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Effects of using multiple hands and fingers on haptic performance in individuals who are blind

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Abstract. In a previous paper we documented that sighted participants complete haptic tasks faster with two hands and multiple fingers, but that these benefits are task specific. The present study investigates whether these effects are the same for participants who are blind. We compared the performance of fourteen blind participants on seven tactile-map tasks using seven finger conditions. As with sighted participants, blind participants performed all tasks faster with multiple fingers. Line-tracing tasks were faster with fingers added to an already in-use hand, and sometimes when added to the second hand. Local and global search tasks were faster with multiple fingers and two hands. Distance comparison tasks were performed faster with multiple fingers, but not two hands. Lastly, moving in a straight line was faster with multiple fingers. These results reinforce our previous finding that the haptic system performs best when it can exploit the independence of multiple fingers. Furthermore, in every instance that an effect was different between sighted and blind participants, the blind participants benefitted more from two hands or multiple fingers than the sighted participants. This indicates that the blind participants have learned, through experience or training, how to best take advantage of multiple fingers during haptic tasks.

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

1 Introduction

In a previous paper we addressed the issue of whether using two hands and multiple fingers provide any perceptual advantage over a single index finger (Morash, Connell Pensky, & Miele, 2013). This topic had been examined before (eg Klatzky, Loomis, Lederman, Wake, & Fujita, 1993; Lappin & Foulke, 1973; Loomis, Klatzky, & Lederman, 1993; Overvliet, Smeets, & Brenner, 2010) but never with as many finger conditions (seven) or as many tasks (seven) as we used. We found that it was always beneficial to use more than a single index finger, but the specific benefits were task dependent. For example, when searching for a landmark on a tactile map, adding a finger reduced the time to find the target, with each additional finger providing a smaller benefit. There was no special benefit gained by using two hands, as the search times using both index fingers (on different hands) were equal to, or slower than, using the index and middle finger on only the right hand. This contrasted to line-tracing tasks, where the only significant benefit from multiple fingers was in allowing for multiple hands. Going from one to two hands significantly reduced task-completion time, but adding fingers to an already in-use hand provided no benefit. Distance comparison tasks were also faster with multiple fingers, and sometimes two hands. Lastly, moving in a straight line was faster with multiple fingers, but particularly slow when using both index fingers.

These previous results were found with blindfolded sighted participants. The purpose of the current study is to examine the performance of individuals who are blind, to see if the same results hold. Individuals who are blind and sighted differ in how many fingers/hands they prefer to use during haptic exploration. Therefore, haptic performance may differ between

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individuals who are sighted and blind, especially with regards to the effect of multiple hands and fingers on haptic exploration. Previous studies have demonstrated that participants who are blind prefer to use two hands and multiple fingers, whereas sighted participants will often elect to use one hand and only one or two fingers (Davidson, 1972; Rovira, Deschamps, & Baena-Gomez, 2011; Symmons and Richardson, 2000). Participants who are blind will often, coincidentally, perform with higher accuracy or faster speed than sighted participants at haptic tasks (Davidson, 1972; Heller, 1989; Rovira et al., 2011). This may be because blind participants prefer to use particularly effective multihand/finger strategies.

For example, Davidson (1972) asked participants, sighted and blind, to determine whether a ruler-sized stimulus was bent to be convex, concave, or straight. Participants who were blind made fewer errors and tended to grip the stimulus with four fingers, while the sighted participants were more likely to pinch or sweep the top of the stimulus with one or two fingers. When sighted participants were instructed to grip the stimulus like the blind participants, their curvature judgments were better than when using the sighted strategies of pinching and sweeping.

However, not only sighted participants, but also participants who are blind, may fail to use the most effective multihand/finger strategies. For example, Berlá, Butterfield, and Murr (1976) found that some blind adolescents performed better at identifying raised-line outlines of states and countries on a map than others. The successful participants used line-tracing strategies that ensured the outline of the state or country was completely traced, whereas unsuccessful participants would often stop a tracing too early or late. In a later study the authors trained a new group of blind adolescents to trace the raised-line outlines by placing their nondominant index finger on the line as a reference (Berlá & Butterfield, 1977). The dominant index finger began and ended tracing from this location, ensuring that the entire shape was covered exactly once. This strategy led to significantly better performance in the trained participants than in a group of untrained participants (groups were chosen to have similar initial performance). The findings of these previous reports suggest that successful haptic strategies, using multiple fingers and two hands, may not be spontaneously elected in sighted and, sometimes, blind participants. Therefore, effective haptic strategies may be learned through a considerable period, likely many years of intensive tactile-media experience, or only through explicit training.

Therefore, it is possible that participants who are blind, through their long-term experience with tactile media, and explicit training using these media in orientation and mobility interventions, have acquired different haptic strategies than normally sighted individuals. If the most effective strategies involve multiple fingers and two hands, there may be differences between multihand/finger benefits for sighted and blind individuals. The current study investigates this possibility by repeating the procedure used in Morash et al. (2013) with a group of participants who are blind.

This research uses tactile maps as stimuli. Therefore, results from the current study are immediately relevant to the design and use of tactile maps for people with visual impairments. As with sighted people using visual maps, blind individuals can effectively use tactile maps for gaining spatial knowledge (Perkins & Gardiner, 2003), and the spatial image gained from a tactile map may be functionally equivalent to that from a conventional visual map (Giudice, Betty, & Loomis, 2011). Exploring the tactile map of an unknown environment can provide equivalent or better information on the spatial layout of an environment to a blind user than directly exploring the environment (Bentzen, 1972; Blades, Ungar, & Spencer, 1999; Espinosa, Ungar, Ochaíta, Blades, & Spencer, 1998; Ungar, 2000). However, efficacy of tactile-map use is affected by the hand-movement strategies that the explorer employs (Berlá & Butterfield, 1977; Blades, Ungar, & Spencer, 1999). The current study addresses the issue of multihand/finger strategies.

In total, participants perform seven tasks with the tactile-map stimuli, which cover a large range of haptic activities possible on a tactile display. These include two line-tracing tasks, which ask participants to determine the number of lines, and whether any line on the map contains a loop. There is also a global search task, to locate a target somewhere on the display, and a local search task, to locate a target closest to a landmark. There is also a straight-line movement task, and two distance comparison tasks.

2 Materials and methods

The methods used in the current study were identical to those used in Morash et al. (2013). The only differences were that the current study used participants who were blind, and used R for statistical analyses (The R Foundation for Statistical Computing, Vienna, Austria). The protocol was approved by the Smith-Kettlewell Eye Research Institute's Institutional Review Board, and informed consent was obtained from all participants prior to their participation.

2.1 *Participants*

Fourteen blind adults were recruited for participation. All participants could read contracted (grade 2) braille and were right handed. Given that braille is typically read with two hands, participants self-reported handedness based on which hand they preferred to use when eating or throwing a ball. The average age was 44.6 years (SD = 18.2 years), with the average age of blindness onset being 1.6 years (SD = 3.0 years). None of the participants found their residual vision, if they had any, useful for navigation or reading tactile maps. Participant information is shown in table 1.

