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The use of proprioception and tactile information in haptic search

K.E. Overvliet [a,b,c,*], J.B.J. Smeets [a], E. Brenner [a]

[a] Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands
[b] Parc Científic de Barcelona, Universitat de Barcelona, Barcelona, Spain
[c] Departament de Psicologia Bàsica, Universitat de Barcelona, Barcelona, Spain

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ABSTRACT

To investigate how tactile and proprioceptive information are used in haptic object discrimination we conducted a haptic search task in which participants had to search for either a cylinder, a bar or a rotated cube within a grid of aligned cubes. Tactile information from one finger is enough to detect a cylinder amongst the cubes. For detecting a bar or a rotated cube amongst cubes touch alone is not enough. For the rotated cube this is evident because its shape is identical to that of the non-targets, so proprioception must provide information about the orientation of the fingers and hand when touching it. For the bar one either needs proprioceptive information about the distance and direction of a single finger's movements along the surfaces, or proprioceptive information from several fingers when they touch it simultaneously. When using only one finger, search times for the bar were much longer than those for the other two targets. When the whole hand or both hands were used the search times were similar for all shapes. Most errors were made when searching for the rotated cube, probably due to systematic posture-related biases in judging orientation on the basis of proprioception. The results suggest that tactile and proprioceptive information are readily combined for shape discrimination.

1. Introduction

Searching for objects in our surroundings is a task we perform every day. Imagine trying to find a pen in your bag while talking to someone. You have to explore the objects in your bag one by one to decide which one is a pen. There are some studies dedicated to haptic search. However, most of them focus on objects that are smaller than the fingertips, and the participant touches multiple items simultaneously (e.g. Lederman & Klatzky, 1997; Overvliet, Mayer, Smeets, & Brenner, 2008; Overvliet, Smeets, & Brenner, 2007b). In daily life you will rarely encounter this situation. The goal of this study is to investigate haptic search behaviour under conditions that are more like our experience in daily life. When you search for an object in your bag you must often combine tactile and proprioceptive information to distinguish one object from the other because the way surface orientation changes along the object is usually characteristic for the object. Thus, you normally explore the object dynamically with several fingers. We therefore compare search for geometrical shapes that can be distinguished from each other either by touch alone, by touch together with static proprioception or by a combination of touch and dynamic proprioception. To be able to make accurate measurements we do not really use a natural environment, but place the objects in a grid. Thus, issues such as moving obstacles out of the way are not considered.

People seem to be quite good at discriminating between objects by touch. For example, Norman, Norman, Clayton, Lianekhammy, and Zielke (2004) showed 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 when tracing the lines with the two index fingers simultaneously. Lederman and Klatzky (1987) defined several 'exploratory procedures' with which people extract important features from objects in order to recognise them, such as enclosure to determine the general shape and volume of an object, and contour following to determine the object's exact shape. In terms of the information that is used, judging features such as surface smoothness or curvature only requires touch, whereas judging other features such as the relative orientations of surfaces also requires information from proprioception about the position(s) of the finger(s) in space or of the configuration of the hand. Finally, for judging features such as size, tactile information is less important than proprioception, and might not be needed at all. For example, if objects mainly differ in how soft they are, tactile information is critical for discriminating between them (Srinivasan & LaMotte, 1995), whereas objects that mainly

* Corresponding author. Present address: Research Institute MOVE, Faculty of Human Movement Sciences, VU University, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands.
E-mail address: krista.overvliet@gmail.com (K.E. Overvliet).

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differ in size can even be recognized quite reliably without any cutaneous input (Berryman, Yau, & Hsiao, 2006).

To investigate how important proprioception is in shape discrimination, we designed a haptic search task in which participants had to search for simple geometric objects hidden within a grid of cubes. In the first experiment the participants were only allowed to use their index finger. This has the advantage that the role of proprioception is easily defined. We used two display sizes to check that the search times that we find are really only determined by the time needed to identify each item.

A second point of interest is how people scan their environment haptically. Smith, Gosselin, and Houde (2002) conducted an experiment in which participants had to tactually explore a surrounding in order to find a raised or a recessed square. They measured the finger path and the forces that were applied to the surface. They showed that participants all used similar left to right movements of the index finger to scan the environment. For the raised squares, participants also used a relatively constant contact force. We too investigated scanning strategies in an earlier haptic search experiment (Overvliet, Smeets, & Brenner, 2007a). The participants in that task had to scan a row of small items (raised circles and crosses on swell paper) with either one or three fingers to find a target. The distance between the items had an influence on the search strategies participants used. When the items were further apart, participants tend to move very quickly in between items and stood still on an item. However, when the items were close to each other, participants scanned them with a steady velocity.

Another comparison that was made in this study was that between the use of one or three fingers. Using three fingers did not reduce the search time. This lack of effect of using more fingers might be caused by the inability to process information of more than one item in parallel, rather than of more than finger. We here examine whether using more fingers also fails to speed up searching for objects that are larger than the fingertips, in which case many fingers simultaneously feel the same object. We intuitively expect combining information from many fingers to be particularly useful when proprioception as well as touch is needed to recognize the objects. We therefore compared the search times when using a single finger (experiment 1) to those when using the whole hand (experiment 2) and even two hands (experiment 3).

