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Effects of using multiple hands and fingers on haptic performance

Valerie S Morash[1], Allison E Connell Pensky[1], Joshua A Miele[2]
[1] Department of Psychology, University of California, Berkeley, CA 94720, USA;
e-mail: valmo@berkeley.edu; [2] Smith-Kettlewell Eye Research Institute, San Francisco, CA 94115, USA
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Abstract. It remains controversial whether using two hands and multiple fingers provides any perceptual advantage over a single index finger. The present study examines this long-running question in the haptic-exploration literature by applying rigorous, psychophysical, and mathematical modeling techniques. We compared the performance of fourteen blindfolded sighted participants on seven tactile-map tasks using seven finger conditions. All tasks were benefited by multiple fingers, but it varied whether multiple fingers were beneficial on one hand, two hands, or both. Line-tracing tasks were performed faster when two hands were used, but not more than one finger per hand. Local and global search tasks were faster with multiple fingers, but not two hands. Distance comparison tasks were also performed faster with multiple fingers, and sometimes with two hands. Lastly, moving in a straight line was faster with multiple fingers, but was especially difficult with just two index fingers. These results provide empirical evidence that multiple hands and fingers benefit haptic perception, but the benefits are more complex than simply extending the tactile field of 'view'. This analogy between touch and vision fails to account for the autonomous movements and sensations of the fingers, which we show benefit the haptic perceptual system.

Keywords: haptic, tactile, perception, tactile maps, tactile exploration

1 Introduction

There are conflicting reports in the literature regarding the benefits of using multiple hands and/or multiple fingers for haptic exploration of objects and tactile figures. This question is fundamental to haptic science—similar to asking whether two eyes or two ears provide a perceptual advantage, which they do through spatial vision (stereopsis) and spatial hearing. However, while some haptic scientists report a benefit from using multiple hands and fingers as a result of increased haptic 'view' and 'anchoring' (defined below; eg Klatzky et al 1993; Lappin and Foulke 1973; Millar and Al-Attar 2004), others report a single finger being sufficient for haptic exploration (eg Jansson and Monaci 2003; Loomis et al 1991; Overvliet et al 2007). Unfortunately, it is difficult to synthesize these findings because of marked differences in stimuli and procedure. Furthermore, most previous work has compared only a limited number of conditions—for example, one and two fingers—providing only a partial picture of differential performance. If detectable performance benefits occur only after adding several fingers, or adding a finger on a separate hand, earlier experiments would miss this effect.

The current study aims to build a basis for direct comparison of contradictory prior findings using carefully counterbalanced psychophysical methods and mathematical models. The study incorporates a relatively large number of haptic exploration tasks (seven) and large number of finger conditions (seven), as well as both one-handed and two-handed conditions. The goal is to examine performance on many of the tasks described in the literature (eg search, line tracing, and evaluation of spatial relationship) in a single, rigorous experimental framework with a broad range of finger and hand conditions.

One way that multiple fingers could benefit perception is by providing a greater tactile 'view', increasing the throughput of tactile information by increasing the tactile surface area (the *Tactile Surface Area* hypothesis). This popular explanation has emerged, particularly, in the discussion of why performance at naming tactile raised-line drawings is remarkably poorer than naming visual line drawings, reasoning that touch has a lower spatial resolution (acuity) and smaller field of view than vision (eg Klatzky et al 1993; Lappin and Foulke 1973; Lederman et al 1990; Loomis et al 1991). Along these lines, using five fingers rather than one provided better blindfolded sighted performance in naming raised-line drawings of common objects (Klatzky et al 1993), and two fingers rather than one provided faster blindfolded sighted detection of Braille symbols (Lappin and Foulke 1973). The Tactile Surface Area hypothesis can also explain a diminishing return from additional fingers, in which the second finger provides a greater performance boost than the third, and so on—a pattern which has been documented for identification of 3-D objects (Jansson and Monaci 2004). This is to be expected when the added fingers are the less-acute fingers with smaller finger pads, such as the little finger. However, there are reports of nonsignificant performance differences for blindfolded sighted participants when they use one or two fingers in naming raised-line drawings of common objects (Loomis et al 1991), one or two fingers in naming raised-line outlines of European countries (Jansson and Monaci 2003), and one or three fingers in searching for a target hidden in a raised-line array of symbols (Overvliet et al 2007).

Additionally, the Tactile Surface Area hypothesis cannot explain why some perceptual tasks (eg search and detection) are performed better with two fingers on separate hands than two similar fingers on the same hand (Craig 1985; Lappin and Foulke 1973; Overvliet et al 2010). These results imply that hand and finger independence, in movement and sensation, provides a perceptual advantage. Benefits from multiple hands have been documented in several reports, particularly with blind participants. For example, tasked with identifying outline states on a tactile map, blind pupils (elementary to high school aged) had trouble using their dominant index finger to trace a single full outline of the state; they frequently stopped their trace too early or too late (Berlá et al 1976). This was remedied by placing the nondominant index finger where tracing began and should stop while tracing with the dominant index finger (Berlá and Butterfield 1977). In this way, the nondominant index finger served as an 'anchor', which is a finger held stationary while other fingers actively explore. This suggests that an anchor may serve an important perceptual role as a spatial reference.

Another function of an anchor may be to facilitate object-centered or world-centered spatial representations. Haptic perception is prone to spatially locating objects in relation to the perceiver's body or body part(s), in contrast to locating objects in relation to each other or a world-based coordinate system (Klatzky 1998; Morash et al 2012a). This may make object perception more difficult, because object features often have meaningful relationships to each other, but not to the perceiver's body (Millar and Al-Attar 2004; Ungar et al 1997). Therefore, using two hands, one as an anchor, may benefit perception by promoting object-centered or world-centered spatial representations. Supporting this, blindfolded sighted participants made fewer errors in reconstructing a tactile map if an anchor hand was applied to the map border during learning, even if the body–map relationships were disrupted during reconstruction through map rotation (Millar and Al-Attar 2004). Also, blind tactile-map users found it beneficial to reference locations in relation to a landmark or map border, which could be facilitated through using an anchor finger on these landmarks (Bentzen 1972), and were more successful in using the map for navigation if they employed one hand as an anchor while the other explored the map (Perkins and Gardiner 2003).

Lastly, spanning a distance using two fingers—for example, an anchoring thumb and roving index finger—could provide a more accurate spatial cue than using an index finger alone, moving it back and forth along the distance. The latter strategy relies on path integration for distance measurement, which is known to suffer from cumulative errors (Klatzky 1998). In contrast, comparing the simultaneous spatial locations of two spanning fingers would be more accurate. Thereby, an anchor and exploring finger provide spatial information to the haptic perceptual system that is unavailable to a single finger. Therefore, using multiple fingers could provide a benefit similar to the benefits gained from using two eyes or two ears.

2 Materials and methods

2.1 *Participants*

Fourteen normally sighted adults were recruited for participation. All reported being right handed, stating that they commonly wrote, ate, and would throw a ball with their right hand. Nine were female, and the mean age was 24 years (SD = 4.1 years). The participants were asked what previous exposure they had to tactile materials, such as Braille, tactile maps, or tactile graphics. Three participants reported no exposure to such materials, and eleven reported having minimal experience—for example, with Braille on elevator buttons. The protocol was approved by University of California, Berkeley's Committee for Protection of Human Subjects, and informed consent was obtained from all participants prior to their participation.

