possible that differences in spatial concentrations, such as focusing on map borders or symbols differently, in one-finger and five-finger trials could lead to differential appearance of systematic movements. To examine this possibility, the overall concentration of participants’ index finger locations were visualized as spatial densities. Index finger locations were averaged within each map, across participants, to construct two-dimensional spatial densities using kernel density estimation, with a Normal kernel, bandwidth chosen using the Normal reference distribution, about 3 cm [27, p. 130].

2) 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 that could not be associated with a condition or 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. Coder percent agreement and Cohen’s Kappa were used to establish that the systematic strategies were clearly apparent and reliably coded. Typical disagreements between coders were over whether a trajectory contained a parallel sweep, zigzag, or combination, as these patterns could be very similar. Therefore, the codes for zigzags and parallel sweeps were combined into a single indication of zigzag or parallel sweep.

Participants’ total zigzags/parallel-sweeps and spirals for one-finger and five-finger search were compared using separate planned nonparametric Mann-Whitney U tests.

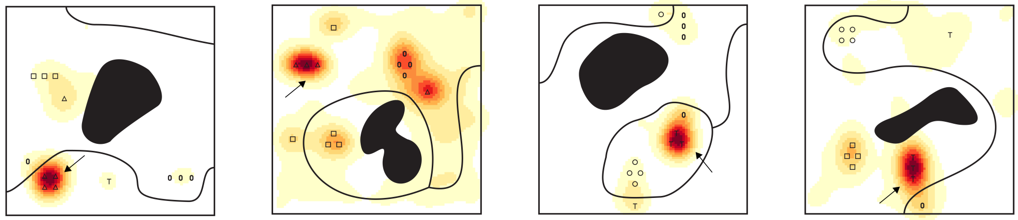
A previous study that used the same stimuli and search task, with a different group of sighted participants and no finger tracking, found that five-finger search was significantly faster than one-finger search [28]. To rule out the possibility that more systematic strategies occurred in one-finger search 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. These truncated trajectories were recoded and reanalyzed.

III. Results

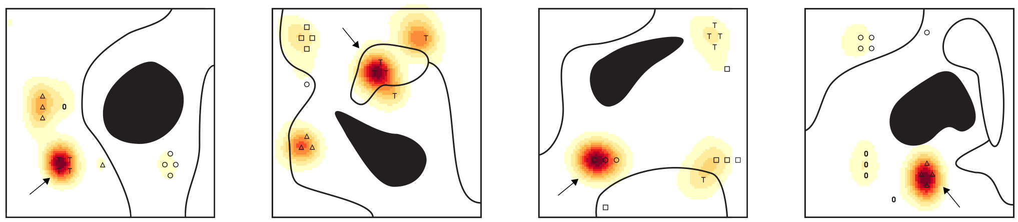
The average distance between participants’ thumbs and little fingers was 9.03 cm (SE = 0.60 cm). In contrast, the diameter of the index finger is approximately 2 cm. Therefore, the relative ratios of radius to stimulus width/height was, for the fingertip (radius 1 cm) approximately 0.03, and for the hand (radius 4.5 cm) approximately 0.15. These can be located within the simulation results in Figure 3.

A. Spatial Densities

The spatial distributions associated with a random selection of four one-finger and four five-finger search maps are shown in Figure 5. The highest densities of finger positions were located on target clusters. A lower, but apparent increase in density was also associated with distractor clusters and loose symbols. There were no apparent effects of map borders, paths, or lakes on finger location distributions. Spatial densities appeared more diffuse, not as concentrated around symbol features, for one-finger search trials.



(a) One-Finger Search, Index Finger



(b) Five-Finger Search, Index Finger

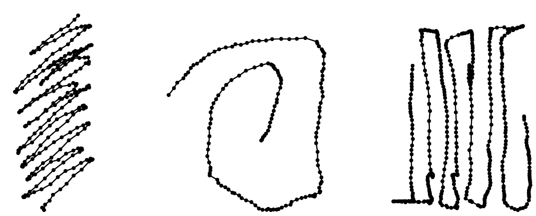
Fig. 5: Two-dimensional kernel density estimates of finger locations, averaged across participants. Target clusters are marked with arrows. Black lines are raised on the stimuli, and the large black areas are recessed and textured.