2. Experiment 1

2.1. Method

Participants had to find either a cylinder, a bar or a rotated cube within a grid of aligned cubes. Only one finger could be used. We measured two different display sizes: 9 and 36 objects.

2.2. Participants

Eight participants took part in the experiment. Seven of them were right handed. Their mean age was 33 years (range 26–49). All participants were naive concerning the goal of the experiment at the time of the experiment. Informed consent was obtained from each participant.

2.3. Stimuli and apparatus

Wooden objects were placed on a table in a grid of either 3 by 3 or 6 by 6 objects, with 8 cm between their centres. The objects were fixed to the table by gluing LEGO® tiles (LEGO Group, Billund, Denmark, item#: 306826) to the bottom of each object and attaching them to four LEGO® base plates (item#: 626), that were glued to a plastic surface to form a larger square base. In between the objects we also attached LEGO® tiles (see Fig. 1). The non-targets were aligned cubes with edges of 2.5 cm. The target was either a bar of 2.5 by 5.0 by 2.5 cm, with its long edges aligned with either a row or a column of the non-targets, a cube that was rotated by 45° relative to the non-targets, or a cylinder with a diameter of 2.5 cm and a height of 2.5 cm. The position of the target was determined at random, but ensuring that the positions were evenly distributed over the four quadrants of the grid. There were four possible starting positions: just outside the grid at the centre of each of its sides. A copy of the target was placed at the starting position so that the participants could feel the characteristics of the target before each trial. IREDs were attached to the nails of both the participants' index fingers so that their movements could be tracked by an Optotrak system.

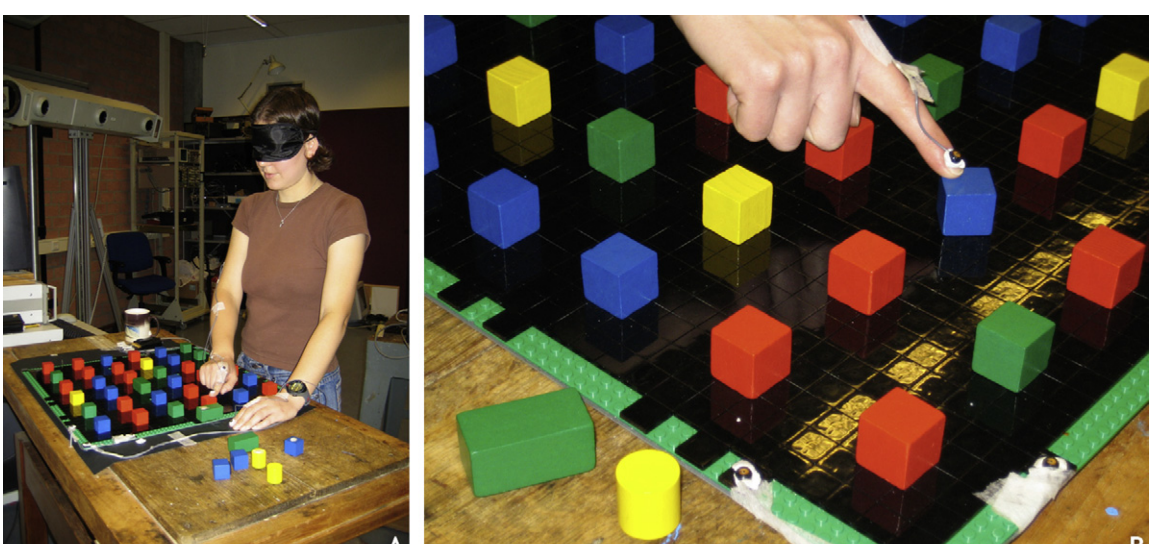

Fig. 1. (A) A participant performing the task in experiment 1. (B) Close up of the display with a participant touching one of the targets: a rotated cube. The two other possible targets, a cylinder and a bar, can be seen in the foreground.

2.4. Procedure

There was one block of twenty trials for each combination of shape (cylinder, bar or rotated cube) and number of objects (9 or 36). The six blocks were presented in a different randomized order for each participant. The participants were blindfolded and the height of the table was adjusted to each participant's preference. Two practice trials were given before starting each block. At the beginning of each trial the experimenter placed the tip of the index finger of the participant's dominant hand at the copy of the target that was placed at one of the four starting positions (randomly selected). Once the starting signal was given the participant could start exploring the objects. As soon as they found the target they had to lift the index finger of their non-dominant hand that was resting on the table during the trial. The maximum exploration time was 100 s. Participants were told that they had given a wrong answer whenever they did so.

2.5. Analysis

We analysed the fingers' trajectories on the basis of the data recorded at 250 Hz by the Optotrak. Total search time was defined as the time from the moment the dominant hand started to move until the moment that the index finger of the non-dominant hand started moving upwards. To be able to compare conditions with different numbers of objects and in order to remove the variability due to how lucky the participants were in choosing the quickest scan pattern to search for the target, we calculated the average amount of time that a participant spent on an object by dividing the total search time by the number of explored objects. We then used these values to fairly compare the different conditions. To reduce the influence of outliers we then calculated the median (rather than the mean) of these average amounts of time spent per object (on successful trials) for every participant and condition. We evaluated whether the factors shape (bar, rotated cube, cylinder) and display size (9 or 36) had a systematic influence on these median times using a repeated measures ANOVA.