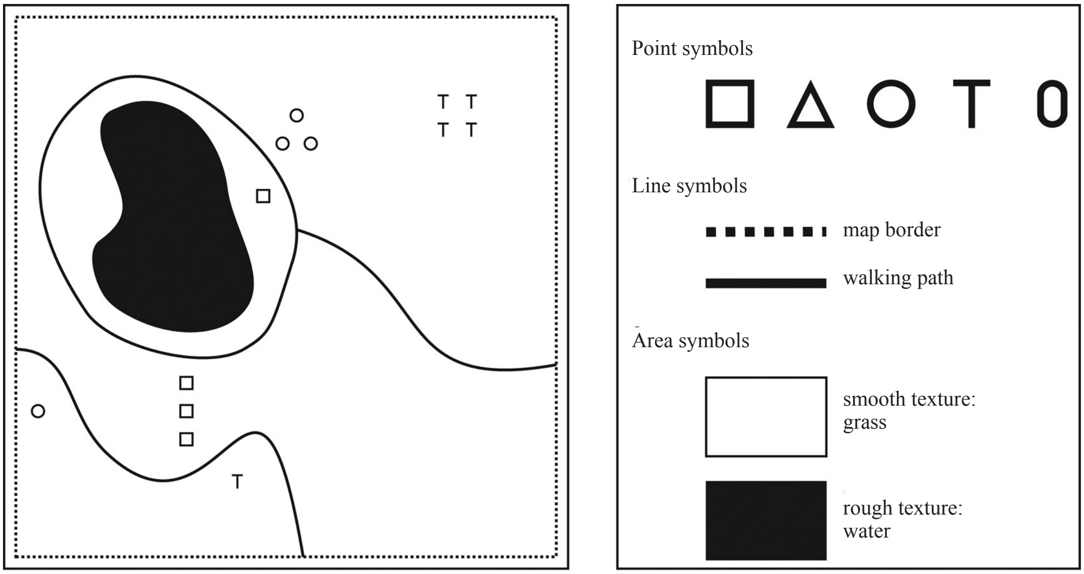
2.2 *Stimuli*

The stimuli were tactile maps, which are similar to simplified visual maps with the map symbols raised and/or textured to make them accessible to touch. These were constructed from clear, laser-cut acrylic. Each map represented a fictitious park, and included point symbols: circles, squares, ovals, Ts, and triangles, which represented the locations of bathrooms, drinking fountains, trash receptacles, etc. Solid lines were used to represent walking paths, and bumpy lines traced the map border. An area of water on each map, a lake, had a perimeter of 14 in and was rough and slightly recessed. The rest of the map surface was smooth and represented grass. The point symbols were distributed such that there were three clusters of point symbols per map—for example, a diamond-shaped cluster of Ts. These clusters served as landmarks, which could be unambiguously referenced. There were 5 specific cluster shapes: square, diamond, vertical line, horizontal line, and triangle. The point symbols arranged into a specific cluster were all the same (see figure 1a). Additional point symbols, outside of the clusters, were included so that each map had 13 total point symbols. Specifications of the map symbols, sizes, textures, elevations, spacing, and quantities were based on established recommendations. These parameters and further documentation on the stimuli can be found in Morash et al (2012b, 2012c). An example map stimulus is shown in figure 1.

Seven groups of eight maps were designed so that question parameters were the same for each map group (described in subsection 2.4). These map groups were pseudorandomly assigned to finger conditions for each participant, using a Latin-square design to ensure that no condition was consistently assigned to a particular map group. Maps were presented to the participant in blocks of seven, containing a representative from every condition. The order of the conditions within each block was randomized

2.3 *Finger conditions*

Seven conditions were tested: 1 through 5 fingers on the dominant (right) hand, 2 index fingers, and all 10 fingers (figure 2). The selection of 1–5 fingers on the dominant hand was to reveal, in maximum detail, how increasing fingers affected performance—whether it be linear or quadratic (due to diminishing benefit). There were two two-hand conditions: 2 index fingers and all 10 fingers.



(a) (b)

Order	Question type	Quantity per map (condition)	Example question (answer)
1	path loop	1 (8)	Is there a path with a closed loop? (Yes)
2	path number	1 (8)	Are there one or two paths? (Two)
3	cluster search	3 (24)	Please locate the cluster of circles and say 'here'.
	cluster direction	2 or 3 (20)	From this cluster or circles, which symbol is directly to the right? (T)
	cluster closest	2 or 3 (20)	From this cluster of circles, which symbol is closest? (Square)
4	distance cluster	2 (16)	Which is closer to the cluster of Ts, the cluster of circles or the cluster of squares? (Circles)
5	distance lake	2 (16)	Which is closer to the lake edge, the cluster of squares or the cluster of Ts? (Squares)

(c)

Figure 1. Example stimulus and related questions. (a) Example layout of a tactile-map stimulus shown from a top-down view (30% scale). Each map depicted a fictitious park, and was sized 12 in by 12 in. (b) Map symbol key (100% scale). (c) A subset of questions from the map in (a) (see subsection 2.4). Map groups were randomly assigned to finger conditions separately for each participant.

2.4 *Tasks and questions*

Seven tasks were selected based on the proposed benefits of multiple hands and fingers—for example, searching and line tracing. The reason for including a relatively large number of tasks was to examine whether disagreement in previous studies was attributable to task differences. Each task had 1–3 questions associated with it per map. Within a question, map features were referred to as 'paths', 'lakes', and shape names as 'circle', 'square', etc. Within a map, task order was chosen so that tasks would not interfere with each other. For example, questions about the spatial relationships between the clusters (distance cluster) occurred only after the participant had located the clusters (search). Otherwise, question ordering was randomized.

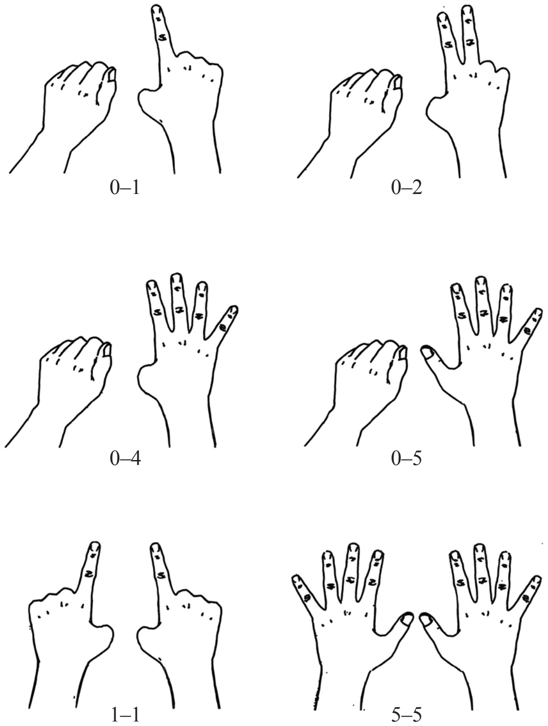


Figure 2. Finger conditions: seven conditions were tested: 1 through 5 fingers on the dominant (right) hand, 2 index fingers, and all 10 fingers. These are indicated with the notation L–R, where L is the number of fingers on the left hand and R is the number of fingers on the right hand. Unused fingers were taped to the palm, while the unused hand rested in the participant's lap.

