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Salient features in 3-D haptic shape perception

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Shape is an important cue for recognizing an object by touch. Several features, such as edges, curvature, surface area, and aspect ratio, are associated with 3-D shape. To investigate the saliency of 3-D shape features, we developed a haptic search task. The target and distractor items consisted of shapes (cube, sphere, tetrahedron, cylinder, and ellipsoid) that differed in several of these features. Exploratory movements were left as unconstrained as possible. Our results show that this type of haptic search task can be performed very efficiently (25 msec/item) and that edges and vertices are the most salient features. Furthermore, very salient local features, such as edges, can also be perceived through enclosure, an exploratory procedure usually associated with global shape. Since the subjects had to answer as quickly as possible, this suggests that speed may be a factor in selecting the appropriate exploratory procedure.

When we reach into our pocket, we can easily take out our keys from among all other objects we might have in there. However, finding the right key among other keys by touch is much more difficult. Some searches are easy, whereas others are not. Often, it is a specific feature of an object that makes it stand out among others. In the haptic modality, such features can be, for instance, material properties, size, weight, or shape. This study focuses on the haptic perception of 3-D shape and the relative saliency of specific shape features. In this context, we consider any shape property that can be used to distinguish two shapes from each other to be a shape *feature*.

How much an item stands out among other items—that is, its saliency—has been researched extensively in the visual domain, using the visual search paradigm (e.g., Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989). Usually, subjects are asked to respond as quickly as possible as to whether a certain target item is present among varying numbers of distractor items. Response times are then recorded as a function of the number of items. The additional search time needed per item, or the slope, is a measure of how efficiently the search was performed. When a search is performed at maximum efficiency, this slope is near zero, and the target item is said to *pop out*. For near-zero slopes, the search time is thus independent of the number of items, and the search is processed in parallel. Search is performed more serially if all the items are processed sequentially, and response times increase with the number of items. In the target-present trials, on average only half of the items are visited before the search is terminated, whereas in target-absent trials, all the items have to be visited. Therefore, the ratio between the slopes for target-absent and target-present trials for serial search is often 2. In practice, a wide range of slopes and ratios are found, and there is no clear-cut transition between parallel and serial searches (Wolfe, 1998). It would be very valuable to investigate whether such a range of slopes exists in the haptic domain and what the typical values are. This way, a framework can be established with which to compare haptic search slope values, which would facilitate the interpretation of these slopes.

When target and distractor item identities are interchanged, this sometimes leads to large differences in search slope. Such a difference is labeled a *search asymmetry*. It has been suggested that these asymmetries arise when two items are distinguished on the basis of a single feature that is present in the one item and absent or reduced in the other. When this distinguishing feature is present in the target item and absent in the distractor items, the target will pop out, whereas the reverse case will yield serial search. Such asymmetries have been used to identify certain features as *visual primitives* (e.g., Treisman & Gormican, 1988; Treisman & Souther, 1985). It is still an open question whether *haptic primitives* exist or even what the definition should be.

The visual search paradigm has been successfully extended to the haptic domain. In the haptic modality, there are several ways in which items can be presented to subjects. For instance, the items can be pressed onto the subjects' separate fingers (Lederman, Browse, & Klatzky, 1988; Lederman & Klatzky, 1997). These studies showed that material properties such as roughness might be especially good candidates for haptic primitives. However, flat search slopes were not found, and in the absence of other information besides response times, these slopes are difficult to interpret. Note that when items are pressed to the fingers, the maximum number of items is, of course, restricted to the number of fingers, and also exploratory movements are restricted to small finger movements. The items can also be distributed over a surface, allow-

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ing subjects to sweep over the surface, using their whole hand (Plaisier, Bergmann Tiest, & Kappers, 2008a). In this study, there were no restrictions on exploratory movements, and subjects were free to choose an optimal strategy. For conditions in which the type of movement over the display showed a clearly parallel character, a ratio of 2 was found between the slopes for target-absent and target-present trials. For conditions in which the exploratory strategy had a serial character, this ratio was somewhat smaller than 2. Especially when the exploratory strategy was serial, the subjects tended to search (parts of) the display repeatedly, because they were uncertain as to whether they had searched the whole display. This resulted in a difference in offset but not in a large slope difference.