The errors that participants made were divided into three categories: indicating that a normal cube was the target, indicating that the starting position (which had the same shape as the target but was outside the grid) was the target, and not finding the target within the maximum time of 100 s. The fact that participants mistook the object at the starting position for the target was an unexpected artefact of our design, indicating that the participants made large errors in judging the proprioceptive information, and did not notice that their hand was outside the grid.

2.6. Results and discussion

Some examples of scan patterns on individual trials are shown in Fig. 2. Participants tend to be very systematical, adopting either a 'zigzag' strategy (A,B) or a 'reading' strategy (C), going line by line or column by column through the display. Participants used different ways to touch the objects, for example, in Fig. 2A the edges of the objects are touched and in Fig. 2B the participant tends to scan over the top of the objects. In most respects these strategies were

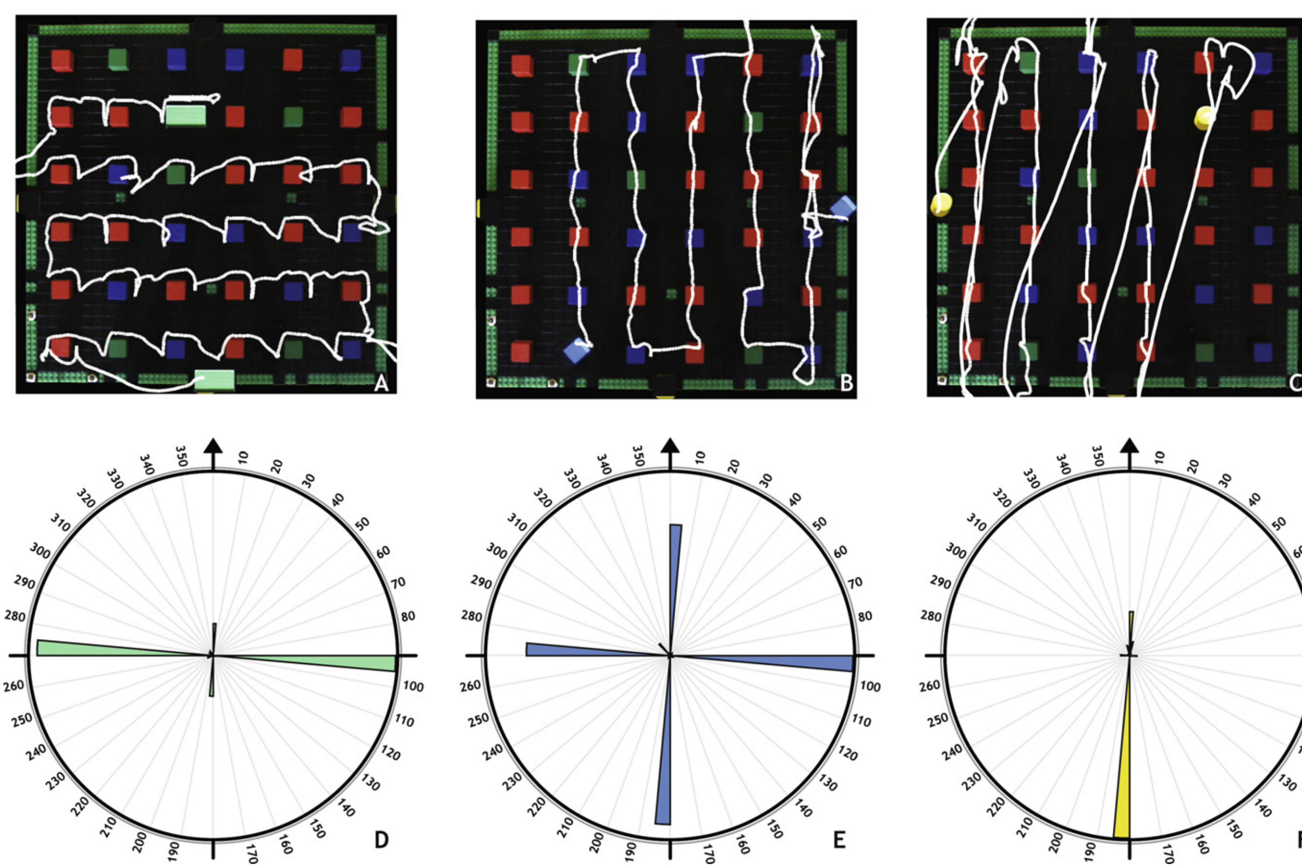

Fig. 2. Typical scan patterns for three different participants in the first experiment (one finger). (A) The target was a bar and the starting position was at the bottom. Search time in this trial was 46 s. (B) The target was a rotated cube and the starting position was at the right. Search time in this trial was 36 s. (C) The target was a cylinder, and the starting position was at the left. Search time in this trial was 23 s. D, E and F show the frequencies of scan directions of a block of trials. The same combinations of participants and shapes are shown as in the examples in A–C (D: bar, S6; E: oriented cube, S1; F: cylinder, S3). The size of each bin is 10°, and the length of the bar represents the frequency of the group of directions.

characteristic of the participant rather than of the shape. However, the strategy for finding the bar was different in that participants had to touch at least two sides of each object to determine whether either was longer than that of the cubes because the orientation of the bar was varied (Fig. 2A).