2.4.1 *Tasks 1 and 2: path loop and path number.* The first and second questions for each map were "Is there a path with a closed loop?" and "Are there one or two paths?" These questions were related to previous research on line tracing (eg Berlá and Butterfield 1977; Jansson and Monaci 2003) and raised-line drawings, which involves line-tracing behaviors (eg Klatzky et al 1993; Loomis et al 1991). The paths were balanced so that within each condition there were four maps with and four maps without closed loops, two of each with 2 paths and two with 1 path. Additionally, the path and loop lengths were kept constant across conditions [distances reported in Morash et al (2012c)].

2.4.2 *Tasks 3–5: cluster search, direction, and closest.* After the path-related questions on a map, participants were asked 3 cluster search questions (eg "Please locate the cluster of ovals and say 'here' "), 2–3 direction questions (eg "From this cluster of ovals, which symbol is directly below?"), and 2–3 closest question (eg "From this cluster of ovals, which symbol is closest?"). Search and closest questions related to previous work on search and detection (eg Lappin and Foulke 1973; Overvliet et al 2007, 2010). Direction questions were based on research suggesting that an anchor finger may facilitate straight-line movement (Lederman and Campbell 1983). These questions were grouped so that questions referencing a particular cluster occurred sequentially, with the cluster search question first, direction question(s) second, and closest question last.

In total, 24 cluster search, 20 direction, and 20 closest questions were asked in each finger condition and were balanced across conditions in the following ways. Cluster search questions were balanced so that for every condition the same unique clusters were searched for. The locations of these clusters were not significantly different across conditions. The direction questions were balanced so that there were equal numbers of 'square', 'triangle', 'circle', 'T', and 'oval' answers; equal numbers of 'right', 'left', 'above', and 'below' instructions; and 20 specific distances between the cluster and answer that were the same for every condition (1.0–6.9 in). Closest questions were balanced similarly: there were equal numbers of 'square', 'triangle', 'circle', 'T', and 'oval' answers; equal numbers of rightwards (315°, 45°), leftwards (135°, 225°), upwards (45°, 135°), and downwards (225°, 316°) directions in which the answer could be found; and 20 specific distances between the cluster and answer that were the same for every condition (0.8–3.2 in). Complete lists of distances for all tasks can be found in Morash et al (2012c).

2.4.3 *Tasks 6 and 7: distance cluster and distance lake.* After the 3 groups of cluster-related questions (tasks 3–5), participants were asked 2 questions about the spatial relationships between the clusters on a map (eg "Which is closer to the cluster of Ts, the cluster of squares or the cluster of ovals?"), followed by 2 questions about clusters and the lake (eg "Which is closer to the lake edge, the cluster of triangles or the cluster of circles?"). These tasks referenced previous work on spatial perception (eg Bentzen 1972; Millar and Al-Attar 2004; Perkins and Gardiner 2003) and raised-line drawings, which require spatial comprehension (eg Klatzky et al 1993; Loomis et al 1991). The participants answered 16 distance cluster questions and 16 distance lake questions per condition, and the 16 sets of distances being compared were the same for each condition (distance cluster 0.6–4.8 in, distance lake 0.5–4.5 in).

2.5 *Procedure*

Participants were enrolled in the study for 12–15 hours. This was spread across multiple days: typically 2–3 hours per day for 4–6 days within a 2-week period, as was convenient for the participant. During the experiment, participants were encouraged to take breaks between maps.

2.5.1 *Tactile acuity and fingertip area.* We measured the tactile acuity for each participant's 10 fingers to ensure that acuity was normal, and not reduced due to injury or disease (eg diabetes). Acuity was assessed by measuring two-point threshold, which is a long-used measure of tactile acuity and refers to the distance between two points (pins pressed into the skin) at which the two points feel like one. Acuity was measured at the beginning and end of each participant's enrolment, with the participant blindfolded, using the same procedure as in Stevens (1992): a forced-choice adaptive method, often referred to as a 'two up, one down' staircase, with a 0.25 mm step size. The only difference between Stevens's and our method was that Stevens used a manual device, whereas we created a small machine that could be controlled through Matlab (Mathworks, Inc.) to position and raise/lower the points. This reduced the time to measure two-point threshold from Stevens's 20 minutes to about 5 minutes per finger.

During two-point threshold measurement the participant's hand rested palm down on a flat surface with the finger pad centered over an oval opening. The points were positioned beneath this opening, and were raised upwards to make contact with the finger pad. Contact was made for 0.5 s before the points were lowered. There was a 1 s pause between trials, during which time the points were in the lowered position and adjusted to the desired separation. After each trial, the participant was asked "one point or two?" and the experimenter entered the response using a keyboard. The participant was given verbal instructions to answer "one" when there was no separation and "two" when the points were separated. Thereby, thresholds were obtained with an objective measure, which contrasts to the alternative procedure of gradually reducing the distance between two points until the participant indicates a subjective sensation of one point, which is known to produce inconsistent results (Craig and Johnson 2000). Additionally, our procedure always presented two points, with either zero or nonzero separation, so that the total area of skin contacted was the same in all trials. Had one and two points, literally, been used, no spatial processing would have been necessary to perform the task (Johnson and Phillips 1981). No practice trials were allowed.

There are limitations to the two-point threshold measure we used. Most notably, Craig and Johnson (2000) argued that the two-point limen does not measure tactile acuity. One of their reasons is that the perceived pattern of points on the skin changes with distance; percepts can vary between one point, two points, a line, a circle, or a dumbbell shape. Participants must adopt criteria to decide which patterns should be labeled as one point versus two. These criteria can vary considerably between participants and within the same participant over time. Additionally, nonspatial intensity information can be used to disambiguate between one and two points. A single point will feel 'sharper' than two points separated by a small distance.

In addition to each finger's tactile acuity, we measured each fingertip's surface area by tracing the outline of the fingertip to the first knuckle. The participant's hand was placed on a white sheet of paper, palm down. The participant was asked to rest the hand without applying any pressure. The tracing was made using a fine-tip pen as close to the skin as possible. This procedure was used in place of analyzing video images because it was not subject to distortions due to camera angle (ie projective transformation). We measured the area of these tracings using Photoshop (Adobe, Inc.).

2.5.2 *Training and instructions.* Before the main experiment participants took part in one hour of blindfolded training to become familiar with the stimuli, tasks, and setup. Each participant was randomly assigned a finger condition to use for training, such that each condition was used by two of the participants. The participants were informed that the stimuli were maps of fictitious parks. They were instructed to use their fingertips for exploration and not their palms. Otherwise, the participants were never provided with suggestions as to how to explore the maps. Unused fingers were comfortably taped to the palm. All training took place with the participants blindfolded and used the same setup as the main experiment (figure 3). The training included point symbol training, cluster training, and map training.