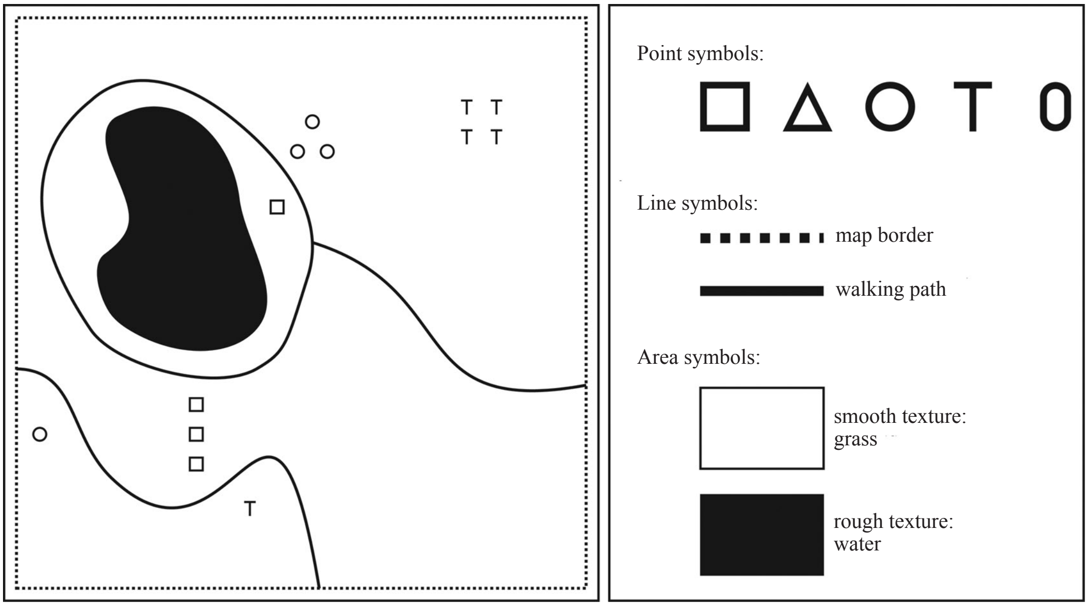
Table 1. Participant information. Light perception indicates whether the participant could detect light and, additionally, determine light direction. Form perception refers to the participant's ability to detect large forms, such as buildings.

Participant	Age/ years	Gender	Age of onset	Light perception	Form perception	Formal map training	Regularly use tactile maps
1	22	F	0	direction	–	yes	–
2	57	M	0	direction	–	yes	–
3	65	M	3 months	yes	–	–	–
4	66	M	0	–	–	–	–
5	27	F	0	–	–	yes	–
6	37	F	0	direction	large forms	yes	–
7	48	M	0	direction	–	–	yes
8	22	M	3 years	–	–	yes	yes
9	35	F	13 months	–	–	yes	yes
10	36	M	8 years	–	–	yes	–
11	34	F	9 years	–	–	–	–
12	65	M	10 months	–	–	yes	–
13	34	F	0	–	–	yes	–
14	77	F	0	–	–	–	–

Note: F = female; M = male.

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 maps were from the Tactile Map Open Stimulus Set (Morash, Connell Pensky, & Miele, 2012a, 2012b). Each map was 12 in by 12 in in size, and manufactured from clear acrylic. These maps represented fictitious parks, and contained point symbols—circles, squares, ovals, Ts, and triangles—to represent the locations of features, such as trash cans and picnic benches. Solid lines on the maps represented walking paths, and a large textured area on each map represented a lake. All maps were surrounded by a dotted line, 0.25 in from the map edge, to indicate the map border. On every map there were three clusters of symbols, configured as a square, diamond, vertical line, horizontal line, or triangle-shaped arrangement of a single symbol type—for example, a square-shaped cluster of Ts. These clusters served as landmarks that could be unambiguously referenced. Further details on the map symbols, sizes, textures, and other quantities can be found in Morash et al. (2012a, 2012b, 2013). An example map stimulus is shown in figure 1.



(a) (b)

Figure 1. Example stimulus, replicated from Morash et al. (2013). (a) Example layout of a tactile-map stimulus shown from a top-down view (25% scale). Each map depicted a fictitious park, and was sized 12 in by 12 in. (b) Map symbol key (100% scale).

Seven groups of eight maps were designed so that question parameters were the same for each map group. The map groups were pseudorandomly assigned to finger conditions for each participant, ensuring that no map group was consistently assigned to a particular condition. Maps were presented to the participants in a randomized block design, where every block of seven maps contained a representative from each condition, and orders were otherwise random.

2.3 *Conditions*

There were seven finger conditions: 1 through 5 fingers on the dominant (right) hand, 2 index fingers, and all 10 fingers. When the left hand was not in use, the participant rested the hand in his or her lap. When fingers were not used on an in-use hand, the unused fingers were curled and bound to the palm with medical tape.

2.4 *Tasks*

Participants completed several tasks for each of the 56 maps (delivered in randomized order as described in section 2.2). Each task had 1–3 questions associated with it per map, a total of 13–15 questions per map, and 784 questions per participant. Within a question, map features were referred to as ‘paths’, ‘lakes’, ‘circles’, ‘squares’, etc. The question order for each map was chosen so that questions did not interfere with each other, but was otherwise random.

For example, a participant would be asked to find a cluster of squares before being asked what symbol was closest to that cluster of squares. The tasks for each map were as follows.

2.4.1 *Tasks 1 and 2: path loop and path number.* The first and second tasks for each map were "Is there a path with a closed loop?" and "Are there one or two paths?"

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 squares and say 'here'"), 2–3 direction questions (eg "From this cluster of squares, which symbol is directly to the right?"), and 2–3 closest questions (eg "From this cluster of squares, which symbol is closest?"). These were grouped so that all of the questions relating to a particular cluster were asked together. In total, 24 cluster search, 20 direction, and 20 closest questions were asked for each finger condition per participant.

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 clusters on a map (eg "Which is closer to the cluster of squares, the cluster of Ts or the cluster of ovals?"), followed by 2 questions about the proximity of symbol clusters to the lake edge (eg "Which is closer to the lake edge, the cluster of Ts or the cluster of ovals?").

2.5 *Procedure*

The procedure had three parts: training, the main experiment, and measuring two-point threshold.

2.5.1 *Training.* The training procedure ensured that participants could discriminate and recognize symbols and symbol clusters, and that they were generally familiar with the tactile-map stimuli and the types of questions they would be asked. Each participant was randomly assigned a finger condition for training. First, the participants were familiarized with the symbols and symbol clusters, and had to successfully recognize and name each symbol and cluster shape before continuing. Second, the participants were allowed to explore three training maps, similar to those used in the main experiment. With the first map, the participants were allowed to freely explore the map, and discussed the different map features with the experimenter. The participant was also given examples of each question. With the second and third maps, the participants were asked questions identical to those in the main experiment, and instructed not to move their hands until hearing a beep, which indicated the end of the question. The participants were also instructed how to answer in a stereotyped manner—for example, "here" instead of "it's here". On both the second and third training maps, the participants were asked one or more question from each task. All training examples/questions were the same for each participant, and delivered from a predecided script. Every participant demonstrated with these training maps that he or she could successfully parse the tactile maps and answer questions in this format, did not require further training, and was allowed to move on to the main experiment. The training procedure was the same as that used in Morash et al. (2013), and the blind participants had no difficulties in completing the training.