In order to view whether these examples were characteristic for a participant, we made rose plots of each participant's distribution of scanning directions of all trials of each block: for each movement between two objects, we determined the direction between the centres of two consecutively scanned objects. Plots for three participants are shown in Fig. 2D–F. Some participants move back and forth horizontally (Fig. 2D), others use a (vertical) reading-like strategy (Fig. 2F), and yet others scan in a different direction for different starting positions (Fig. 2E). We examined whether there was any evident relationship between the strategy and search times or number of errors, but we did not find any.

Fig. 3A shows the exploration times per object for each condition. We performed a repeated measures ANOVA with factors display size (9 or 36) and shape (bar, rotated cube, or cylinder) on the time each participant spent on each object and found a main effect of shape of the target ($F_{(2,14)} = 51.7$, $p < 0.001$), but not of display size ($F_{(1,7)} < 1$).

We performed post hoc Tukey/Kramer tests to investigate for which shapes the times differ from each other. We found that both the bar and the oriented cube had higher search times than the cylinder ($p < 0.05$). The time per object was highest when the bar was the target. This is undoubtedly because participants had to explore both sides of each object to be able to discriminate the bar from the cubes, as is clearly visible in Fig. 2A. The rotated cube was discriminated from the other cubes a little (but significantly) more slowly than the cylinder, suggesting that it takes longer to discriminate objects from each other when you need proprioception to make the distinction.

Participants made different kinds of errors. Their most common error (on average 2% of the trials) was indicating that they had found the target while touching a non-target. These are the most interesting errors, and are shown in Fig. 3B. They occurred particularly frequently when the target was a rotated cube. A second type of errors was that the participants indicated that the starting position (which had the same shape as the target) was the target (which occurred on about 1% of the trials). In the bar condition a third type of errors occurred: participants also occasionally failed to find the target within the allocated time (this occurred on about 0.67% of the trials). Interestingly, no errors at all were made for the cylinder, for which no proprioceptive information was needed to discriminate it from the cubes.

In summary, in this experiment we showed that when proprioception is needed to solve the task, discrimination between shapes takes longer and produces more errors. Display size had no effect on the time that was spend per object, indicating that the time needed to identify the objects and move between them determines the search time. We found no benefit or cost associated with only having to scan a few items.

3. Experiment 2

In an earlier study on haptic search with finger movements we showed that increasing the number of fingers that participants are allowed to use does not decrease search times (Overvliet et al., 2007a). It seemed that participants could not integrate information that was received from the different fingertips and that the time that it costs to switch between the fingers even slows down the search. This was a rather surprising finding, so we wanted to investigate whether this effect also takes place in a task in which objects are used that are larger than the fingertips. From a different study we have some suggestion that if the fingers feel the same object they do not work completely independently (Overvliet et al., 2008). In the second experiment participants had to perform the same search task as in experiment 1, but they were allowed to use the whole hand.

3.1. Method

The same eight participants took part and the same setup was used as in experiment 1. The only difference was that the participants were allowed to use their whole hand to scan the display (Fig. 4). Because we did not find any differences in the time spent per object between displays with 9 and 36 objects in the one finger experiment, we only used displays with 36 objects in this experiment. We attached IREDs to all the fingertips, but for the analysis we only used the one on the middle finger. The participants took part in this experiment approximately 6 months after experiment

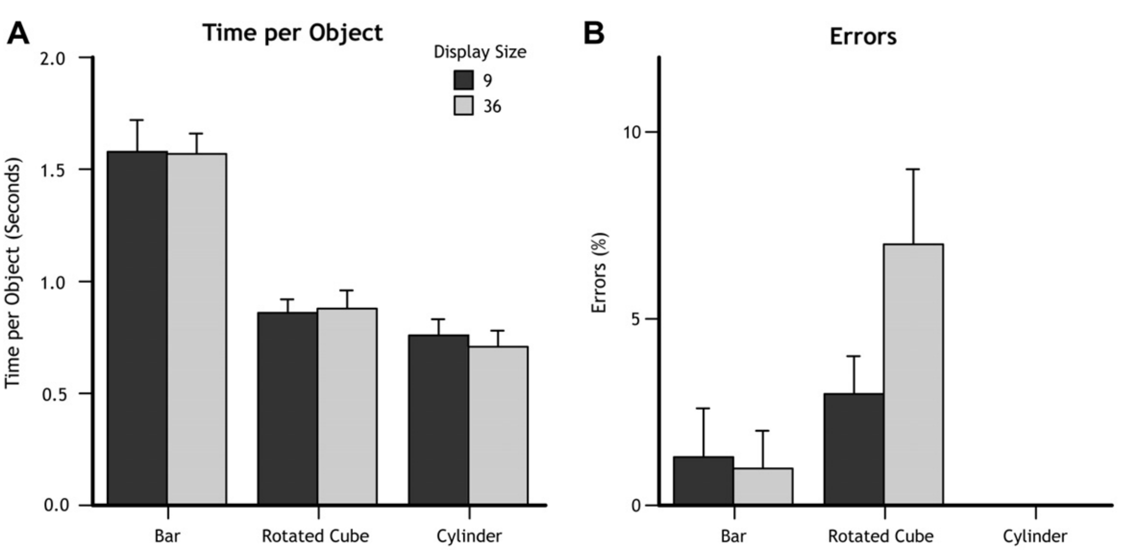

Fig. 3. Results of experiment 1. (A) Average time spent per object explored. The median time across trials was determined for each participant and condition. The figure shows means and standard errors (of these median times) across participants. (B). Mean percentage of trials in which participants indicated that a non-target was the target for each shape and display size (with standard errors). All conditions are within participant.