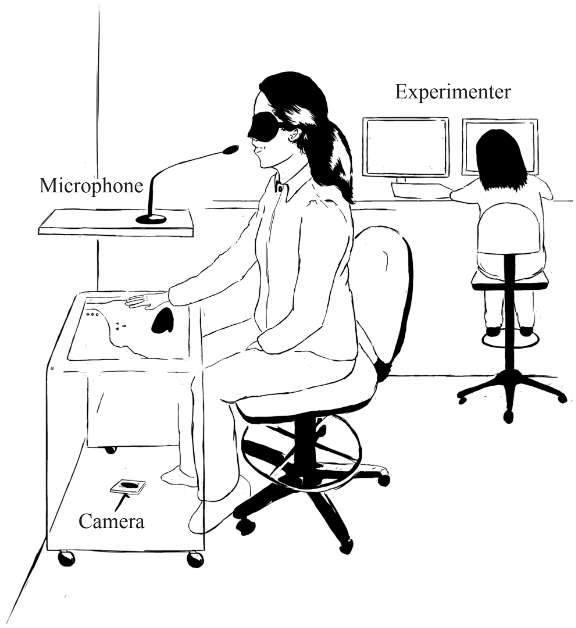


Figure 3. Experimental setup. The participant was seated at a custom-made clear table, was blindfolded, and had unused fingers taped to his or her palm. The map stimulus (made of clear acrylic) was placed on top of the table, and viewed from below by a video camera. A shelf above the table held a microphone that recorded the participant's voice responses. The experimenter, who sat to the side of the participant, viewed two computers, one that controlled the experiment and one that showed and recorded the video (from the camera below the participant's table).

During the point symbol training the participant learned the shape and name of each of the five point symbols (shown in figure 1b). The participant was allowed to continue only after correctly recognizing and naming 10 symbols, each symbol twice, in random order. Following this, each participant learned the five types of clusters. The participant was only allowed to continue after correctly naming the cluster shape and symbol type of five random clusters, each a different cluster shape composed of a different symbol. The map training made use of three separate training maps, which were similar to the experimental map stimuli. Using the training maps, the participant was familiarized with the general layout and makeup of the map stimuli and flow of the questions. Participants were given instructions on how to answer in a standardized fashion—for example, answering "here" instead of "it's here", not to move his or her fingers until after a question was asked and a 'go' tone was played, to not speak until answering, and to stop exploring after answering.

2.5.3 *Main experiment.* The main experiment progressed through the 56 map stimuli in a randomized predetermined order (as explained in subsection 2.2). The participant was seated at a custom-made clear table, was blindfolded, and had unused fingers taped to his or her palm (figure 3). The experiment was controlled through a primary computer that delivered questions in audio form, and recorded the participant's voice responses through a microphone placed on a shelf above the table. A second computer continuously recorded a video of the experiment from below the table. The experimenter sat to the side of the participant and was able to view both computer monitors. For each question the experimenter pushed a button on the primary computer, which delivered an audio prompt instructing the participant to prepare for the upcoming question by placing his or her index finger(s) at the bottom middle of the map (path loop, path number, cluster search, distance cluster, and distance lake questions) or on the relevant cluster (direction and closest questions). The experimenter checked that the participant did this correctly by viewing the video feed on the secondary computer. Then, the experimenter would press a button on the primary computer to deliver the question's audio, followed by the 'go' tone and initiation of the voice recording. The participant was instructed to wait for the tone before answering or moving his or her hands. Once the participant had answered, the experimenter would stop voice recording on the primary computer, and move on to the next instruction.

2.6 *Analysis*

Statistical tests were done using STATA (StataCorp, LP), except for generalized linear models, which were estimated using Matlab.

2.6.1 *Relating task performance to finger condition.* Trials were excluded when interrupted by personnel intrusion and when the participant asked for a question to be replayed after touching the map (ie the participant forgot the question). Analysis of nonexcluded trials can be conceptualized as being two-staged. The first stage assessed whether a question was answered from memory (without touching the map) or with map exploration. These touch/notouch data were binomial distributed, so an ANOVA, which assumes normality, was not appropriate for analysis. Instead, a Kruskal–Wallis test, a nonparametric version of the one-way ANOVA, assessed whether touching the map was related to finger condition. This could occur if a finger condition that provided a good mental representation of the map was associated with more answering from memory.

The second stage of analysis examined the response times of questions answered with exploration, not by memory (questions answered from memory had uniform and low response times). No fruitful analysis could be conducted on the accuracy data because there were so few incorrect trials. Participants were near 100% accurate for all tasks and conditions (table 1). Had the participants been given a time limit for responding, there would have been more inaccurate trials. Therefore, the response-time data were used to relate task performance to finger condition.

Table 1. Summary of trial statistics: retained trials, accuracy, and frequency of answering from memory per task across participants.

	Retained trials/total	Accuracy (SE) %	Number of questions answered from memory per finger condition (left–right fingers)						
			0–1	0–2	0–3	0–4	0–5	1–1	5–5
Path loop	776/784	99.36 (0.29)	0	0	0	0	0	0	0
Path number	419/784	97.57 (0.55)	55	50	50	53	48	50	49
Cluster search	2331/2352	99.40 (0.16)	0	0	0	0	0	0	0
Cluster direction	1881/1960	96.22 (0.43)	0	0	0	0	0	2	0
Cluster closest	1889/1960	96.63 (0.41)	0	0	0	1	0	0	0
Distance cluster	1246/1568	95.58 (0.52)	32	32	33	31	32	41	28
Distance lake	1503/1568	98.00 (0.35)	4	3	2	5	1	5	3

2.6.2 *Extraction of response times from audio recordings.* Voice recordings were enhanced using minimum-mean square error spectral amplitude estimation with Voicebox, a free speech processing toolbox for Matlab (Brookes 2006; Ephraim and Malah 1984). This process produced better noise reduction than simple filtering (low-pass, band-pass, etc). Nonresponses, such as lip smacks and frustration noises, were manually removed from the recordings. Using what remained, a response time was identified as the first instance the signal surpassed 5% maximum amplitude.

2.6.3 *Modeling.* The response time measurements were highly variable, as trials differed not only in finger condition but also in map parameters and participants (figure 4). Therefore, the relationships between conditions and response times were examined with linear models that accounted for these other variables. Had these variables been ignored, they could have biased results or reduced the power of the analyses. For example, the model of cluster direction response times (eg "From this cluster of squares, what symbol is directly below?") included participant indicators, distances (in inches), direction indicators (eg 'left'), answer indicators (eg 'circle'), and other parameters that affected response times. Including these variables in the models enabled their effects to be separated from those of number of hands and fingers.

The models allowed response times to follow a gamma distribution, which accurately captures response-time nonnegativity and positive skew (Baayen and Milin 2010; Haaijer et al 2000; Jansen 1997; Maris 1993; Palmer et al 2011). A log-link was used, so that the effects of variables in the models were multiplicative rather than additive. This allowed effects to be measured in percentages rather than seconds, and accounted for slower participants having greater variation in time (but not percentages) than faster participants.

Intuitively, the models fit the log of the response times, which stabilized the variance, using a traditional additive model. This can be reinterpreted as modeling response times (without the log) using a multiplicative model. These details are captured in the explicit form of the model shown below:

$$\ln(Y_{pt}) = \mu + \pi_p + f_t + h_t + f_t h_t + A_t + B_t + \ldots + Z_t + \varepsilon_{pt} ,$$

where Y_{pt} is the response time of participant p on trial t, μ is the general intercept, π captures the specific effect of participant p, f is the effect from number of fingers, h is the effect from number of hands, A–Z are effects related to the specific trial—for example, distances, direction indicators, and answer indicators—and ε captures the error. This model differs from a conventional general linear model in only the log-link, the logarithm on the left side of the equation, and allowing Y_{pt} to follow a gamma distribution.