2.5.2 *Main experiment.* The main experiment took 12–15 hours to complete per participant, which was spread across multiple days: typically 2–3 hours per day for 4–6 days. Participants were seated at a clear table, above which a microphone recorded voice responses, and below which a video camera pointed upwards to record participant hand movements (figure 2). The experimenter sat to the side of the participant, and pushed a button to proceed to the next question in the experiment. Then, the computer played an audio file that asked the participant to place his or her index finger(s) at the bottom middle of the map for most tasks (ie path loop, path number, cluster search, distance cluster, and distance lake questions), or on the relevant cluster for the upcoming question (ie cluster direction and cluster closest questions).

Once the experimenter had confirmed that the participant had done this correctly, another button was pushed to play the question through the computer, after which a beep played to signal the participant to begin exploring the map and answer the question. The computer began collecting video and audio data coincident with the beep. Once the participant had answered, the experimenter stopped the audio and video recordings, and moved on to the next question.

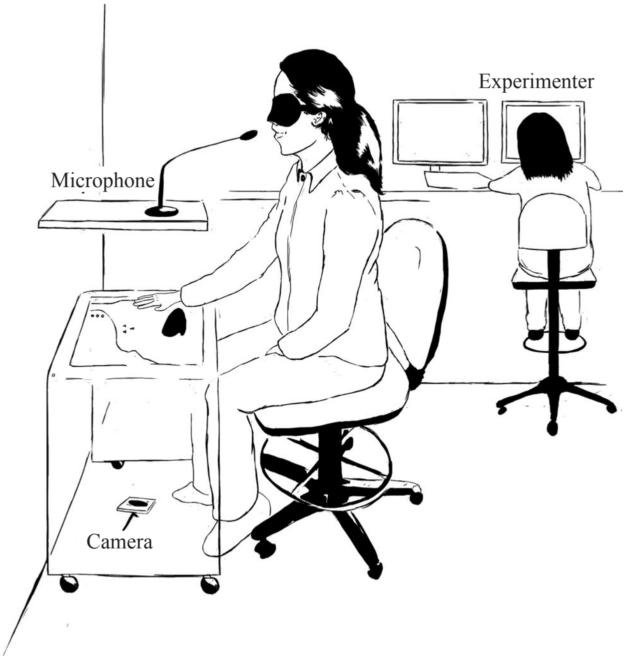


Figure 2. Experimental setup, replicated from Morash et al. (2013). The participant was seated at a custom-made clear table, was blindfolded, and had unused fingers taped to his or her palm. The map stimulus (made of clear acrylic) was placed on top of the table, and viewed from below by a video camera. 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).

2.5.3 *Two-point threshold measurement.* After the main experiment had completed, we measured the two-point threshold of the participants' ten fingers. The participants reported normal tactile sensitivity prior to their participation, which was confirmed with the two-point threshold measurements. The blind participants' two-point thresholds were also collected to see if the patterns of sensitivity (ie which fingers were more sensitive than others) were the same as for sighted participants. Two-point threshold was measured with the device and procedure described in Morash et al. (2013), which was a mechanized implementation of a forced-choice adaptive method, a 'two-up, one-down' staircase with 0.25 mm step size, used by Stevens (1992). In the previous report with sighted participants we did not observe any difference in thresholds before and after the experiment (Morash et al., 2013), so we measured the blind participants' thresholds only once, at the end of their participation. We decided to measure two-point thresholds after, rather than before, the main experiment to keep participants interested in the study and avoid participant withdrawal. Measuring two-point thresholds required 5 minutes per finger, 50 minutes total, and was quite tedious.

2.6 *Analysis*

Data processing and handling were done in Matlab (The MathWorks, Inc., Natick, MA), and all statistical analyses were done in R.

2.6.1 *Relating task performance to finger condition.* Analysis was composed of two stages. In the first stage trials were categorized based on whether they were answered from memory (without touching the map) or after map exploration. These touch/no-touch data were related to finger condition using a Kruskal–Wallis test, a nonparametric version of the one-way ANOVA, with the one factor being finger condition (conditions 1–7). A finger condition would be associated with answering from memory when that finger condition provided a good mental representation of the map, or because explorations using that finger condition provided opportunity to learn the answer to later questions. Trials in which the participant asked for a question to be replayed after touching the map (ie the participant forgot the question) were excluded from analysis.

The second stage of analysis examined the response times of questions answered with exploration, not from memory. Questions answered from memory had uniform and low response times. As with sighted participants, blind participants were near 100% accurate on all tasks and conditions (table 2), so no fruitful analysis could be done with the accuracy data. Had the participants been given a time limit for responding, there may have been more inaccurate trials. Therefore, the response-time data were used to relate task performance to finger condition.

Table 2. 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	780/784	97.83 (1.51)	0	0	0	0	0	0	0
Path number	621/784	96.53 (1.32)	8	7	8	13	9	10	5
Cluster search	2350/2352	100.00 (0.00)	0	0	0	0	0	0	0
Cluster direction	1956/1960	96.12 (0.51)	0	0	0	0	0	0	0
Cluster closest	1954/1960	94.53 (0.95)	0	0	0	0	0	0	0
Distance cluster	1557/1568	95.16 (0.77)	1	0	0	2	2	2	0
Distance lake	1566/1568	98.15 (0.63)	0	0	0	0	0	0	0

2.6.2 *Extraction of response times from audio recordings.* Voice recordings were processed in Matlab. These were first enhanced, using minimum-mean square error spectral amplitude estimation (Brookes, 2006). Then, spurious noises, such as lip smacking and frustration utterances, were manually removed from the recordings. Using what remained, the first instance of the signal surpassing 5% maximum amplitude was taken as the response time. This was the same procedure as that used in Morash et al. (2013).

2.6.3 *Relating participant age to mean response times.* The blind participants in the current study had a relatively large range of ages, from 22 to 77 years old. Previous work with blindfolded sighted participants revealed an age-related decline in haptic picture naming (Overvliet, Wagemans, & Krampe, 2013). To examine whether age influenced response times in the current study, we computed the Pearson correlation between participants' age and mean response time for each task.

2.6.4 *Modeling.* The response-time measurements were related to finger conditions using generalized linear models. These models allowed response times to follow a gamma distribution, which more accurately captures the nonnegativity and positive skew of response times than a normal distribution (Baayen & Milin, 2010; Haaijer, Kamakura, & Wedel, 2000;

Jansen, 1997; Maris, 1993; Palmer, Horowitz, Torralba, & Wolfe, 2011). Response times that were larger (slower) had larger variances than those that were shorter (faster). This yoking between mean and variance is a feature of the gamma distribution. It is also the reason why we display only data averaged across participants following mean normalization, so that slow participants with large variances do not dominate apparent trends. A log-link was used in the models, which restricted predicted response times to be positive. The log-link also resulted in multiplicative, rather than additive, effects in the models.

