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Acta Psychologica 127 (2008) 51–56

acta psychologica

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Haptic search is more efficient when the stimulus can be interpreted as consisting of fewer items

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Received 22 September 2006; received in revised form 11 January 2007; accepted 15 January 2007
Available online 28 February 2007

Abstract

In a typical haptic search task, separate items are presented to individual fingertips. The time to find a specific item generally increases with the number of items, but is it the number of items or the number of fingers that determines search time? To find out, we conducted haptic search experiments in which horizontal lines made of swell paper were presented to either two, four or six of the participants' fingertips. The task for the participant was to lift the finger under which they did not feel (part of) a line. In one of the conditions separate non-aligned lines were presented to the fingertips so that the number of items increased with the number of fingers used. In two other conditions the participants had to find an interruption in a single straight line under one of the fingertips. These conditions differed in the size of the gap. If only the number of items in the tactile display were important, search times would increase with the number of fingers in the first condition, but not depend on the number of fingers used in the other two conditions.

In all conditions we found that the search time increased with the number of fingers used. However, this increase was smaller in the single line condition in which the gap was large enough for one finger to not make any contact with the line. Thus, the number of fingers involved determines the haptic search time, but search is more efficient when the stimulus can be interpreted as consisting of fewer items.

PsycINFO classification: 2320

Keywords: Sensory perception; Haptic perception; Tactile perception; Proprioception; Haptic search

1. Introduction

Search experiments are generally used to get more insight into how information is processed. Many studies have been conducted on visual search. Only a few have been conducted on haptic search. However, several studies have investigated haptic object recognition. For example, Norman, Norman, Clayton, Lianekhammy, and Zielke (2004) found that the accuracy with which naturally shaped objects were discriminated was almost as precise when the stimuli were presented haptically as when they were presented visually. Behrmann and Ewell (2003) showed that participants were good at discriminating between two line patterns by tracing the lines with the two index fingers simultaneously. These results indicate that people are quite accurate in object recognition tasks in the haptic modality.

What all visual and haptic search tasks have in common is that the target must be found amongst a number of other objects. How long it takes to find a target amongst a group of distractors depends on the properties of the target in relation to the distractors. When the target is clearly different from all the other objects in one or more feature dimensions, it does not matter how many items there are in the display. It takes about the same time to find the target in the presence of various numbers of distractors (parallel search). When the difference between target and distractors is less distinctive, search times increase with the number of

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doi:10.1016/j.actpsy.2007.01.001

items in the display (serial search). Although not all search theories make this strict distinction between serial and parallel processing, search tasks are generally used to determine the basic feature dimensions of perception (Duncan & Humphreys, 1989; Duncan & Humphreys, 1992; Julesz, 1984, 1986; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe, Cave, & Franzel, 1989; Wolfe & Horowitz, 2004).

Lederman and Klatzky (1997) investigated the basic properties in haptic processing by presenting different kinds of stimuli to their participants' fingertips and determining how soon after contact they could find the target. They distinguished four dimensions: the material (how rough, hard or warm the material feels), abrupt surface discontinuities (a raised bar among flat surfaces or a deep hole between shallow holes), relative orientation (the target had a different orientation than the distractors), and continuous 3-D surface contours (slant or curvature). Material and abrupt surface discontinuities produced low search function slopes, indicating more or less parallel search. Relative orientation and continuous 3-D surface contours produced relatively steep slopes, indicating serial search.

A recent study (Overvliet, Smeets, & Brenner, submitted) also found that search times increased with the number of items when the target differed from the distractors in one of several spatial features, whereas the time needed for detecting a line amongst empty sensors is independent of the number of fingers. The difference was interpreted in terms of the tactile properties of the individual items. However, there is an alternative interpretation. A surface without protrusions may be considered to be a single item, irrespective of the number of fingers touching it. Thus, rather than the number of fingers, the number of 'objects' may be critical. The results of Lederman and Klatzky (1997) and Overvliet et al. (submitted) could be explained in terms of the number of items rather than of the number of fingers used. If so, items must be recognized by their material properties or by the way in which they can be combined to form surfaces.