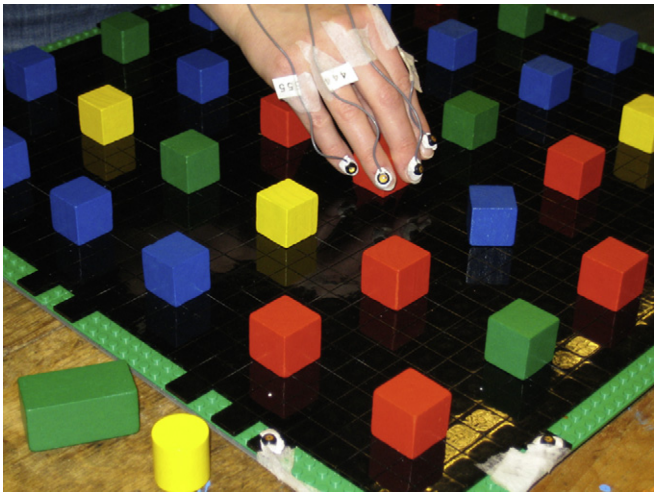

Fig. 4. Close up of the display with the participant touching a non-target with the whole hand.

1, so we do not expect any influence of the former experiment. To analyse the data we used a repeated measures ANOVA with 2 factors: shape (bar, rotated cube and cylinder) and hand (one finger or whole hand).

3.2. Results and discussion

The search times per item are shown in Fig. 5A. The light bars are the data for display size 36 from experiment 1 (they are the same as the light bars of Fig. 3). We performed a repeated measures ANOVA with factors fingers (one or all) and shape (bar, rotated cube or cylinder) on the times per object. We found a main effect of fingers ($F_{(1,7)} = 21.4$, $p < 0.001$), a main effect of shape ($F_{(2,14)} = 65.4$, $p < 0.001$) and an interaction between these two factors ($F_{df=(5,35)} = 33.7$, $p < 0.001$). Tukey/Kramer post hoc tests indicated that search times for the bar are different from ones for both the cube and the cylinder ($p < 0.05$); which is obviously mainly due to the very long search times for the bar in experiment 1. To investigate whether the effect of number of fingers used is present in all three shape conditions, we performed paired samples *t*-test comparing one finger with the whole hand search for each of the different shapes. For the bar and the rotated cube we found that searching with the whole hand is significantly faster than searching with only one finger (bar, $t_{df=15} = 6.6$; rotated cube, $t_{df=15} = 2.9$; both significant at a Bonferroni corrected α of 0.017). For the cylinder we did not find a significant difference.

When using the whole hand the most common errors that participants made were indicating that a non-target was the target, which they only did when searching for the rotated cube (Fig. 5B). Even in that case, however, they made fewer errors when using the whole hand than they had when using one finger in experiment 1, although the difference was not significant. Participants indicated that the object at the starting position was the target in 0.67% of the trials.

In our previous study, we found no benefit in using more than one finger for finding objects that are smaller than a fingertip (Overvliet et al., 2007a). Comparing the results of the two experiments in this study indicates that using more fingers speeds up search times significantly when searching for larger objects. This was not the case for discriminating a cylinder from the cubes. For discriminating the cylinder from cubes participants only needed to consider tactile information, as was the case for the raised line stimuli in our earlier study. Thus, it would appear that search times are only faster when using more than one finger simultaneously when proprioception is needed to make the distinction. An obvious advantage of using more fingers is that the position of a finger within the configuration of the hand is likely to be determined more accurately than its position in space. However, we cannot conclude that this is the only origin of the difference in our study because detecting the rotated cube does not involve detecting relative positions and orientations within the object, and for the bar having to move the finger along the edges of each item when only using one finger could easily explain the difference in performance.

4. Experiment 3

In this experiment, we allowed the participants to scan the display with two hands. By doing so we could investigate whether people can process information coming from two hands in parallel. If this is possible the time per cube will be about half of the time per cube in experiment 2.