In such a search task, the type of hand movement that was made over the display is a better criterion for distinguishing between parallel and serial search than is the ratio between target-present and target-absent slopes. This shows that exploratory strategies are valuable for interpreting search times and that caution should be taken when visual search models are used to interpret haptic search times.

In the haptic modality, the optimal manner of presenting the items depends on the exploratory movements needed to extract a certain type of information. Lederman and Klatzky (1987) investigated which hand movements are typical for extracting various object properties. These included, for instance, lateral motion for roughness perception, pressure for hardness perception, and enclosure for global object shape. They also showed that object recognition can be impaired when these exploratory movements are constrained (Lederman & Klatzky, 2004). Overvliet, Smeets, and Brenner (2008) found, in a search task in which items were 3-D shapes fixed in a grid, that search times were greatly reduced when the subjects were allowed to enclose the items, as compared with when they were allowed only to explore them with one finger, showing the effect of constraining exploratory strategies on haptic search times. Therefore, when human performance needs to be optimal, one should be cautious as to the constraints that are put on exploratory movements.

Cutaneous shape perception has been researched mostly in terms of edges and curvature. A sphere is an example of a shape that does not have edges and is defined only by curvature, whereas a cube does have edges and only flat surfaces (no curvature). Extensive research has been done into the underlying cutaneous signals involved in tactile shape perception. The mechanoreceptors in the skin have been shown to be sensitive to the edges of stimuli (Phillips & Johnson, 1981). Furthermore, humans can discriminate curvatures that are pressed onto the finger pad (Goodwin, John, & Marceglia, 1991; Jenmalm, Birznieks, Goodwin, & Johansson, 2003), and they can judge the orientation of a cylinder pressed to the finger pad fairly well (Dodson, Goodwin, Browning, & Gehring, 1998). Lederman and Klatzky (1997) found that search for a target item with an edge among distractors without edges, where the items were pressed to the finger pads, was relatively efficient. Note that in all of these studies, an item was presented to the finger pads only. In daily life, however, we often hold multiple 3-D objects in our hand. These objects can be freely manipulated and rearranged in the hand. Furthermore, curvature and edges are only two of the features that can be used to haptically recognize a 3-D shape. Other examples of features that can be used as a cue for shape recognition are surface area, acuteness of the angles, and symmetry. In 3-D solid shapes, several of these features can be present simultaneously, and they can be interrelated. Studying perception of isolated shape features is very important, but it is not clear how perception of one feature influences perception of another. Therefore, in the present study, we used well-characterized 3-D shapes that differed in several shape features.

To investigate the saliency of shape features in the haptic modality, we adopted a search task in which subjects had to grasp multiple items in the hand. The items consisted of 3-D shapes suspended from wires. This way of presenting the items allowed the subjects to enclose the shapes and to manipulate and rearrange the items in their hand. Enclosure is, as was mentioned before, the typical exploratory procedure for global shape. In the present case, there was not one object, but several items were presented simultaneously. The fastest way to explore them would be to grasp them and, thereby, enclose them in the hand. For difficult searches, it could be necessary to explore each item sequentially. To facilitate this, the subjects were allowed to release items from the hand. At the same time, releasing items from the hand can be interpreted as an indication of a serial search strategy. This does not mean that search is by definition performed in parallel if no items are released from the hand. However, when items are released from the hand, search has a serial character. Because we left the exploratory movements largely unconstrained, we allowed the subjects to choose the most efficient strategy for optimizing their performance.

With this design, two experiments were carried out. In the first experiment, the subjects had to search for a cube among spheres and for a sphere among cubes. If these conditions did not yield the same results, there was a search asymmetry, which would lead to the conclusion that one shape was more salient than the other. In the second experiment, three types of shapes were used as target items that were presented among cubes or spheres as distractor items. This would provide insight into the effect of the shape of the distractor items on the efficiency of search for a certain target shape. Note that in this study, saliency is defined with respect to the relative difference between target and distractor items, and not as an absolute value. Finally, the results from both experiments were taken into one analysis in order to investigate the relationship between search efficiency and the difference in several shape features between target and distractor shapes (feature contrast).