B. Systematic Strategies

Participants' index-finger scan paths included zigzags, parallel sweeps, and spirals (Figure 6). The inter-reliability of the coders indicated that the systematic strategies were readily apparent, based on percent agreement and Cohen's Kappa [29]. Agreement for spirals was 99.3%, $\kappa = 0.93$; and for zigzags/parallel-sweeps was 98.6%, $\kappa = 0.97$.

The number of trials containing systematic strategies (Figure 6) was significantly greater in one-finger than five-finger trials based on Mann-Whitney U tests (spiral $z = 1.99$, $p = 0.047$; zigzags/parallel-sweeps $z = 2.67$, $p = 0.008$).

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 finding is consistent with that from a previous study, using the same stimuli with a different group of sighted participants, which did not involve finger tracking [28]. However, trial length cannot explain 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 or parallel sweeps and no spirals, and did not eliminate the significant effect for zigzags/parallel-sweeps ($z = 2.62$, $p = 0.009$).



(a) Zigzag (b) Spiral (c) Parallel Sweeps

Fig. 6: Example systematic strategies observed in the current study.

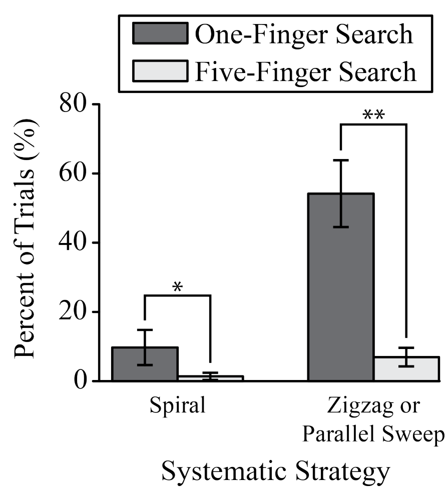


Fig. 6: Average occurrence of systematic strategies. Data are represented as mean $\pm$ SEM.

IV. Discussion

This paper demonstrates that untrained humans spontaneously use systematic search strategies: spirals, zigzags, and parallel sweeps, during one-handed haptic search on an unstructured display, more so when using one finger than five fingers. Differences in five-finger and one-finger search patterns align with search theory: when the detection radius is large, the efficiency benefits from systematic search are reduced, and the searcher may opt for a more random strategy that has lower costs in memory or motor planning. An alternative explanation is that systematic movements arise naturally from the mechanics of the arm. For example, opening and closing the elbow could cause the hand to move in a zigzag pattern. However, such an explanation cannot account for zigzags/parallel-sweeps oriented vertically, parallel sweeps that contain right angles, nor spirals, which are unlikely to be symptoms of the arm's mechanics. Furthermore, the mechanics of the arm cannot account for the differential use of systematic strategies in one- and five-finger search.

The current result provides a possible explanation for disagreement in previous haptic search studies, where some reports observed participants using systematic strategies [17], [18], while others did not [19], [20]. In hindsight, systematic strategies were not observed when the hand's detection radius was large (e.g., five fingers) relative to the search area, and were observed when the detection radius was small (e.g., one finger). Interestingly, a previous study observed that one-finger search without vision was associated with systematic scanning paths, while the same search task with visual information on target/distractor locations (without revealing which was the target) eliminated systematic movements [17]. This can be explained by considering that vision effectively extended the participants' haptic detection radius.

Search efficiency (Figure 3) predicts that systematic search movements would increase due to smaller detection radius (demonstrated in this paper), larger search/stimulus area, and lower motor-planning costs. In regards to the last prediction, it's possible that using a non-dominant hand would increase the effort associated with executing systematic patterns, reducing the relative benefit of using systematic movements.

Participants in the current study used systematic strategies when the efficiency benefits were substantial, and used random movement strategies when the efficiency benefits were presumably not worth the additional movement planning and memory resources. The spatial densities of participants' index-finger trajectories revealed that, although movement strategies were different in one-finger and five-finger search, the spatial concentrations of index-finger locations around symbol-related features were similar. These results underscore the importance of exploratory movement patterns in haptic perception - it not only matters where is touched, but also how the hand and fingers move during touch.

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