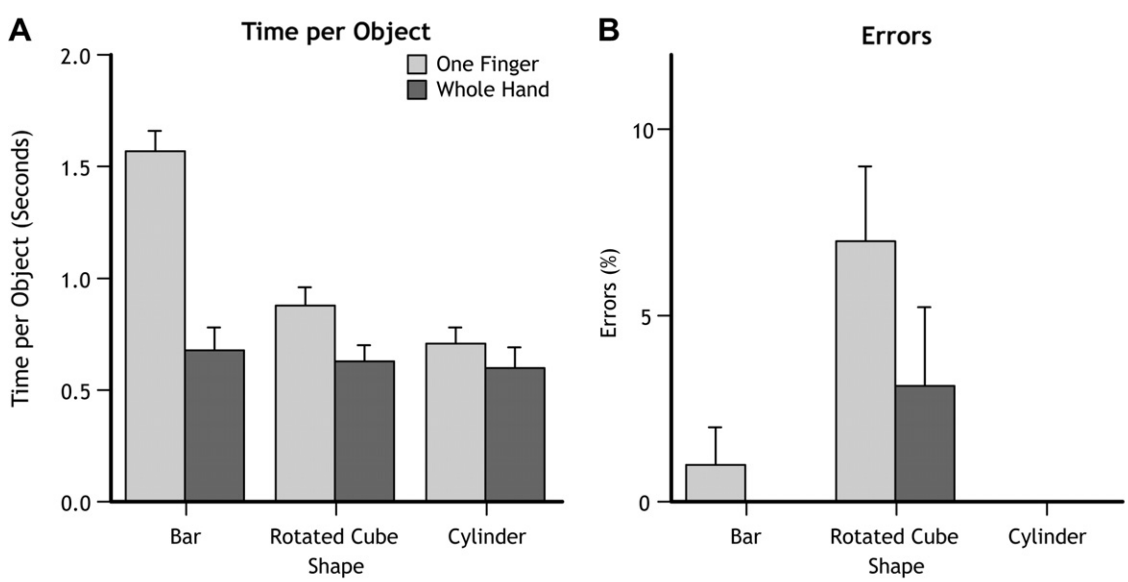

Fig. 5. Results of experiment 2. For further details, see Fig. 3.

4.1. Method

The same setup was used as in experiments 1 and 2. The 8 participants who participated in this experiment had a mean age of 32 years (range 25–47). They were different participants than those in experiments 1 and 2. Two of them stated to be left handed.

In this experiment participants could use both hands to search, and were asked to lift the hand with which they found the target. Both hands started at the same position. Search time was defined from the moment one of the hands started moving, until the moment that the hand that had felt the target (or at least the participant thought so) started moving upwards. As for the previous experiments we performed a univariate ANOVA with factors hands (one or two) and shape (bar, rotated cube and cylinder) on the median times per object.

4.2. Results and discussion

Scan patterns from individual trials of three different participants are shown in Fig. 6. They show that, again, the participants are very systematic in scanning the display. Both hands made similar movements, often resulting in symmetrical scan patterns (A,C). Fig. 6D and E show rose plots of the scan directions for a block of trials of two different participants. Both hands have similar distributions of movement directions, as already could be seen in the examples of Fig. 6A–C. The participant who is represented in Fig. 6D is clearly doing the same up and down scanning movements with both hands, (like in Fig. 6A or B). The frequencies in Fig. 6E for the left hand are similar and might even be a mirrored version of the frequencies of the right hand. This indicates that this participant was scanning symmetrically, and probably changing his strategy depending on the starting position (possibly like in Fig. 6A and C).

The times per object (and those of experiment 2 for comparison) are shown in Fig. 7A. We found a main effect of the number of hands ($F_{(1,10)} = 26.9$, $p < 0.001$), and no effect of shape. Post hoc Tukey/Kramer tests revealed a significant difference between the number of hands used ($p < 0.05$). To be sure that the effect of the number of hands was significant in all the different shape conditions we performed an independent samples t-test for each shape. We found that searching with two hands is significantly faster for all three target shapes (bar $t_{df=15} = 3.05$; oriented cube $t_{df=15} = 3.02$; cylinder $t_{df=15} = 2.96$; Bonferroni corrected α for significance is 0.017). Moreover, we tested whether the time per object for two hands differed from half the time per object for one hand and we did not find any significant effects for any of the shapes (bar $t_{df=7} = 0.40$, oriented cube $t_{df=7} = 1.62$, cylinder $t_{df=7}$1.03; Bonferroni corrected α for significance is 0.017).

Participants made very few errors. The percentages of trials in which the participants indicated a non-target to be a target are shown in Fig. 7B. Non-targets were only mistaken for targets in the rotated cube condition. In the bar and cylinder conditions participants did not make any errors at all. Apparently it is very easy to discriminate these objects with a whole hand. Participants indicated that the rotated cube at the starting position was the target in 0.17% of the trials. The search times were almost halved by using two hands, indicating that information can be processed in parallel over the two hands.

5. General discussion

Our results can be summarised as follows: searching with two hands is always faster than doing so with only one hand. When searching with the whole hand or two hands the time spent per item was very similar for the three target objects. Searching with a single finger is slower than doing so with the whole hand, especially when the target was the bar. The number of objects in the display makes little difference to the time spent per item. Participants made most errors when searching for the rotated cube, irrespective of how they searched. The longer time taken to find a bar when using only one finger is logical because of the need to dynamically explore two sides of each item before knowing that it was a cube or the bar. This explanation is consistent with the results of experiment 2, where finding the bar with the whole hand took about as long as finding the other two targets. When enclosing the object within the hand participants appear to readily recognise its shape. Thus, it was having to move the finger around the object that slowed down the search for the bar when using one finger in experiment 1, rather than having to combine proprioception and tactile information.

The preponderance of errors in finding the rotated cube indicates that proprioceptive information about the orientation of the fingers and hands is used for haptic judgments, but is not reliable enough to lead to 100% correct responses. That it took participants only slightly longer to detect the rotated cube than the cylinder suggests that having to combine touch with information about the orientation of the finger does not take (much) additional time, and thereby does not result in much longer search times.