Knowing what you are going to feel may also help to bind properties into a single item, for example, when carrying a book, we automatically perceive its edge as a single shape and not as four objects touching our fingertips. Imagine that the book has some damage on one edge of the cover. When we hold the book in our hand we will feel the ripped paper. Does the fact that we know how it feels to touch a book help us to detect a possible deviation from the expected shape faster than when we touch an artificial set of 'unrelated' objects?

We hypothesize that the impression of exploring a single complete object will lead to a more efficient search pattern. To investigate this, we compared haptic search when separate small lines were presented to the participants' fingertips with haptic search when a single longer line was used as a stimulus. The task for the participants was to indicate which finger did not have a line under it. When a single line was used this is equivalent to finding the gap in the line. Our hypothesis yields predictions that are between two possible extremes. If only the number of objects is relevant, we expect search time not to increase with the number of fingers in this condition. However, if only the number of fingers is relevant, search time will increase with the number of fingers that explore the single line in the same way as it does for the separate small lines.

2. Method

2.1. Participants

Ten participants took part in the experiment, six male and four female, with an age range of 23–48 years. Two of them stated to be left-handed. Most of the participants were familiar with psychophysical experiments.

2.2. Stimuli and apparatus

The setup consisted of six force sensors, which were designed to have a piece of ZY®-TEX2 Swell paper (Zychem Ltd., Cheshire, England) attached to them. The items were horizontal lines with a line width of 1.4 mm, which protruded about 1 mm from the surface of the swell paper. Each sensor could be positioned separately to accommodate different hand sizes and stimulus positions. The sensor measured whether there was a finger on top of it. To be able to determine reaction time, the apparatus was connected to a computer. The sample rate was 60 Hz. A curtain was placed between the participant and the apparatus to prevent the participant from seeing the display. The apparatus is shown in Fig. 1A.

2.3. 'Separate lines'

In the first condition, the stimulus consisted of separate lines that were positioned beneath the participants' finger pads when in a comfortable (natural) position (Fig. 1B). Each item was a separate 2 cm horizontal line. The target was a piece of swell paper that did not contain a line.

2.4. 'Wide gap'

In the second condition, the stimulus was a 14.5 cm line. The 2 cm wide sensors were spaced with a distance of 0.5 cm between them to avoid fingers touching the sensor that was used for the adjacent finger. The target was a 2 cm gap in the line. Participants now had to adjust their finger positions to the line (Fig. 1C).

2.5. 'Narrow gap'

This third condition was identical to the second except that the participant could feel the edges of the gap at the target. The size of the gap was 50% of the width of the participants' index finger (the used gap size was 0.7 cm, 0.8 cm, or 0.9 cm).