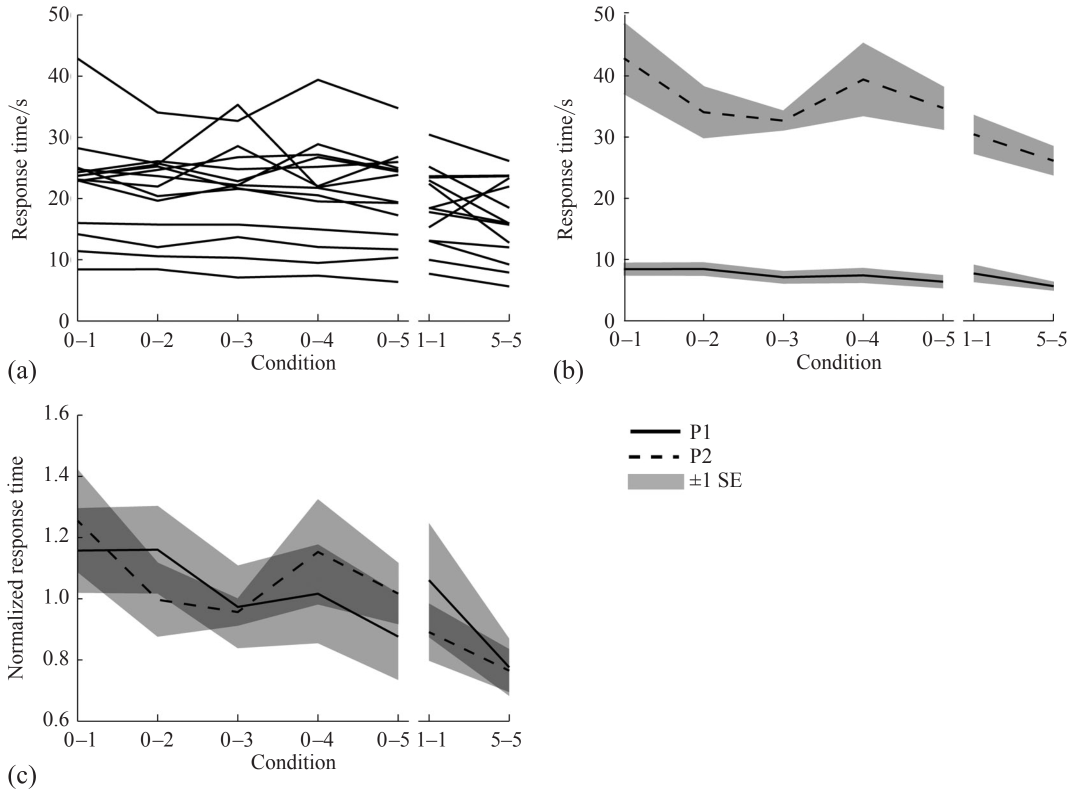


Figure 4. Path loop response times. (a) Average response times from all participants, 1–14, across conditions (left-hand fingers–right-hand fingers). Data appear highly variable due to effects not captured on graph (eg path lengths), as well as differences between participants. (b) Response times from participants 1 and 2 (P1 and P2), the fastest and slowest participants, with ±1 SE. P2 is slower and shows larger variability. (c) Normalized response times (response time divided by participant's average response time) for P1 and P2, with ±1 SE. After normalization, P1 and P2 have more similar values and variances.

Alternatively, the models can be conceptualized as fitting response times with multiplicative effects, as shown below:

$$Y_{pt} = e^{\mu} e^{\pi_p} e^{f_t} e^{h_t} e^{f_t h_t} e^{A_t} e^{B_t} \ldots e^{Z_t} e^{\varepsilon_{pt}} .$$

This second equation is the same as the first after simple algebra. We will discuss model results using this second equation, because it is more straightforward to discuss effects on response times than on log response times. However, these different model forms are mathematically identical.

Two models were compared for each task. In addition to parameter and participant variables, the first model included the variables: number of fingers, number of hands, and the interaction. The second model added a fourth variable: number of fingers squared. This quadratic-finger model would fit the response times better than the first, linear-finger model, if there were diminishing benefits from additional fingers: the first additional finger provided more benefit than the second, and so on. This would appear, graphically, as the left side of an upward-opening parabola, which would be best fit with a parabolic function obtained by including number of fingers squared. This was expected from the Tactile Surface Area explanation discussed in the introduction. The linear-finger and quadratic-finger models were compared using a likelihood-ratio-based test (Fox 2008, pages 385–387; Gill 2001, page 64).

2.6.4 *Tactile acuity and fingertip surface area.* Measures of two-point threshold were used to assess whether the participants' tactile acuities were normal through comparison with those reported by Stevens (1992). Additionally, these measures were used to examine how tactile surface area and acuity varied across fingers.

3 Results

3.1 *Trial exclusion, inaccurate responses, and answering from memory*

The trials retained, accuracies, and numbers of trials answered from memory are shown, per task, in table 1. There were two tasks in which no questions were answered from memory: path loop (the first question asked on each map) and cluster search, which asked participants to identify clusters by touching them. Two other tasks had almost no answers from memory: cluster direction and closest, which had a total of 2 questions and 1 question answered from memory, respectively. The other tasks had more answering from memory, and we used Kruskal–Wallis tests to assess whether answering from memory was related to finger condition. There was not a significant effect of condition on answering from memory: path number ($H_6 = 1.24$, $p = 0.98$), distance cluster ($H_6 = 3.51$, $p = 0.74$), and distance lake ($H_6 = 6.1$, $p = 0.41$). Therefore, we did not anticipate any bias in hand and finger effects due to omitting these trials from response times models. Furthermore, model estimates were unbiased under the assumption of missing at random despite omitting answer-from-memory trials, because the data were missing on only the dependent variable, and models were estimated with maximum likelihood estimation (Allison 2012).

3.2 *Relating response times to finger condition*

Response times varied greatly across participants, and faster participants had less variance in their response times than slower participants. This was one motivation for using a log-link in the models (see section 2). The average of participants' mean response times, across finger conditions and other parameters, were: path loop $M = 20.3$ s (min = 7.3 s, max = 34.3 s, SE = 1.9 s), path number $M = 13.7$ s (min = 5.7 s, max = 21.7 s, SE = 1.4 s), cluster search $M = 10.6$ s (min = 5.1 s, max = 16.0 s, SE = 0.8 s), cluster direction $M = 8.1$ s (min = 3.4 s, max = 14.3 s, SE = 0.9 s), cluster closest $M = 15.9$ s (min = 3.9 s, max = 30.8 s, SE = 1.9 s), distance cluster $M = 15.6$ s (min = 4.9 s, max = 30.9 s, SE = 1.8 s), and distance lake $M = 15.1$ s (min = 5.6 s, max = 25.6 s, SE = 1.6 s). Participants took, on average, between 8–20 s to answer each question. This is quite slow compared with similar visual perception tasks. Additionally, some participants were much faster than others. For example, in the path loop task the fastest participant answered a question in, on average, 7.3 s, while the slowest participant took, on average, 34.3 s. We considered that this variability might be related to gender differences. However, Mann–Whitney U-tests did not find a significant difference between the average response times for females and males on any of the tasks (smallest $p = 0.24$). The response times for each task, normalized by dividing by the average participant response time on the task, are shown in figure 5.