When participants used two hands to explore the display (in experiment 3) the search times were half of what they were when participants were only allowed to use one hand (in experiment 2). Other studies have also shown faster performance when using two hands instead of one. For example Bradshaw, Nicholls, and Rogers (1998) showed that completion times and error rates were higher in an intramanual than in an intermanual tactual matching task. Craig (1985) also showed much better performance in a two-handed pattern recognition task than in a one-handed task.

Berryman et al. (2006) suggested that size perception occurs in two steps: first cutaneous afferents signal skin contact and detect object surface properties, and after that proprioceptive afferents signal finger spread. They show that if no information is provided during the first stage (because the fingertips are anesthetized) there is still enough information to judge object size in the second proprioceptive stage. If a stage can be skipped (so that it takes no time) when it is not expected to provide any information, then a possible explanation for us finding similar search times for all shapes in the whole hand and two hands conditions could be that the first stage is skipped, because the tactile input is the same for both bar and cubes and is thus non-informative. Therefore, discrimination between different kinds of rectangular and cubic shapes might be mainly proprioceptive. If we then also assume that tactile and proprioceptive information processing take about the same amount of time, and the cylinder is discriminated by touch alone from the cubes and the bar and oriented cube are discriminated from the cubes by proprioception alone, we would be able to explain the results. However, a simpler explanation is that tactile and proprioceptive information processing is always combined, irrespective of whether they are essential for the task.

The fact that we always found most errors for the rotated cube could be the result of perceived haptic space showing large deviations from the actual physical space. We obviously aligned our objects in physical space. To be able to find a rotated cube amongst the other aligned cubes participants obviously need to judge the orientations of the cubes, which involves estimating the orientation of their own hand in space. Kappers (1999, 2004) showed that human perception of what is parallel is far from veridical. Large systematic deviations were found in a task in which participants had to rotate a bar in such a way that it felt as if it were parallel to a reference bar (in the horizontal plane). The orientation of the hand has a large influence on these deviations, implying that participants do not take changes in the orientation of their hand