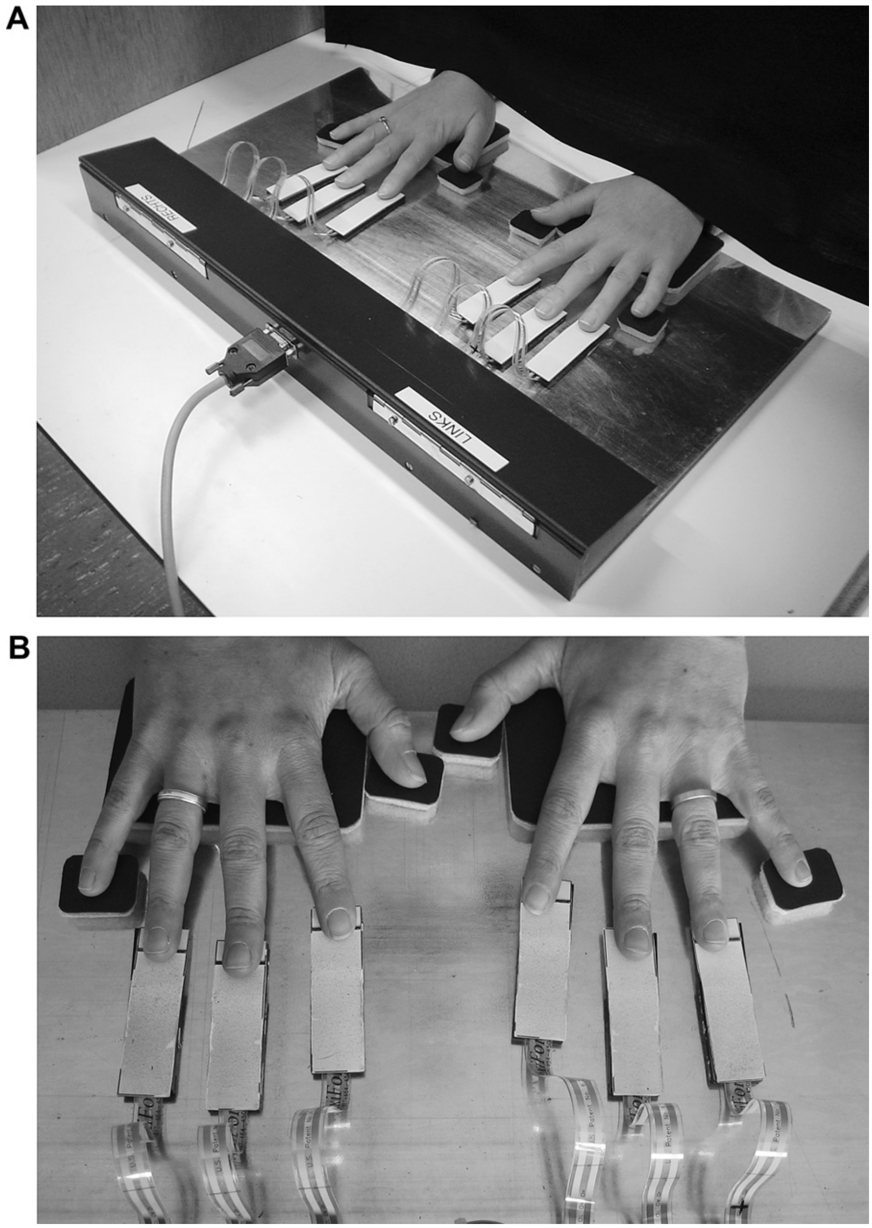

Fig. 1. Setup of the experiment. (A) The apparatus. (B) The 'separate lines' condition. (C) The 'wide gap' condition.

2.6. Procedure

Participants used either two, four or six fingers. In trials with two fingers participants used their index fingers. In trials with four fingers participants used their index and middle fingers. In trials with six fingers participants used their index, middle and ring fingers. Each combination of condition and number of fingers was tested in a separate block. Each block consisted of 40 trials. In 25% of the trials the stimulus did not contain a target. The nine blocks (with all combinations of three conditions and three numbers of fingers used) were presented in random order to each participant, with not more than two blocks a day.

Before each trial, the participants were asked to place their fingertips on the sensor to make sure that they would not misplace their fingers and consequently miss the target. When the fingers were in the correct position, the participants lifted the fingers and the experimenter placed the next stimulus on the sensors. The experimenter started each trial by presenting a 4500 Hz tone. As soon as the participants heard the tone they could lower their fingers on the stimulus. Participants were allowed to move their fingers a little over the stimulus as long as the fingers stayed on the sensors. The participants were instructed to lift the finger under which the target was positioned as soon as they detected it. For trials in which the target was absent, participants were instructed to lift all the fingers as soon as they detected the absence of the target. This procedure (and the analysis presented below) was successfully applied in an earlier study (Overvliet et al., C