GENERAL METHOD

Subjects

Ten paid undergraduate students (6 of them male; mean age, 22 ± 2 years) participated in both experiments. They were all right-handed according to Coren's test (Coren, 1993) and were treated in accordance with the local guidelines. None of the subjects reported any known hand deficits.

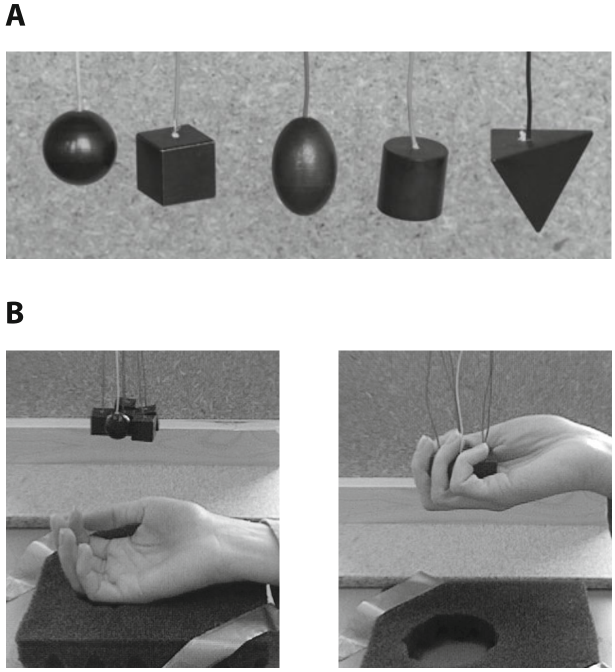

Figure 1. Pictures of the stimuli and setup. (A) The different shapes used in the experiments: from left to right, sphere, cube, ellipsoid, cylinder, and tetrahedron. (B) Pictures of a subject grasping the stimuli. In this case, the target was a sphere, and the distractor items were cubes.

Stimuli and Apparatus

The stimuli consisted of brass shapes, which were suspended from flexible wires. The presented shapes were spheres (radius, 0.93 cm), cubes (edge length, 1.5 cm), ellipsoids (long radius, 1.22 cm; short radius, 0.81 cm), cylinders (height, 1.63 cm; radius, 0.81 cm), and tetrahedra (edge length, 3.1 cm). The different shapes are shown in Figure 1A. These sizes were chosen so that the volumes of the shapes were equal (3.4 cm^3), so as to prevent weight cues. Although the volume was the same, the shapes differed in several other features. These are summarized in Table 1. Here, edge acuteness is defined as the smallest dihedral angle (the angle between two planes of the shape). For a sphere and ellipsoid, this is 180º. Vertex acuteness is defined as the solid angle of a vertex of the shape. Curvature indicates the maximum curvature in the shape, which is defined as the reciprocal of the radius. The longest axis is defined as the longest cross-section through the shape. The aspect ratio is the ratio of the longest and shortest cross-sections through the shape.

Response times were recorded using a custom-built response time measuring device. Time measurement was started when the subject touched any of the items, and the measurement was terminated when a vocal response was registered with a headset microphone. The resulting response time was then returned by the device, with an accuracy of 10 msec (for a detailed description of this device, see Plaisier, Bergmann Tiest, & Kappers, 2008b).

Procedure

Prior to the beginning of a trial, blindfolded subjects placed their dominant hand with the palm upward in a holder. They were instructed to reach upward and grasp all the items simultaneously (illustrated in Figure 1B). The subjects were instructed to respond, as quickly as possible, as to whether or not a target item was present by calling out the Dutch equivalents of "yes" or "no." It was also emphasized that it was important that the answer be correct. They received feedback from the experimenter on whether the answer was correct. Error trials were repeated at the end of a block of trials, and only correct responses were included in the analysis. After initially grasping all the items, the subjects were allowed to release items from their hand during the trial. It was emphasized that they should release items from their hand only if they thought that this was the most efficient strategy. The experimenter scored whether an item was released from the hand during each trial. There were no restrictions on exploratory hand and finger movements.