In addition to participant differences, map parameters also affected response times. For example, questions about paths took more time to answer when the paths were longer. Therefore, models were used to examine the effects of multiple hands and fingers, controlling for participant differences and map parameters. Model estimates are shown in table 2 (only those for the preferred model, linear finger, or quadratic finger). Predicted response times for each task, demonstrating the effects of multiple hands and fingers separate from the effects of other variables, are shown in figure 6.

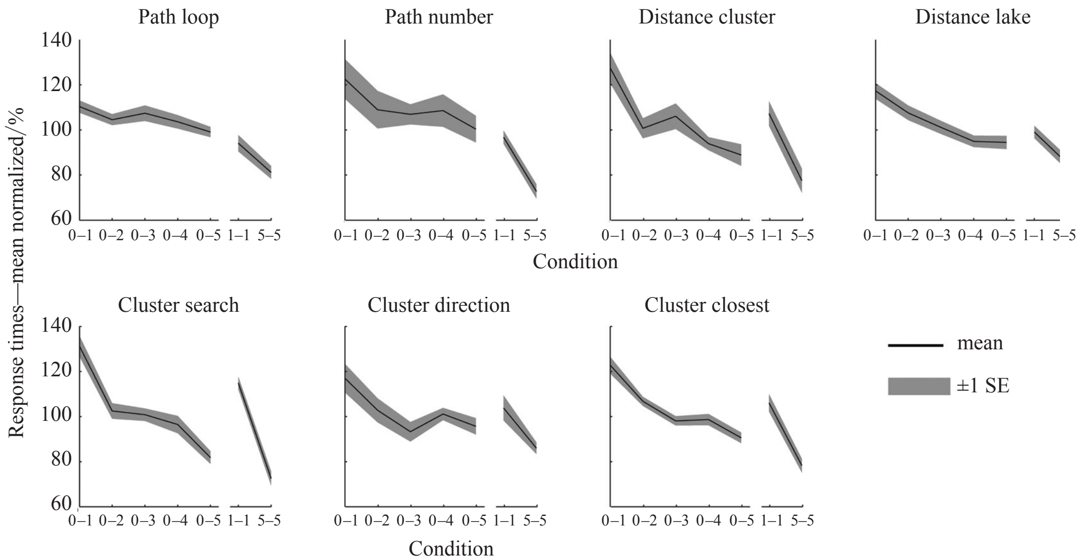


Figure 5. Mean-normalized response times. Average participant response times across conditions (left-hand fingers–right-hand fingers) for each task. Data were normalized by dividing individual response times by the participant's average response time for the task.

Table 2. Model estimates. Exponentiated model estimates (and standard errors) for response time models. Effects are multiplicative: a value of 0.88 is interpreted as a 0.88 multiplication of response time per 1-unit covariate increase. Also shown, the statistic for choosing the quadratic or linear models $F_{\text{quadratic}}$, the goodness-of-fit statistic (difference in model and null-model deviances) ΔD, model dispersion φ, and number of parameters k.

Task $F_{\text{quadratic}}$, ΔD, φ, k	Exponentiated estimated effects (exponentiated SEs)			
	number of hands	number of fingers	number of hands × number of fingers	(number of fingers)^2
Path loop $F_{\text{quadratic}} = 0.25$, $\Delta D = 144^{b}$, $\varphi = 0.363$, $k = 21$	0.88 (1.06)*	0.98 (1.02)	1.00 (1.01)	
Path number $F_{\text{quadratic}} = 1.07$, $\Delta D = 129^{b}$, $\varphi = 0.444$, $k = 21$	0.81 (1.10)*	0.94 (1.04)	1.02 (1.02)	
Cluster search $F_{\text{quadratic}} = 1.36$, $\Delta D = 508^{b}$, $\varphi = 0.76$, $k = 27$	0.94 (1.08)	0.86 (1.03)***	1.05 (1.02)**	
Cluster direction $F_{\text{quadratic}} = 7.37^{a}$, $\Delta D^{b} = 556^{b}$, $\varphi = 0.648$, $k = 36$	1.38 (1.16)*	0.95 (1.03)	0.86 (1.07)*	1.03 (1.01)**
Cluster closest $F_{\text{quadratic}} = 4.64^{a}$, $\Delta D = 581^{b}$, $\varphi = 0.472$, $k = 35$	1.13 (1.11)	0.90 (1.02)***	0.93 (1.05)	1.02 (1.01)*
Distance cluster $F_{\text{quadratic}} = 1.64$, $\Delta D = 389^{b}$, $\varphi = 0.632$, $k = 46$	0.92 (1.08)	0.91 (1.03)**	1.03 (1.02)	
Distance lake $F_{\text{quadratic}} = 3.70$, $\Delta D = 336^{b}$, $\varphi = 0.454$, $k = 42$	0.84 (1.05)***	0.90 (1.02)***	1.04 (1.01)***	

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.
[a] $F_{\text{quadratic}} > F(1, \text{df}_{\text{quadratic}}) \approx 3.85$, comparing linear and quadratic model.
[b] $\Delta D/\varphi > F(k–1, \text{df})$, comparing selected and intercept-only models.