The model for each task was of the following form:

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

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 task—for example, distances, direction indicators, and answer indicators—and ε captures the random error. Effects related to specific tasks are detailed in the appendix. This model differs from a conventional general linear model in only the log-link, the logarithm on the left side of the equation, and in allowing Y_{pt} to follow a gamma distribution. It is easier to interpret this model exponentiated, so that effects are relative to response times rather than log response times. Therefore, we report effects in exponentiated format, which are multiplicative. For example, if $\exp(\hat{f}) = 0.80$—that is, the exponentiated estimate of the effect of number of fingers equals 0.80—adding an extra finger multiplies response time by 0.80 (ie it reduces response time by 20%).

Including the covariates A–Z was important for statistical reasons: first, to guard against specification error and, second, in an effort to ensure that data missingness (due to incorrect trials) was missing at random (MAR). Models were estimated using maximum likelihood estimation (MLE), which, because data were missing on only the dependent variable, could produce unbiased estimates using complete case analysis (listwise deletion) under the assumption of MAR (Allison, 2012).

Two models were compared for each task. The first model included the variables: number of fingers (f), number of hands (h), and the interaction (fh). The second model included an additional variable, number of fingers squared (f^2). This quadratic-finger model would fit the data better if there was a diminishing benefit from additional fingers, which might be expected given that the later-added fingers—for example, the little finger—were smaller and less sensitive (confirmed with two-point threshold measurements). The linear-finger and quadratic-finger models were compared using a likelihood-ratio test (Fox, 2008, pages 385–387; Gill, 2001, page 64).

2.6.5 *Comparing blind and sighted results.* The number of answers from memory by blind participants in the current study, and sighted participants in the previous study (Morash et al., 2013), were compared for each task using χ^2 tests of independence. Blind and sighted participants' mean response times were compared using unequal variance *t*-tests (Welch's *t*-test).

To examine whether estimated effects (model results) were significantly different for participants who were sighted and blind, we used a single model that included both sighted and blind data (combined-data models) for each task. These combined-data models were distinct from the previously described models, which contained data from either sighted participants or blind participants, but not both. Reported effects are from the models that contained either sighted or blind data, and the combined-data models were used to only determine significant differences between these effects. A quadratic-finger term was included in a combined-data model if either sighted or blind data preferred a quadratic-finger model over a linear-finger model. A dummy variable was introduced that indicated whether each datum belonged to a participant who was blind, and interacted with all variables (except intercepts). Significant interactions indicated different effects for sighted and blind participants.

Two-point thresholds for sighted and blind participants were compared using an ANOVA, with factors for visual status (blind or sighted), hand (right or left), and finger (thumb, index, middle, ring, or little). Sighted participants' two measurements per finger (before and after the main experiment) were averaged for comparison with the blind participants' one measurement per finger.

3 Results

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

The number of retained trials, accuracy, and number of questions answered from memory are shown in table 2. Only two questions had any answering from memory: path number and distance cluster. However, the distribution of answering from memory across finger conditions for these questions was not significantly different from chance, demonstrated by Kruskal–Wallis tests (path number $H_6 = 6.0$, $p = 0.42$; distance cluster $H_6 = 6.0$, $p = 0.42$).

3.2 *Relating response times to participant ages and finger conditions*

The average of blind participants' mean response times, across finger conditions and other parameters, were: path loop $M = 12.86$ s (min = 7.91 s, max = 26.64 s, SE = 1.37 s), path number $M = 8.89$ s (min = 4.69 s, max = 20.75 s, SE = 1.15 s), cluster search $M = 6.48$ s (min = 3.96 s, max = 9.44 s, SE = 0.41 s), cluster direction $M = 5.43$ s (min = 2.65 s, max = 11.56 s, SE = 0.67 s), cluster closest $M = 8.66$ s (min = 4.76 s, max = 15.85 s, SE = 0.74 s), distance cluster $M = 12.07$ s (min = 7.14 s, max = 23.34 s, SE = 1.18 s), and distance lake $M = 10.04$ s (min = 6.42 s, max = 16.63 s, SE = 0.79 s). Blind participants took, on average, between 3 s and 13 s to answer each question. The response times across participants for each task, normalized by dividing response times by the participant's average response time on the task, are shown in figure 3.

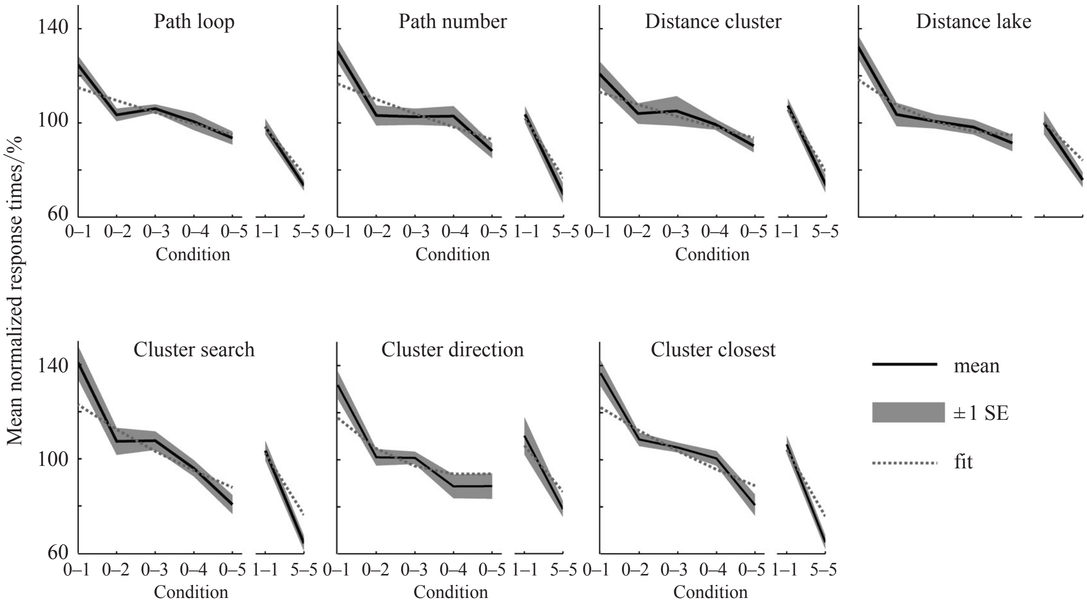


Figure 3. Mean-normalized response times. Average participant response times across conditions (left hand fingers–right hand fingers) for each task. These data are from blind participants in the current study only. Data were normalized by dividing individual response times by the participant's average response time for the task. Also shown are the fits from the models (table 3), omitting effects except those related to number of hands and fingers. Cluster direction and distance lake are the only tasks fit with quadratic trends.