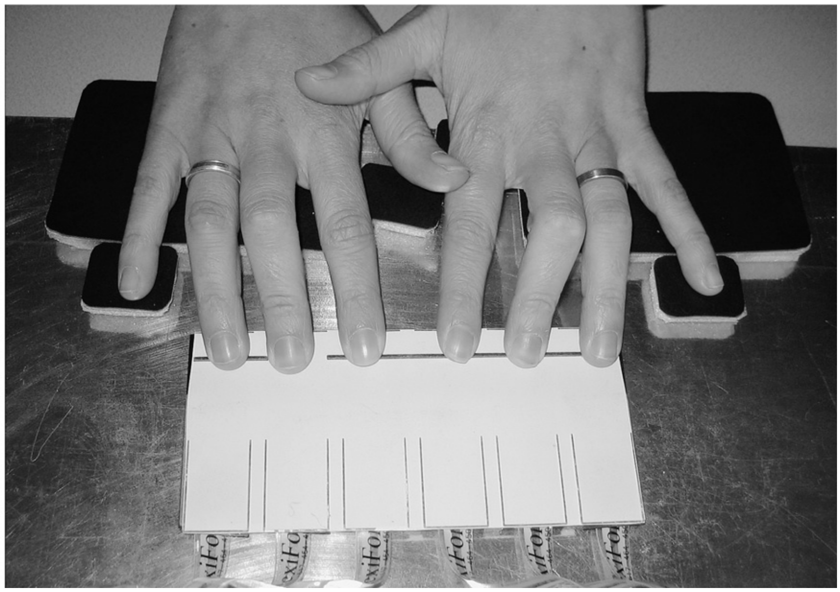

Fig. 1 (*continued*)

submitted) in which we could describe haptic search as either a serial or parallel process.

2.7. Analysis

On target present trials, the reaction time was defined as the time from when the first finger was lowered onto one of the sensors until the finger on the target was lifted. On target absent trials, the reaction time was defined as the time from when the first finger was lowered onto one of the sensors until the first finger was lifted. Trials with reaction times shorter than 100 ms were discarded because such a fast response was considered not to be physiologically plausible. Trials in which participants gave the wrong answer were also deleted. In total 8.9% of the trials were discarded (7.9% in target present and 9.2% in target absent). We checked whether there was a speed-accuracy trade off, but there was no effect of the number of omitted trials on search time. For every participant, condition ('separate lines', 'wide gap', 'narrow gap') and number of fingers (2, 4 and 6) the median search time was computed for the remaining trials. This was done separately for the target absent and target present conditions.

To determine whether there is any effect of the number of fingers, condition or target presence, we used a repeated measures ANOVA with these three measures as factors. Since we found a significant increase in search time with the number of fingers (see Section 3) we fit a serial search model to the data (see Appendix). To check whether our choice for the serial search model with a common intercept for target absent and target present was justified, we fit separate lines through the data points for trials in which the target was present or absent. We did not find a significant difference between the intercepts of the two lines. This indicates that the use of our serial model is justified. If the search times had not increased with the number of fingers we would have fit a parallel search model. To test how well the search model fits the data we used a χ^2 goodness-of-fit test (Press, Flannery, Teukolsky, & Vetterling, 2002). This gives a measure of the relation between the standard errors in the measurements and the deviations from the fit. If χ^2 is bigger than 1, the data points are further from the fit than expected on the basis of their standard errors. The p-values that we give are the probabilities that we should reject the fit. We used a two-tailed t-test to check for differences in slope and intercept between the three conditions.

3. Results

Fig. 2A–C show the haptic search functions. We found main effects for the factors 'number of fingers' ($F_{\mathrm{df}=2} = 32.15$, $p < 0.001$) and condition ($F_{\mathrm{df}=2} = 11.83$, $p < 0.01$). We also found an interaction effect between condition and target presence ($F_{\mathrm{df}=4} = 8.15$, $p < 0.05$). The serial search model fit the data very well in all three conditions ('separate lines': $\chi^2_{\mathrm{df}=4} = 0.45$, $p < 0.05$; 'wide gap': $\chi^2_{\mathrm{df}=4} = 0.11$, $p < 0.01$; 'narrow gap': $\chi^2_{\mathrm{df}=4} = 0.34$, $p < 0.05$), which means that the data points comply with the model. The slopes and intercepts of the fits for the three conditions are shown in Fig. 2D.