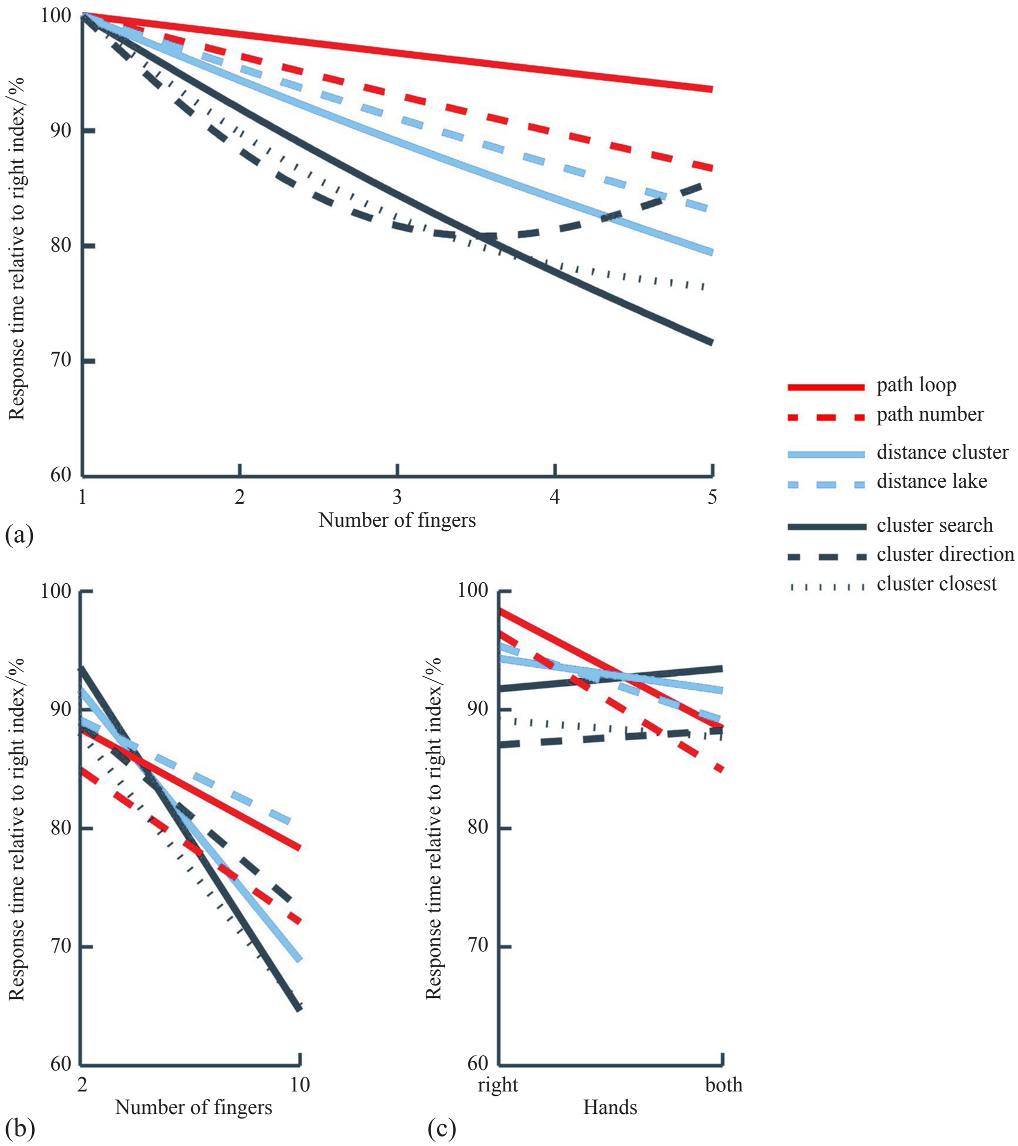


Figure 6. [In color online, see http://dx.doi.org/10.1068/p7443] Model fits for each task, omitting effects except those related to number of fingers and hands, relative to 1 index finger on the right hand. (a) Fits for 1 through 5 fingers on the right hand only (conditions 0–1, 0–2, 0–3, 0–4, and 0–5 as shown in figure 1). (b) Fits for the 2-handed conditions: index–index and all ten fingers (conditions 1–1 and 5–5) connected with straight lines (ie other conditions not shown). (c) Fits for the 2-finger conditions: right-hand index and middle, and both hands' index fingers (conditions 0–2 and 1–1) connected with straight lines (ie other conditions not shown).

3.3 *Tactile acuity and fingertip surface area*

Tactile acuity was measured to establish that participants had normal tactile acuity, and to assess how it varied across the fingers, as this might be related to finger benefits. Tactile acuity thresholds averaged across the two measurements, which did not significantly differ, are summarized in table 3. Overall, the values of the participants' two-point thresholds were similar to those reported for the right index finger of 18–33 year olds by Stevens (1992): $M = 1.95$ mm, SD = 0.69 mm. Only one threshold, that for P1's left middle finger (4.125 mm), would classify as an outlier ($M \pm 3$SD) amongst Stevens's data. Therefore, we concluded that our participants had normal tactile acuity on all of their fingers.

Table 3. Finger acuity: two-point threshold (in mm) as a function of finger, averaged over first and second measurements.

	Two-point threshold (mm)				
	thumb	index	middle	ring	little
Right hand					
Mean	2.01	1.67	1.50	1.80	1.86
SD	0.45	0.53	0.42	0.58	0.46
Left hand					
Mean	2.08	1.32	1.62	1.65	2.04
SD	0.44	0.57	0.83	0.61	0.65
Both hands					
Mean	2.04	1.49	1.56	1.72	1.95
SD	0.33	0.49	0.54	0.54	0.46

We conducted a repeated-measures ANOVA with Greenhouse–Geisser correction on acuity thresholds, for the variables of finger (thumb, index, middle, ring, or little), measurement (before or after the experiment—ie first or second), and hand (right or left), including all interactions. The main effects of measurement ($F_{1,247} = 0.1$, $p = 0.75$) and hand ($F_{1,247} = 0.22$, $p = 0.64$) were not significant; nor were the interactions between measurement and hand ($F_{1,247} = 0.81$, $p = 0.37$), measurement and finger ($F_{4,247} = 1.07$, $p = 0.36$), and measurement, hand, and finger ($F_{4,247} = 0.12$, $p = 0.95$). However, a main effect of finger was significant ($F_{4,247} = 13.32$, $p < 0.001$), as was the interaction between hand and finger ($F_{4,247} = 2.80$, $p < 0.05$). Given the significant interaction between finger and hand, we conducted an ANOVA for each hand separately, collapsed over measurement, to test whether thresholds significantly varied within each hand. An effect of finger was significant in both right ($F_{4,52} = 4.81$, $p < 0.003$) and left hands ($F_{4,52} = 8.63$, $p < 0.0001$). A posteriori comparisons using a Tukey HSD test indicated significant mean differences in the right hand between thumb and middle, and middle and little fingers; and, in the left hand, between thumb and index, thumb and middle, thumb and ring, and index and little fingers. Also, with similar regard to the hand–finger interaction, we examined whether thresholds differed across hands for each finger separately, collapsed over measurement, using t-tests. No finger reached a significant difference with a Bonferroni-corrected threshold ($\alpha = 0.01$, thumb $p = 0.65$, index $p = 0.02$, middle $p = 0.58$, ring $p = 0.28$, and little $p = 0.33$). The only finger to approach significance was the index finger, for which the left hand was more sensitive. This is consistent with previous findings, which suggest that the two-point threshold is lower in the left hand than the right hand for right-handed people (Weinstein 1962; Weinstein and Sersen 1961).

Fingertip areas, which did not significantly differ across hands, are summarized in table 4. We analyzed the fingertip areas using a Greenhouse–Geisser-corrected ANOVA, examining the effect of fingertip area by hand, finger, and their interaction. There was not a significant effect of hand ($F_{1,117} = 0.01$, $p = 0.92$), nor a significant interaction ($F_{4,117} = 0.20$, $p = 0.75$). There was a significant effect of finger ($F_{4,117} = 5.98$, $p < 0.02$). A posteriori comparisons using a Tukey HSD test indicated that the little finger was significantly smaller than the middle finger.

These analyses support the claim that the Tactile Surface Area hypothesis would predict diminishing returns from additional fingers. The little finger is significantly smaller than the other fingers. Furthermore, the order in which fingers were added was from most to least sensitive (index, middle, ring, little, thumb). Therefore, it is reasonable to expect that the later fingers (eg the little finger and thumb) would provide less benefit than earlier fingers (eg the middle finger).

Table 4. Fingertip area: fingertip area (in cm^2) as a function of finger.

	Fingertip area (cm^2)				
	thumb	index	middle	ring	little
Right hand					
Mean	3.21	3.34	3.46	3.33	2.66
SD	1.60	1.19	1.26	1.18	1.10
Left hand					
Mean	3.19	3.16	3.59	3.42	2.57
SD	1.68	1.22	1.62	1.22	1.04
Both hands					
Mean	3.20	3.25	3.53	3.38	2.61
SD	1.54	1.19	1.43	1.19	1.06

4 Discussion

We observed that using multiple fingers, on one or both hands, benefited performance in all seven of our tactile-map tasks. This contrasts to previous research that indicated a single finger was optimal for haptic perception (eg Jansson and Monaci 2003; Loomis et al 1991; Overvliet et al 2007), but agrees with several reports that also noted a benefit from multiple hands and fingers (eg Bentzen 1972; Berlá and Butterfield 1977; Klatzky et al 1993; Lappin and Foulke 1973; Lederman and Campbell 1983; Millar and Al-Attar 2004; Perkins and Gardiner 2003). In our study it was task dependent whether there was a benefit from multiple fingers, two hands, or both. This may explain some of the previous disagreement. Additionally, we found that some finger conditions (eg 1 and 2 fingers) were less different from others (eg 1 and 5 fingers). This was apparent only because we compared a large range of finger conditions, 1 through 5 fingers on the dominant hand and both one-hand and two-hand conditions.