We calculated the correlation between blind participants' age and mean response time for each task. There was not a significant correlation in any task: path loop ($r = 0.07$, $p = 0.780$), path number ($r = -0.08$, $p = 0.804$), search ($r = 0.24$, $p = 0.399$), cluster direction ($r = -0.26$, $p = 0.362$), cluster closest ($r = -0.07$, $p = 0.823$), distance cluster ($r = 0.36$, $p = 0.212$), and distance lake ($r = 0.29$, $p = 0.314$).

Model estimates related to multiple hands and fingers are shown in table 3 (only those for the preferred model, linear-finger model or quadratic-finger model). Predicted response times for each task (model fits), demonstrating the effects of multiple hands and fingers separate from the effects of participant differences and map parameters, are included along with the observed data in figure 3.

Table 3. Model estimates. Exponentiated model estimates (and standard errors) for response time models. Effects are multiplicative: a value of 0.83 is interpreted as a 0.83 multiplication of response time per 1 unit covariate increase. Also shown are 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. A significant difference in estimates between sighted and blind data is indicated with ‡; however, all estimates and other statistics are from blind data only.

	Exponentiated estimated effects (exponentiated SEs)			
Task $F_{\text{quadratic}}$, ΔD, φ, k	number of hands	number of fingers	number of hands × number of fingers	(number of fingers)^2
Path loop	0.83 (1.06)**	0.94 (1.01)*** ‡‡	1.02 (1.01)	
$F_{\text{quadratic}} = 1.07$, $\Delta D = 125.38^{\dagger\dagger}$, $\varphi = 0.12$, $k = 22$				
Path number	0.86 (1.09)	0.93 (1.02)***	1.02 (1.02)	
$F_{\text{quadratic}} = 0.32$, $\Delta D = 150.11^{\dagger\dagger}$, $\varphi = 0.21$, $k = 21$				
Cluster search	0.76 (1.07)*** ‡	0.88 (1.01)***	1.07 (1.01)***	
$F_{\text{quadratic}} = 0.62$, $\Delta D = 402.48^{\dagger\dagger}$, $\varphi = 0.60$, $k = 28$				
Cluster direction	1.34 (1.17)	0.76 (1.07)*** ‡	0.87 (1.07)	1.03 (1.01)*
$F_{\text{quadratic}} = 7.58^{\dagger}$, $\Delta D^{\dagger\dagger} = 631.06^{\dagger\dagger}$, $\varphi = 0.48$, $k = 37$				
Cluster closest	0.81 (1.06)*** ‡	0.89 (1.01)***	1.06 (1.01)***	
$F_{\text{quadratic}} = 0.47$, $\Delta D = 403.79^{\dagger\dagger}$, $\varphi = 0.32$, $k = 35$				
Distance cluster	0.95 (1.07)	0.94 (1.01)***	1.01 (1.01)	
$F_{\text{quadratic}} = 0.10$, $\Delta D = 292.41^{\dagger\dagger}$, $\varphi = 0.33$, $k = 47$				
Distance lake	1.03 (1.14)	0.82 (1.06)***	0.93 (1.06)	1.02 (1.01)*
$F_{\text{quadratic}} = 4.05$, $\Delta D = 193.43^{\dagger\dagger}$, $\varphi = 0.29$, $k = 44$				

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.
‡ $p < 0.05$; ‡‡ $p < 0.01$, comparing effect values for sighted and blind data.
† $F_{\text{quadratic}} > F(1, \text{df}_{\text{quadratic}}) \approx 3.85$, comparing linear and quadratic model.
†† $\Delta D / \varphi > F(k-1, \text{df})$, comparing selected and intercept-only models.

3.3 *Tactile acuity*

No blind participant had unusually high two-point thresholds, so we were not worried that any of the participants had reduced sensitivity on their fingers due to injury or disease. In fact, even though many of our participants were middle-aged (41–63 years old) or elderly (66–91 years old), all two-point thresholds were within nonoutlier range ($M \pm 3\text{SD}$) of Stevens's *young* participants (18–33 years old). The largest two-point threshold was 3.85 mm, belonging to the thumb of P6. This was not unexpected, given that heightened tactile sensitivity of the fingertips among blind individuals is well documented (eg Stevens, Foulke, & Patterson, 1996).

We conducted a repeated-measures ANOVA with Greenhouse–Geisser correction on the two-point thresholds, for the variables of finger (thumb, index, middle, ring, or little) and hand (right or left), including the interaction. The main effect of hand ($F_{1,13} = 2.78, p = 0.119$) was not significant; nor was the interaction between finger and hand ($F_{4,52} = 0.62$, $p = 0.650$). However, a main effect of finger was significant ($F_{4,52} = 13.32$, $p = 0.002$). Average two-point thresholds, collapsed across hands, are shown in table 4. A posteriori comparisons using a Tukey HSD test indicated significant mean differences between index and little fingers ($q = 3.60, p = 0.003$), index and ring fingers ($q = 3.11, p = 0.016$), index finger and thumb ($q = 3.50, p = 0.004$), middle and little fingers ($q = 3.12, p = 0.016$), and middle finger and thumb ($q = 3.02, p = 0.020$).

Table 4. Finger acuity for blind participants. Two-point threshold (in mm) as a function of finger, averaged over hands.

	Two-point threshold/mm				
	thumb	index	middle	ring	little
Mean	1.92	1.48	1.56	1.92	1.96
SD	0.68	0.53	0.63	0.78	0.48

On the basis of the two-point thresholds, the blind participants in the current study showed a similar sensitivity pattern to the previously tested sighted participants (Morash et al., 2013). For both sighted and blind participants, fingers were ordered most to least sensitive—index, middle, ring, little, and thumb—and there were no significant differences in sensitivity between ring, little, and thumb fingers (the least sensitive fingers). Therefore, fingers were added across finger conditions from most to least sensitive.

3.4 *Comparing blind and sighted results*

With regards to answering from memory, both sighted and blind participants had the greatest number of answers from memory for the path number and distance cluster questions (Morash et al., 2013). However, the amount of answering from memory was larger for the sighted participants: for path number 355 versus 60 and for distance cluster 229 versus 7, for sighted and blind, respectively. Sighted participants also had some answering from memory on other questions, on which blind participants had no answering from memory: 2 for cluster direction, 1 for cluster closest, and 23 for distance lake questions. On the basis of χ^2 tests of independence, sighted participants answered significantly more from memory on three questions (no significant difference on the other questions, $p > 0.05$, which had no or almost no answering from memory), path number ($p < 0.001$), distance cluster ($p < 0.001$), and distance lake questions ($p < 0.001$).

The current study's blind participants had significantly faster mean response times than previously tested sighted participants (Morash et al., 2013) in all tasks except for distance cluster. The average of sighted 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). Differences were determined using unequal variance *t*-tests (Welch's *t*-test with Welch correction for degrees of freedom): path loop ($t_{23.71} = 3.17$, $p = 0.004$), path number ($t_{23.26} = 2.67$, $p = 0.014$), cluster search ($t_{19.37} = 4.63$, $p < 0.001$), cluster direction ($t_{24.56} = 2.40$, $p = 0.024$), cluster closest ($t_{17.02} = 3.59$, $p = 0.002$), distance cluster ($t_{22.45} = 1.66$, $p = 0.111$), and distance lake ($t_{18.79} = 2.78$, $p = 0.012$).