The only significant difference between the intercepts was between those of the 'separate lines' and 'narrow gap' conditions ($t_{\mathrm{df}=59} = 2.27$; $p < 0.05$). The slopes of 'separate lines' and 'narrow gap' are both significantly higher than the slope of 'wide gap' ($t_{\mathrm{df}=59} = 3.26$; $p < 0.001$ and $t_{\mathrm{df}=59} = 2.23$; $p < 0.05$, respectively).

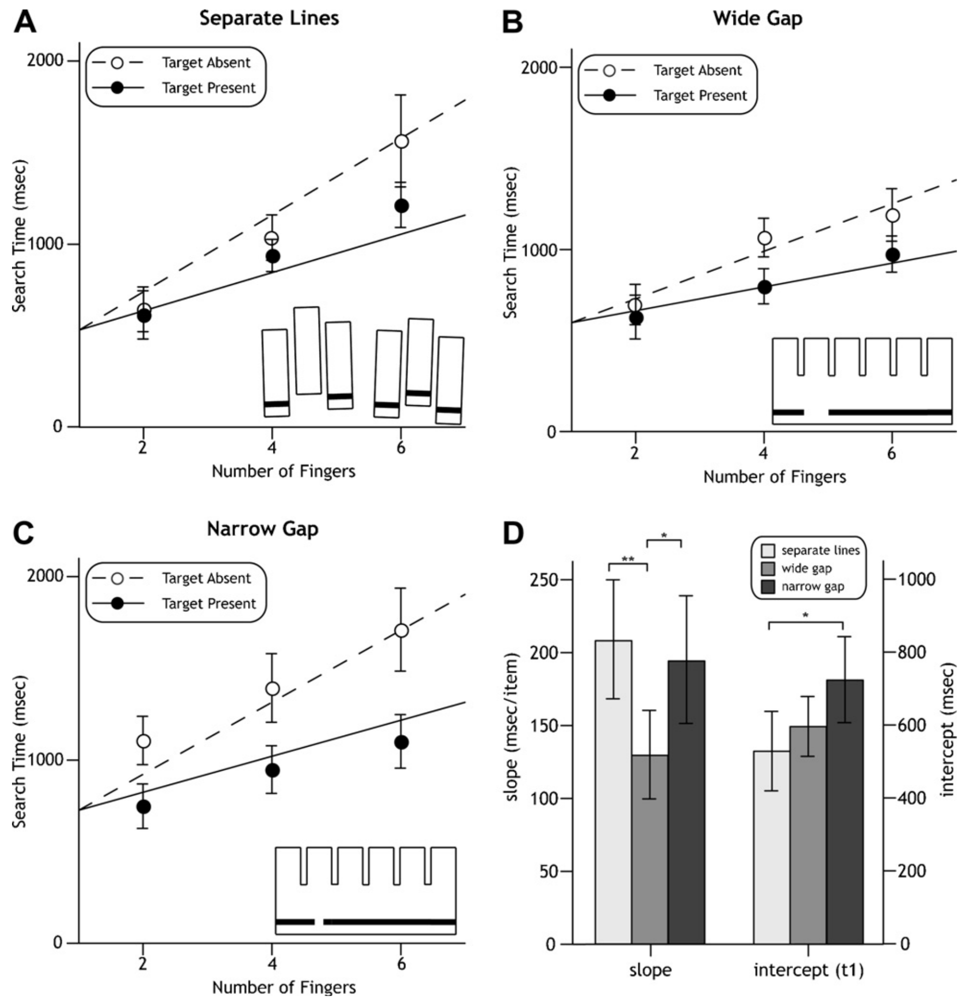

Fig. 2. (A)–(C) Haptic search functions. The data points represent the mean of the participants' individual medians. The error bars represent the standard error of the mean across participants. The lines indicate the best fit of the serial search model (see Appendix). The inset in the right bottom indicates the stimulus: (A) The 'separate lines' condition. (B) The 'wide gap' condition. (C) The 'narrow gap' condition. (D) The slopes and intercepts (t_1) of the haptic search functions in the three conditions. The error bars represent the standard errors of the regression coefficients.