A total of eight experimental conditions were measured. Search for a cube among spheres (Condition 1) and for a sphere among cubes (Condition 2) belonged to Experiment 1. The other six conditions (Experiment 2) were searches for an ellipsoid, cylinder, or tetrahedron among spheres and searches for these same target shapes among cubes. This means that the distractors were either all spheres or all cubes. All the conditions were performed in separate blocks of trials, and the subjects were informed of what shape the target and distractor items would have in that particular block of trials. Each block of trials was preceded by a training session. For each condition, the subjects performed at least 20 training trials, and trials were continued until 10 subsequent trials were correct. It was never necessary to exceed 30 training trials. The subjects were presented with three, four, five, six, or seven items. Seven was the maximum number of items that could be held comfortably in one hand. Each condition consisted of 100 trials, with 20 trials per number of items. A target item was present in half of the trials. Care was taken that the order in which the eight conditions (in both Experiments 1 and 2) were performed was as close to counterbalanced over subjects as possible. Error rates did not exceed 7% in any of the conditions.

Table 1
Values for Several Parameters of the Six Shapes Used in the Experiments

	Shape				
Parameter	Sphere	Cube	Tetrahedron	Cylinder	Ellipsoid
Edge acuteness (deg)	180	90	70	90	180
Vertex acuteness (deg^2)	20,627	5,157	1,791	10,313	20,627
Edge length (cm)	0	1.5	3.1	5	0
Maximal curvature (cm^{-1})	1.1	0	0	1.2	1.86
Longest axis (cm)	1.9	2.6	3.1	2.3	2.4
Surface area (cm^2)	10.9	13.5	18.7	16.5	11.1
Aspect ratio	1	1.7	1.3	1.4	1.5
Number of edges	0	12	6	2	0
Number of vertices	0	8	4	0	0

Note—Volume was constant. Edge acuteness indicates the dihedral angle, vertex acuteness is the solid angle of a vertex, curvature is defined as the reciprocal of the radius, the longest axis indicates the length of the longest cross-section, and aspect ratio is the ratio between the longest and shortest cross-sections.

EXPERIMENT 1

This experiment consisted of two conditions. The subjects had to search for a sphere among cubes or for a cube among spheres. Note that these conditions differ only by interchanging the target and distractor identity. If these conditions yield different results in terms of the slope of the response times as a function of the number of items, this suggests that one shape is more salient than the other one.

Results

The response times averaged over subjects as a function of the number of items are shown Figure 2A. The lines represent linear regression to the response times ($R^2 \geq .86$). The target-present and target-absent slope values for a cube among spheres were 63 ± 8 msec/item (± *SE*) and 200 ± 10 msec/item, respectively. Regression analysis for the sphere among cubes yielded 113 ± 30 msec/item and 520 ± 30 msec/item for target-present and -absent trials. Note that the ratios between target-absent and target-present search slopes are rather larger than 2 and that they differed considerably between the two conditions. For the cube among spheres, this ratio was approximately 3, whereas for the sphere among cubes, it was almost 5.

A 2 × 2 (condition × target presence) repeated measures ANOVA was performed on the slopes of the single subjects' response times. This yielded significant main effects for condition [$F(1,9) = 28.5$, $p < .001$, $\eta_p^2 = .8$], target presence [$F(1,9) = 42.9$, $p < .001$, $\eta_p^2 = .8$], and the interaction term [$F(1,9) = 14.2$, $p < .01$, $\eta_p^2 = .6$]. The significant effect for condition indicates that there is a search asymmetry. Cube among spheres yields a smaller slope than does the reversed condition. The significant effect for target presence shows that slopes were significantly larger for target-absent trials, which has commonly been found in both haptic and visual search tasks. The significant interaction term indicates that the slope difference between target-present and target-absent trials depended on the condition. This is clear from the difference in the ratio between the slopes from target-present and target-absent trials in the two conditions.

Figure 2B shows the percentage of trials on which at least one item was released from the hand. It can be seen from this figure that items were released mainly in target-absent trials and, specifically, when the distractors were cubes. A 2 × 2 (condition × target presence) repeated measures ANOVA on the percentage of trials on which an item was released from the hand showed significant main effects for condition [$F(1,9) = 12.5$, $p < .05$, $\eta_p^2 = .6$] and target presence [$F(1,9) = 10.1$, $p < .05$, $\eta_p^2 = .5$]. Also, the interaction term between condition and target presence was significant [$F(1,9) = 13.9$, $p < .01$, $\eta_p^2 = .6$].