To examine whether estimated effects from the models were significantly different for participants who were sighted and blind, we used a single model for each task, with both sighted and blind data; and a dummy variable that indicated if the participant was blind or sighted interacted with all predictor variables. Significant interactions were found for path loop number of fingers ($p = 0.001$), cluster search number of hands ($p = 0.027$), cluster direction number of fingers ($p = 0.019$), and cluster closest number of hands ($p = 0.025$), indicating that these effects had significantly different values for participants who were sighted and blind. The model estimates related to number of hands and fingers are depicted graphically in figure 4. This forest plot (confidence interval plot) shows the estimated effects from the separate models that contained either sighted or blind data (not both). Significant differences between the estimated effects are boxed, and were determined using a combined-data model that contained both sighted and blind data.

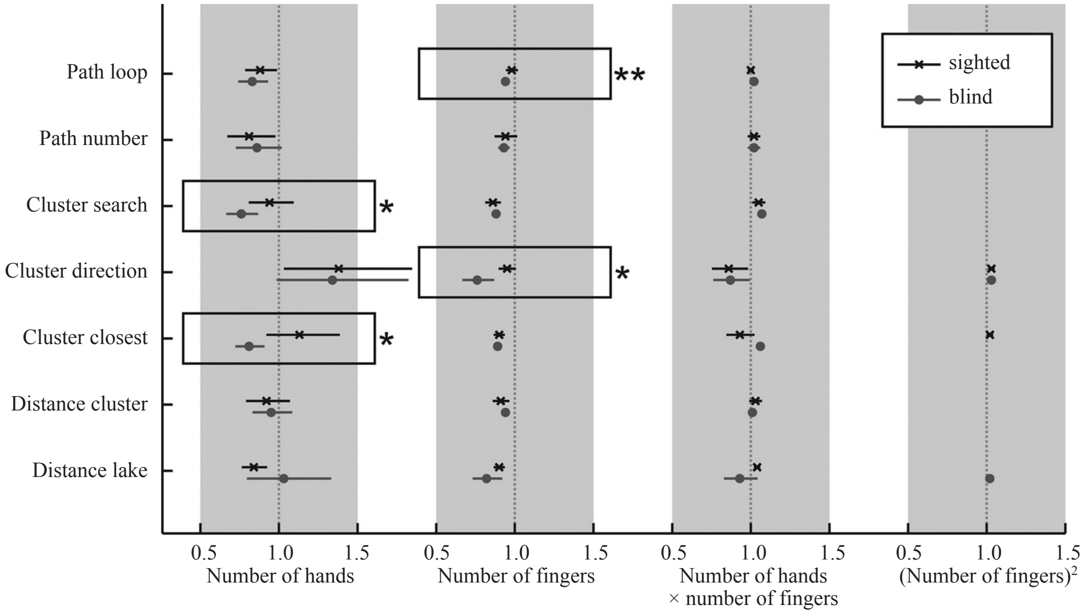


Figure 4. Model estimates. Exponentiated response-time model estimates for sighted and blind participants with 95% confidence intervals. These effects were estimated in separate models for sighted and blind data. Effects are multiplicative: a value of 1 indicates no effect, <1 indicates a reduction in response time, and >1 indicates an increase in response time. Significant differences in effects between sighted and blind participants are boxed (* $p < 0.05$; ** $p < 0.01$). Significant differences between effects were determined in combined-data models, which contained data from both sighted and blind participants.

An ANOVA on two-point thresholds, with factors for visual status (blind or sighted), hand (right or left), and finger (thumb, index, middle, ring, or thumb) found no significant effect of visual status ($F_{1,26} = 0.02$, $p = 0.932$). Given that tactile acuity is known to decline with age for sighted, but not blind, individuals (Legge, Madison, Vaughn, Cheong, & Miller, 2008), it is likely that the blind participants would have had significantly better tactile acuity than the sighted participants had they been matched on age and the sighted participants were older.

4 Discussion

The current study demonstrates that blind participants perform haptic tasks faster when using two hands and multiple fingers. Blind participants had significantly lower response times when determining whether a path on a map contained a loop (path loop) with two hands and more fingers. They were also significantly faster at determining if there were one or two paths on a map (path number) with more fingers. Global search (cluster search) and local search (cluster closest) were significantly faster with two hands and more fingers, although fingers added to the left hand were less beneficial. Straight-line movement (cluster direction) was significantly faster with more fingers, with a diminishing benefit from each additional finger. Lastly, distance comparison tasks (distance cluster and distance lake) were significantly faster with more fingers, with a diminishing benefit from each additional finger for distance lake. These results are limited to perception with the dominant hand alone and both hands together, given that fingers on the nondominant hand were not finely sampled. 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.

It is interesting to note that the benefits of using multiple hands and fingers were seemingly apparent to blind participants from the beginning of their participation. It was not uncommon for participants to complain about low-finger or one-handed trials, especially the single-index-finger trials. Participants would complain that these trials inhibited their ability to feel the stimulus, were not enjoyable, took too long, or were difficult. The experimenter was careful to never affirm or deny any of the participants' statements regarding task difficulty, to avoid affecting the experimental results. In our previous study (Morash et al., 2013) sighted participants did not produce such complaints early in the experiment. This is consistent with the finding that untrained blindfolded sighted participants prefer to use a single index finger when exploring a tactile graphic (Symmons & Richardson, 2000). However, once they had participated for several hours, the sighted participants would begin to generate such complaints.

The current blind participants had benefits from two hands and multiple fingers that were largely the same as those documented previously with sighted participants (Morash et al., 2013); however, blind participants were overall faster and had additional benefits from multiple hands or fingers in some specific instances. One explanation for differences between the current study's blind participants and prior study's sighted participants is that the blind participants were older than the sighted participants. Although age-related declines have been observed in sighted participants tasked with naming objects in raised-line drawings (Overvliet et al., 2013), we did not observe a relationship between participants' ages and mean response times for any task. Also, the blind participants were overall faster, not slower, than the younger sighted participants. It is possible that blind individuals' continued practice and expertise with tactile materials reduced or prevented any age-related decline. This is consistent with research suggesting that sighted experts at fine motor skills, such as typewriting or piano playing, show little or no age-related decline in these abilities (for a review see Krampe, 2002). This is also consistent with results that sighted individuals show an age-related decline in tactile acuity, but blind individuals maintain high tactile acuity into old age (Legge et al., 2008).