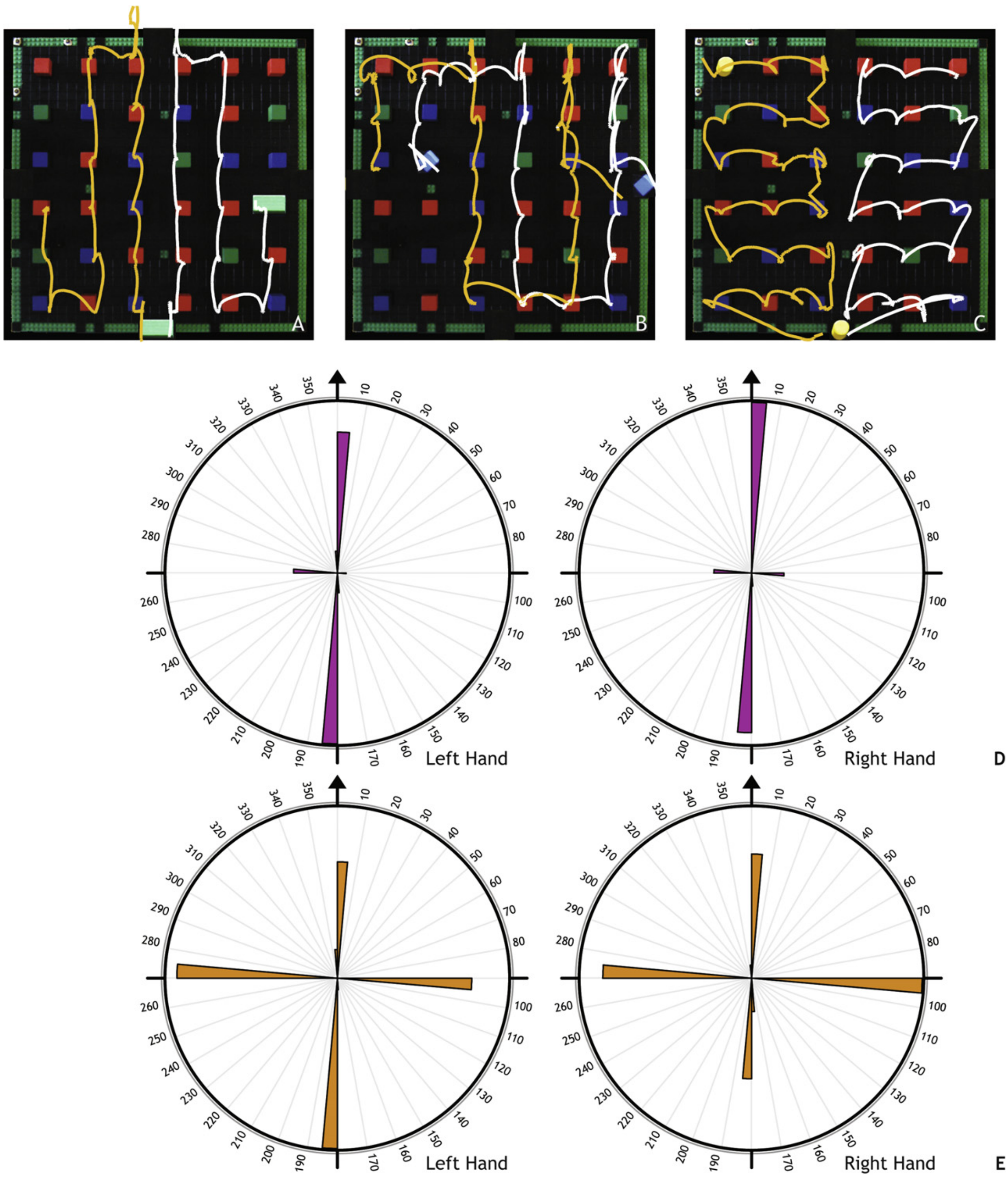

Fig. 6. Typical scan patterns for three different participants in experiment 3 (two hands). The white and yellow lines indicate the different hands. (A) The target was a rotated cube and the starting position was at the bottom. Search time was 13 s. (B) The target was a rotated cube and the starting position was at the right. Search time was 15 s. (C) The target was a bar and the starting position was at the bottom. Search time was 9 s. D and E show the frequencies of scan directions of a block of trials of two different participants. In the left panel the scan directions of the left hand are shown and in the right panel the scan directions of the right hand are shown. For further details, see Fig. 2.

across the workspace sufficiently into account (Kappers & Viergever, 2006). Finding more errors for the larger display size when searching for rotated cubes in experiment 1 is in line with the findings of Kappers et al.: for the larger display size the overall distances are larger so that the orientation of the hand changes more during the exploration of the display, so the systematic errors will also be larger. These systematic errors probably underlie many of the incorrect responses.

The way the participants scanned the display was very systematic. Both with one and two hands they always chose a scan strategy in which they were making ‘zigzag’ or reading movements. This is consistent with the results of Smith et al. (2002), where participants also used a systematic ‘zigzag’ strategy to scan a haptic display. Apparently this systematic scanning is necessary for the participant to be able to keep track of the position of their hand. That keeping track of positions is difficult is evident from the fact

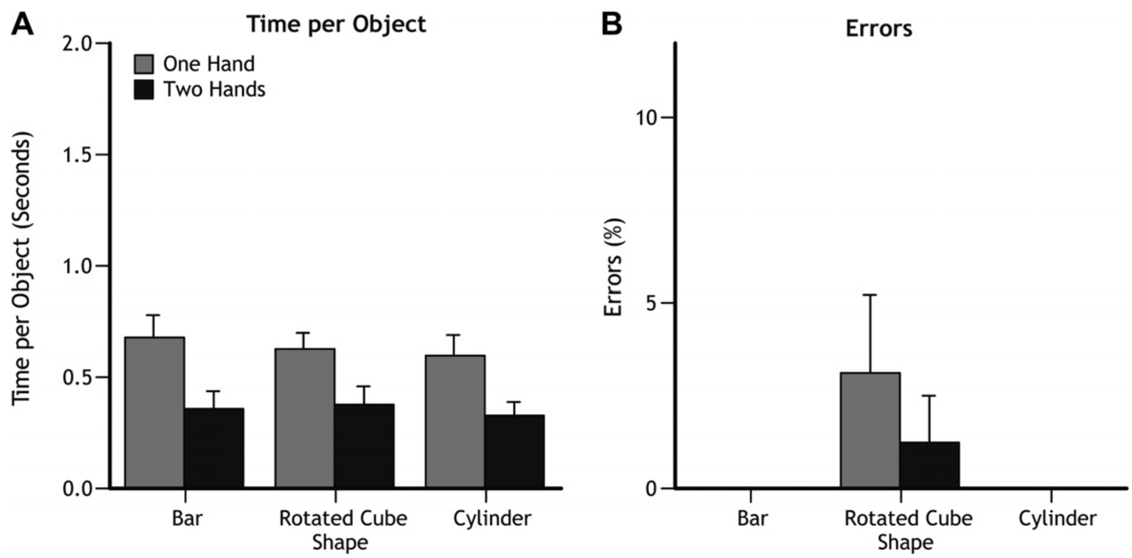

Fig. 7. Results of experiment 3. The differences between one and two hands are between participants, the shape conditions are within participant. For further details, see Fig. 3.

that participants regularly indicated a starting position as being the target. A study by Ballard, Hayhoe, and Pelz (1995) showed that participants, who had to copy patterns of coloured blocks, also performed very systematic. They reason that participants chose not to operate at the maximum capacity of short-term memory, but instead try to minimize its use. This could be an explanation for the current results as well. By adopting a 'zigzag' or reading strategy, participants did not have to store information about the location of their hand in short-term memory, and thus minimized their use of short-term memory.

In sum, a cylinder can be discriminated from cubes by touch alone, while finding a bar or an oriented cube needs proprioception as well. For the bar, one needs knowledge about the relative positions of the fingers, whereas detecting the oriented cube requires information about the orientation of the fingers relative to the display. That all these discriminations took about equally long when searching with the whole hand suggests that either there is not much cost (in terms of time taken) in combining all these sources of information, or information is not combined and each source takes the same amount of time. The oriented cube could be found using touch alone if participants made very precise movements (detecting collision with a corner rather than an edge or an edge rather than a surface), but finding the bar is completely impossible without considering any proprioception.

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