Although a relatively large number of conditions were included in the current study, some possible finger conditions were omitted. Importantly, fingers on the nondominant hand were not finely sampled. Therefore, results are limited to perception with the dominant hand alone and both hands together. Results for the nondominant hand may be different if the two hands are differently sensitive or are different in their abilities to make coordinated finger movements. Additionally, results are specific to our choice of stimuli, and are most applicable to the perception of two-dimensional surfaces, such as tactile maps. Our findings are unlikely to generalize to other areas of haptic perception, such as recognizing patterns that fit within the size of a fingertip.

The current study focused on tasks that have been examined for multiple-finger benefits before. In previous research, proposed benefits from multiple fingers included increasing the tactile field of view, line-tracing strategies, and spatial anchors. The Tactile Surface Area hypothesis originated in an analogy between touch and vision. Raised-line drawings of common objects (eg a spoon) are very difficult to recognize by touch, but are easily recognized in visual form (Klatzky et al 1993; Loomis et al 1991). A potential explanation is that vision has higher acuity and a larger field of view than touch. Therefore, increasing the tactile field of view, by increasing the number of fingers, should improve tactile recognition of objects in raised-line drawings. This has been affirmed in some studies (eg Klatzky et al 1993) but not others (eg Loomis et al 1991).

Beyond raised-line drawings, increased tactile view would benefit searching tasks. However, not all previous work has supported this (eg comparing 1 and 3 fingers—Overvliet et al 2007). We included two searching tasks: a global search task, which asked participants to search for a landmark somewhere on the map (cluster search), and a local search task, which asked participants to search for a symbol closest to a landmark (cluster closest). Both global and local search tasks were performed faster with more fingers. Additional fingers reduced response times more on the dominant hand than the nondominant hand in global search, and with diminishing returns in local search (table 2). These patterns are only partially explained by finger acuity and surface area. We observed that later-added fingers were smaller and less sensitive, but found no difference in acuity or surface area between hands (tables 3 and 4). Therefore, tactile surface area can explain the diminishing benefit from additional fingers in the local search task, but not the decreased usefulness of fingers on the nondominant hand in the global search task. The global search result indicates that the independence of multiple hands has a significant effect on haptic exploration.

Multiple hands are also predicted to play an important function in line tracing, either by allowing the perceiver to mark a location on a line with one finger while tracing with another (Berlá and Butterfield 1977) or by allowing two fingers to start at the same location on a line and trace in opposite directions (Jansson and Monaci 2003). We examined two line-tracing tasks: deciding if a path on the map had a loop (path loop) and whether there were one or two paths on the map (path number). Both of these tasks were performed faster when two index fingers were used. Adding fingers on a single hand or on both hands provided no further benefit. This implied that, by using two-handed strategies, our participants were able to access information unavailable to a single finger. For example, to determine if a path looped, the participant would commonly start his two index fingers in one location, and move them in opposite directions. If the two fingers reunited, the path formed a loop. This strategy is similar to one described by Jansson and Monaci (2003) as “embracing”. These two-handed perceptual strategies could be considered important exploratory procedures (Lederman and Klatzky 1987) for objects containing many lines—for example, tactile graphics.

To investigate the benefit of an anchor finger, which may provide a spatial reference and thereby improve haptic perception (Millar and Al-Attar 2004), we included two spatial tasks: distance comparisons between two sets of landmarks (distance cluster), and comparing the distances of two landmarks to a lake (distance lake). If anchors benefitted these tasks, we expected a benefit from two hands. One of these tasks was benefitted by using two hands: distance lake. In contrast, both tasks were improved with additional fingers (less benefit on the second hand for distance lake). A possible explanation is that an anchor finger, used for spatial reference, could be on the same hand as an exploring finger. Alternatively, we observed many participants preferred to use two fingers to span a distance rather than tracing back and forth along the distance. The latter measures the distance using path integration, which is subject to cumulative errors (Klatzky 1998). If using multiple fingers to span a distance provides a more accurate measurement, this is evidence of a perceptual benefit attributable to multiple hands and fingers. Further research is needed to investigate this possibility.

Neither of the spatial tasks used in this study required absolute distance judgments, such as measuring the distance between map features in inches. This was a deliberate decision to avoid confusion about absolute distance scales—for example, if a participant was unfamiliar with imperial units or had poorly internalized the size of an inch. In these situations poor task performance would not be indicative of poor spatial abilities, but rather poor understanding and use of distance units. However, this means that the results of our distance-comparison tasks may not be generalizable to absolute-distance tasks. It is possible that stronger evidence of beneficial anchoring would be found with absolute distance judgments. This possibility could be a topic of future study.

Another topic warranting further exploration is the effect of skill level on multihand and multifinger haptic performance. In particular, blindfolded sighted participants are likely to have distinctly different strategies and performance characteristics than experienced haptic observers such as high-functioning blind Braille readers. Blind observers are likely to use more effective and consistent haptic strategies (Davidson 1972; Hollins 1986), and they may have more practice using multiple hands and fingers for perceiving two-dimensional tactile figures. Sighted individuals may be less aware that multiple fingers provide a benefit (Symmons and Richardson 2000), and be less practiced at coordinating hand and finger movements for tactile exploration.

Lastly, we observed that participants did worse with 4 and 5 fingers on the dominant hand than 3 when asked to move in a straight line (cluster direction). This pattern is apparent in the raw data (figure 5) and model fits (figure 6). We noticed that participants had difficulty moving in a designated direction. For example, when asked to move to the right, a participant might move their hand to the right but with an upwards 30° angle, unaware of their mistake. Possibly, adding more than 3 fingers on the dominant hand contributed to this problem. It would be interesting to know if blind participants have similar difficulties and show the same pattern of performance. Through experience with tactile materials, blind individuals may be more coordinated or have developed strategies to prevent additional fingers from interfering with straight-line movement.

In summary, we have shown that a range of perceptual tasks are performed better with two hands and more fingers, likely due to a combination of increased tactile view, two-handed line-tracing strategies, and spatial anchoring. However, these benefits are task-specific. For example, search is always improved by more fingers, but line tracing is performed best with two index fingers. Amongst the benefits of multiple hands and fingers, anchoring may be the most similar to benefits from two eyes (stereopsis) and two ears (spatial hearing). The stipulation is that anchoring provides spatial information to multiple fingers that is unavailable to a single finger.

The current study also offers theoretical understanding of the ways in which haptic and visual perception differ. Unlike vision, where the visual sensors are held contiguous on the retina, the tactile sensory area is spread across autonomous fingers. Several researchers have proposed that this puts the haptic sense at a disadvantage (eg Hollins 2000, pages 344–345), because it makes integration across the fingers computationally difficult. However, the current study illustrates that optimal haptic strategies take advantage of the fingers' independence.

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