We were initially surprised that the blind participants in the current study answered fewer questions from memory than the sighted participants in our previous study (Morash et al., 2013). Given that other reports show that blind individuals perform better at short-term and working memory tasks than sighted individuals (eg Catteneo & Vecchi, 2011; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013), one might expect more answering from memory by blind participants. In contrast, blind answering from memory was significantly less than sighted answering from memory for path number questions (45% answers from memory versus 8%), distance cluster questions (15% versus less than 1%), and distance lake questions

(2% versus 0%), while other questions had virtually no answering from memory from either sighted or blind participants. However, this is not necessarily evidence of poorer memory in blind individuals, but could alternately be explained by blind participants answering questions faster than sighted participants, possibly due to more effective exploration strategies. Sighted participants took, on average, 8–20 s to answer a question, while blind participants took, on average, 3–13 s to answer a question (omitting answers from memory). The shorter time it took for blind participants to execute haptic exploration and answer questions may have reduced the opportunity, and need, to memorize map information that could be useful for a later question.

In terms of the benefits from two hands and multiple fingers (table 3 and figure 4 in this report; table 2 in Morash et al., 2013), these benefits were not significantly different in sighted and blind participants for path number, distance cluster, and distance lake questions. The lack of significant difference in path number is surprising, given that sighted participants had a significant benefit from multiple hands, whereas blind participants had a significant benefit from multiple fingers. However, these models had a considerable amount of missing data due to answering from memory (45% sighted, 8% blind). Therefore, the path loop results may be more appropriate for establishing blind–sighted differences on line-tracing tasks.

Distance cluster and distance lake questions also showed no significant differences in multihand/finger benefits between sighted and blind participants. Distance cluster models indicated a significant reduction in response times with additional fingers, but not two hands, for both sighted and blind participants. In contrast, distance lake models indicated a significant reduction in response times with multiple fingers and two hands for sighted participants, but only with multiple fingers for blind participants. However, this difference between sighted and blind participants on the distance lake task was not validated by a model with combined sighted and blind data. Perhaps benefits from two hands were present for some, but not all, blind participants, which could also explain the relatively large standard error associated with the number-of-hands effect in the distance lake model for blind participants (table 3 and figure 4). Such individual differences could be the topic of future research.

The apparent equivalency in multihand/finger benefits in distance-comparison models for participants who were sighted and blind suggests that these groups of participants used similar strategies to complete distance comparison tasks. The most effective strategies, for both sighted and blind participants, involved two hands and multiple fingers. We had previously proposed that sighted participants may have spanned distances with two index fingers, or a thumb and index finger, which would provide a more accurate measure of distance than moving a single finger, back and forth, along the distance (Morash et al., 2013). The latter relies on path integration, which is known to suffer from cumulative errors (Klatzky, 1998). Therefore, our results indicate that both sighted and blind participants use effective multihand/finger strategies to compare distances, possibly spanning the distances with multiple fingers, and these strategies do not rely on extensive haptic-media experience or explicit training (of which, the sighted participants had none). However, these strategies may be honed with experience, as blind participants were overall faster than the sighted participants on the distance lake task.

On the remaining tasks, we observed differences in multihand/finger benefits for sighted and blind participants. On path loop questions, sighted participants were benefitted by two hands but not multiple fingers (Morash et al., 2013), whereas both two hands and multiple fingers benefited the blind participants. This difference in number-of-fingers effects was confirmed by a model with combined sighted and blind data (table 3 and figure 4). In our previous report we proposed that the benefit provided by two hands to the sighted participants was due to divergent line-tracing strategies (Morash et al., 2013). Two hands may have allowed the sighted participants to mark a location on a line with one finger while tracing with another (Berlá & Butterfield, 1977), or to use two fingers to trace in opposite directions around a closed line (Jansson & Monaci, 2003). It is not clear how either of these two-handed strategies would be aided by multiple fingers. Therefore, blind participants must be using some other strategy, either alone or in conjunction with these two-handed strategies, to perform line-tracing tasks quickly. One possibility is that the blind participants may be able to execute the aforementioned sighted two-handed strategy with a single hand. Perhaps blind individuals are more adept at using their nonindex fingers, and can simultaneously mark and trace lines using different fingers on the same hand.

In global search (cluster search) and local search (cluster closest) tasks, blind participants had a benefit from multiple hands that sighted participants did not have. This was reflected both in models containing only sighted or blind data and in the model with combined data. This two-hand benefit was substantial—blind participants gained a 24% and 19% reduction in search time when using two hands, for global and local search, respectively. This suggests that blind participants were capable of parallelized search using two hands, while sighted participants were not. It is unknown if blind participants learned this skill spontaneously through their haptic experiences, if it was learned through explicit instruction, or some combination. This could be a topic of future research.

Previous research showed that blindfolded sighted participants could use their two hands in parallel to search for a target among a grid of distractors. The participants tended to make similar movements with their two hands, often resulting in symmetrical scan patterns (Overvliet, Smeets, & Brenner, 2008). Furthermore, sighted participants have demonstrated a capacity to integrate static information across two fingers of different hands better than two fingers on the same hand (Overvliet, Smeets, & Brenner, 2010). Therefore, it could be predicted that both blind and sighted participants would have shown benefits from two-handed haptic search, but only the current study's blind participants demonstrated such an effect. One explanation is that the previous study's stimuli were highly constrained, being laid out in a grid (Overvliet et al., 2008). Our tactile-map stimuli did not provide an intrinsic structure on which to organize search strategies, unlike a grid of stimuli that facilitates sequentially scanning rows or columns. It is possible that, unlike the blind participants, previous sighted participants in Morash et al. (2013) were unable to spontaneously generate systematic strategies that could allow for parallel search with two hands in the absence of intrinsic structure in the stimuli. Blind participants in the current study may have been explicitly taught, or learned through experience, methods that support parallel haptic search on relatively unconstrained tactile displays.

The straight-line movement task (cluster direction) had similar effects of multiple fingers and two hands for participants who were sighted and blind. The major difference was that, for blind participants, there was a significantly greater reduction in response times from additional fingers (blind 24% reduction, sighted 5% reduction). Sighted participants had a strange pattern of performance on this task, where additional fingers initially decreased, but later increased, response times—that is, sighted participants were slower with 4 and 5 fingers on the dominant hand than 3 (Morash et al., 2013). We had observed that the sighted participants had difficulty moving in a straight line, often moving at an unintended angle, and suggested that this was somehow exacerbated by additional fingers on the dominant hand. We did not observe the same issue in the blind participants, for whom performance did not get worse with the addition of fingers 4 and 5 on the dominant hand. However, sighted and blind participants showed a similar increase in response time due to a second hand. These effects were not significantly different from one another, although only the sighted effect was significantly different from 1 (1 indicates no effect). For both sighted and blind participants, using two index fingers was slower than using the index and middle fingers on the dominant hand. Straight-line movement appears to be a difficult task for both sighted and blind participants, and future research may examine if this is due to errors in movement direction, or some other cause.

As mentioned in the introduction, the results of the current study are directly applicable to tactile maps used by blind individuals, and may also be extended to the design of other tactile displays used by people who have visual impairments. It is important for such displays to support multiple fingers and hands, because a single finger will never produce optimal performance. As such, if the task to be performed with a display is accomplished best with multiple hands (eg line tracing), the device should be designed so that both hands are free to explore, not so that one hand is necessarily holding or supporting the display. Tactile displays and associated training should encourage users to use more than a single index finger, because novice users may unwisely adopt this strategy (Symmons & Richardson, 2000).