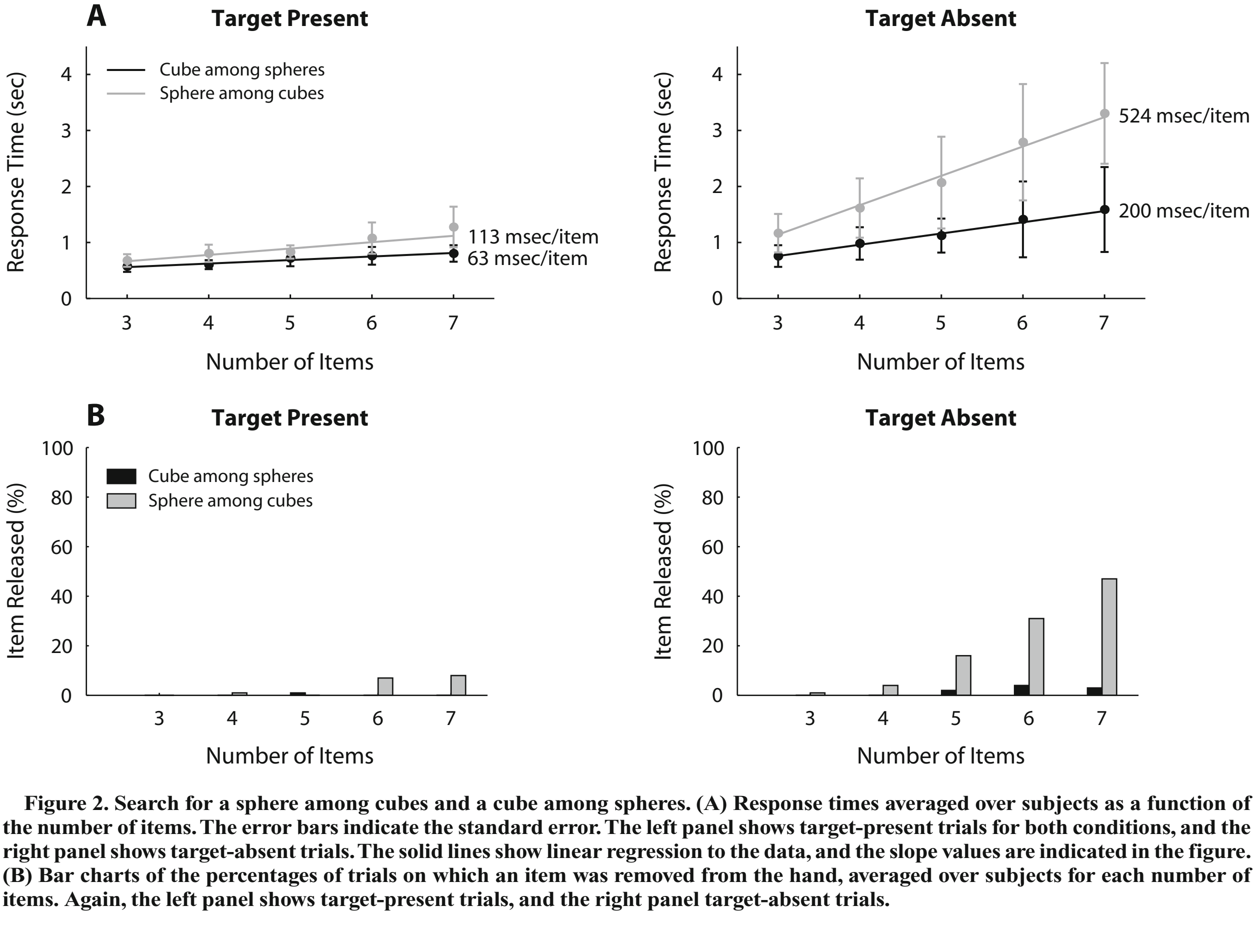

Figure 2. Search for a sphere among cubes and a cube among spheres. (A) Response times averaged over subjects as a function of the number of items. The error bars indicate the standard error. The left panel shows target-present trials for both conditions, and the right panel shows target-absent trials. The solid lines show linear regression to the data, and the slope values are indicated in the figure. (B) Bar charts of the percentages of trials on which an item was removed from the hand, averaged over subjects for each number of items. Again, the left panel shows target-present trials, and the right panel target-absent trials.