4. Discussion

In the introduction we hypothesized that the impression of exploring a single complete object will lead to a more efficient search for a gap. We compared conditions for which stimuli under the participants' fingers could or could not be considered to be a part of a single larger object. The results confirmed the hypothesis. However, we found an increase in search time with the number of fingers in all conditions, so the number of fingers involved in the search process is important as well as the number of objects that are presented. We found a lower slope of the search function in the 'wide gap' condition than in the 'separate lines' condition, despite the awkward finger position. The intercepts did not differ, which is logical because when only one finger is used there is no difference between the tasks. The participant only needs to decide whether there is a 'line' or 'nothing' under his or her fingertip. The 'narrow gap' condition does have a different intercept. Apparently it is more difficult to decide whether there is a 'line' or a 'line with a narrow gap' under your fingertip, than to decide whether there is a 'line' or 'nothing' under your fingertip. This is also clear from the difference in slopes between the 'large gap' and 'narrow gap' conditions.

The shallower slope in the 'wide gap' than in 'separate lines' condition demonstrates that the participants benefited from the fact that they could consider the lines to be parts of a single object. We cannot tell whether this is mediated by them feeling that the lines form a single object or by us having told them that it is so. In other fields of research a similar effect is found. For instance, performance is faster and more accurate when two target properties have to be identified on the same object than when each of the property appears on a different object (Baylis, 1994; Baylis & Driver, 1993; Cepeda & Kramer, 1999; Mapelli, Cherubini, & Umilta, 2002).

In the 'narrow gap' condition, in which line endings could be felt under one finger, the gap was not detected faster. The 'narrow gap' even seemed to be more difficult to detect, as is evident from the longer search times. Participants clearly did not benefit from feeling the line endings on both sides of the narrow gap. It even took them more time to detect such a gap than to detect the absence of a line. Thus, the gap appears to be "filled in" perceptually when the line endings are close together, as has previously been proposed for visual stimuli (Lamote & Wagemans, 1999).

Earlier research has shown that a parallel haptic search pattern is possible when participants have to find a similar item to those used here amongst empty pieces of swell paper (Overvliet et al., submitted). In the 'separate lines' condition of this experiment, the characteristics of targets and distractors are reversed with respect to that study. The fact that we now found a serial search pattern reveals an asymmetry in haptic search. Search asymmetry is a phenomenon that was first found by Treisman and Gormican (1988) and is considered to provide evidence for the importance of a feature in perception. When the feature is present in the target, the search pattern is parallel. When the feature is present in the distractors, but absent in the target, one has to check every item for the absence of this particular feature, so a serial search pattern emerges. Thus, the search asymmetry that we found confirms Lederman and Klatzky's (1997) conclusion that a bump is one of the features that is registered early in haptic processing.

In conclusion, the search process is more efficient when the stimuli form a complete object. However, the number of fingers involved in the search process is more important than the number of objects that have to be explored.

Appendix. Serial search model

In serial search, when the target is present, it will on average be found after scanning half of the distractors; the 'effective' number of items scanned is therefore 1.5, 2.5, and 3.5 for 2, 4, and 6 items in the display. In the target absent condition, all items have to be scanned to be sure that there is no target present, so the effective number of items equals the total number of items. As a result of this, the slope of the search function in the target present condition will be half the magnitude of that for the target absent condition. For the serial search model, we fit a single linear regression to the search times as a function of the effective number of items of each condition. In order to conform to the tradition in the search literature, we report the slope of the search time in the 'target-present' trials as a function of the number of items. This slope is by definition half of the slope in the 'target-absent' case or half of the slope in terms of the effective number of items. This results in the following search functions with slope s (increase in time per item) and intercept t_1 (time for one item) for the target present (1) and target absent (2) conditions:

$$RT(n) = t_1 + (n-1)s \tag{1}$$

$$RT(n) = t_1 + (n-1)2s \tag{2}$$

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