In summary, the current study indicates that, like sighted individuals, blind participants perform haptic tasks faster when using two hands and multiple fingers. This is further evidence that the haptic system performs best when it can take advantage of the independent movement and perception of multiple fingers. Furthermore, blind participants were overall faster at completing haptic tasks; and in every instance that an effect was different between sighted and blind participants, the blind participants had additional benefits from multiple hands or fingers. Therefore, blind participants have learned, through experience or training, how to further exploit the independence of the hands and fingers. These results have important implications for the development of haptic displays and training—namely, that haptic interfaces need to support and encourage multiple-finger contacts, especially for users who are blind, and that effective multihand/finger strategies may not occur spontaneously, but instead develop through only extensive tactile-media experience and/or training. These results also have important implications for the design of future research into task performance in blind individuals, in that the performance of blindfolded sighted participants cannot be used to predict the performance of blind participants.

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Appendix. Model parameters

Each task's model was of the following form:

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

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 random error.

Each model produced estimates of the general intercept and participant-specific intercepts. As is typical, the number of coefficients associated with factor variables was the number of factor levels minus one (13 coefficients for a total of 14 participants, etc). Also, each model produced estimates for the coefficients related to number of fingers, number of hands, the interaction, and (if providing significant improvement in fit) number of fingers squared. These are reported in the results section. Lastly, each model produced estimates for coefficients related to the variables *A–Z*. These variables were task specific, as detailed below.

Path loop

Example question: "Is there a path with a closed loop?"

Independent variables *A–Z*:

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Nonloop length: length (in cm) of path forming the loop.
- Loop length: length (in cm) of path not forming the loop.
- Loop or not: factor (2 levels) indicating whether there is a loop or not.
- One or two paths: factor (2 levels) indicating whether there are one or two paths.

Path number

Example question: "Are there one or two paths?"

Independent variables *A–Z*:

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Nonloop length: length (in cm) of path forming the loop.
- Loop length: length (in cm) of path not forming the loop.
- Loop or not: factor (2 levels) indicating whether there is a loop or not.
- One or two paths: factor (2 levels) indicating whether there are one or two paths.

Cluster search

Example question: "Please locate the cluster of squares and say 'here'."

Independent variables *A–Z*:

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Search order: number (1–3) search on the map; first = 1, last = 3.
- Distance from middle: length (in cm) from middle of the map to the cluster center.
- Cluster shape: factor (5 levels) indicating whether cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Cluster symbol: factor (5 levels) indicating whether cluster symbol shape is square, circle, triangle, T, or oval.

Cluster direction

Example question: "From this cluster of squares, which symbol is directly to the right?"

Independent variables *A–Z*:

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Distance: length (in cm) from starting cluster to answer symbol.
- Direction: factor (4 levels) indicating whether direction is right, left, down, or up.

- Cluster shape: factor (5 levels) indicating whether starting cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Cluster symbol: factor (5 levels) indicating whether starting cluster symbol shape is square, circle, triangle, T, or oval.
- Answer symbol: factor (5 levels) indicating whether answer symbol shape is square, circle, triangle, T, or oval.
- Path intercept: factor (2 levels) indicating whether cluster-to-symbol path crosses a path or not.
- Lake intercept: factor (2 levels) indicating whether cluster-to-symbol path crosses the lake or not.

Cluster closest

Example question: “From this cluster of squares, which symbol is closest?”

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Distance: length (in cm) from starting cluster to answer symbol.
- Angle: factor (4 levels) indicating whether cluster-to-symbol line is rightwards (315º–45º), leftwards (135º–225º), downwards (225º–315º), or upwards (45º–135º).
- Cluster shape: factor (5 levels) indicating whether starting cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Cluster symbol: factor (5 levels) indicating whether starting cluster symbol shape is square, circle, triangle, T, or oval.
- Answer symbol: factor (5 levels) indicating whether answer symbol shape is square, circle, triangle, T, or oval.
- Path intercept: factor (2 levels) indicating whether cluster-to-symbol line crosses a path or not.

Distance cluster

Example question: “Which is closer to the cluster of squares, the cluster of Ts or the cluster of ovals?”

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Difference in distance: length (in cm) difference between cluster-to-answer and cluster-to-alternative distances.
- Main cluster shape: factor (5 levels) indicating whether main cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Main symbol: factor (5 levels) indicating whether main symbol shape is square, circle, triangle, T, or oval.
- Answer cluster shape: factor (5 levels) indicating whether answer cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Answer symbol: factor (5 levels) indicating whether answer symbol shape is square, circle, triangle, T, or oval.
- Answer path intercept: number (0, 1, 2) indicating whether cluster-to-answer line crosses 0, 1, or 2 paths.
- Answer lake intercept: factor (2 levels) indicating whether cluster-to-answer line crosses the lake or not.
- Answer angle: factor (4 levels) indicating whether cluster-to-answer line is rightwards (315º–45º), leftwards (135º–225º), downwards (225º–315º), or upwards (45º–135º).
- Alternative cluster shape: factor (5 levels) indicating whether alternative cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Alternative symbol: factor (5 levels) indicating whether alternative symbol shape is square, circle, triangle, T, or oval.

- Alternative path intercept: number (0, 1, 2) indicating whether cluster-to-alternative line crosses 0, 1, or 2 paths.
- Alternative lake intercept: factor (2 levels) indicating whether cluster-to-alternative line crosses the lake or not.
- Alternative angle: factor (4 levels) indicating whether cluster-to-alternative line is rightwards (315º–45º), leftwards (135º–225º), downwards (225º–315º), or upwards (45º–135º).

Distance lake

Example question: "Which is closer to the cluster of squares, the cluster of Ts or the cluster of ovals?"

- Map order: number (1–56) of map the participant is on; first = 1, last = 56.
- Difference in distance: length (in cm) difference between lake-to-answer and lake-to-alternative distances.
- Answer cluster shape: factor (5 levels) indicating whether answer cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Answer symbol: factor (5 levels) indicating whether answer symbol shape is square, circle, triangle, T, or oval.
- Answer path intercept: factor (2 levels) indicating whether lake-to-answer line crosses a path or not.
- Answer angle: factor (4 levels) indicating whether lake-to-answer line is rightwards (315º–45º), leftwards (135º–225º), downwards (225º–315º), or upwards (45º–135º).
- Alternative cluster shape: factor (5 levels) indicating whether alternative cluster is diamond, horizontal line, vertical line, triangle, or square shaped.
- Alternative symbol: factor (5 levels) indicating whether alternative symbol shape is square, circle, triangle, T, or oval.
- Alternative path intercept: factor (2 levels) indicating whether lake-to-alternative line crosses a path or not.
- Alternative angle: factor (4 levels) indicating whether lake-to-alternative line is rightwards (315º–45º), leftwards (135º–225º), downwards (225º–315º), or upwards (45º–135º).