Discussion

The search slopes for target-present and target-absent trials in the sphere-among-cubes condition were significantly larger than those for a cube among spheres, indicating a search asymmetry.

This suggests that a cube among spheres is more salient than a sphere among cubes. It was also found that the ratio between target-absent and target-present slopes was much larger for the sphere-among-cubes condition than for the reverse condition. This difference in the ratio between target-absent and target-present slopes was accompanied by a difference in the number of trials on which items were released from the hand. An analysis of the item release data showed that this happened significantly more often in target-absent trials when the distractors were cubes. The analysis of the search slopes, together with the item release data, indicates that the subjects switched their strategy during a trial from only grasping all the items in target-present trials to releasing items in target-absent trials, especially when the distractors were cubes. This strategy difference between target-present and target-absent trials could, therefore, explain why the ratio between the search slopes was much larger than is usually found in visual search tasks.

The most important difference between the present search task and all previous search tasks reported in the literature is that, in the present study, item positions could be actively rearranged. The subjects could slide the items along each other; therefore, physical interactions between the shapes could have influenced search efficiency. A handful of cubes is more difficult to manipulate and rearrange than spheres, because cubes do not slide along each other as easily as spheres do. The cubes have, for instance, a larger mutual contact area than do spheres, so the frictional forces are larger. A possible explanation for the large difference in target-absent and target-present search slopes is, then, that a sphere slides easily out from between cubes when the shapes are grasped, but when there are only cubes, this, of course, does not happen. In that case, the subjects might have been uncertain as to whether there really was no target present and may have adopted a more serial search strategy, leading to larger search times. To investigate the differences in search efficiencies when the distractor items were cubes, as compared with when they were spheres, Experiment 2 was performed.

EXPERIMENT 2

This experiment consisted of six search conditions. These conditions were searches for an ellipsoid, cylinder, or tetrahedron target among spheres and among cubes as distractor items. By comparing search efficiency for one of the target shapes among cubes with search for the same target shape among spheres, we could investigate the effect of distractor shape on search efficiency for each target shape.

Results

Figure 3A shows the response times averaged over subjects as a function of the number of items for each of the target shapes among spheres, whereas the response times for the target shapes among cubes are shown in Figure 3B. The lines represent linear regression to the response times, and the slopes obtained are indicated in the figure. This figure shows that search for an ellipsoid among cubes was very efficient, whereas among spheres it was the most inefficient condition. Also, search for a tetrahedron among spheres was more efficient than search for a tetrahedron among cubes. This indicates that search efficiency depended on whether the distractors were cubes or spheres.

Linear regression was also performed on the single subject's data. Figure 4 shows the obtained slopes averaged over subjects. A 2 × 3 × 2 (distractor shape × target shape × target presence) repeated measures ANOVA on these slopes yielded significant main effects for distractor shape [$F(1,9) = 6.5$, $p < .05$, $\eta_p^2 = .4$], target shape [$F(1.2, 10.7) = 17.2$, $p < .005$, $\eta_p^2 = .7$], and target presence [$F(1,9) = 90.1$, $p < .001$, $\eta_p^2 = .9$]. The interactions between distractor shape and target shape [$F(1.3, 11.6) = 51.2$, $p < .001$, $\eta_p^2 = .8$] and between distractor shape and target presence [$F(1,9) = 14.5$, $p < .01$, $\eta_p^2 = .6$], as well as the interaction between distractor shape and target presence [$F(2,18) = 5.8$, $p < .05$, $\eta_p^2 = .4$], were significant. Also, the interaction of distractor shape, target shape, and target presence was significant [$F(2,18) = 16.6$, $p < .001$, $\eta_p^2 = .6$].

Figure 5 shows that the percentage of trials on which an item was released from the hand increased with the number of items and that the percentage of item release trials was largest for target-absent trials for both distractor shapes. In general, an item was removed on a larger percentage of trials when the distractors were cubes than when the distractor items were spheres. A 2 × 3 × 2 (distractor shape × target shape × target presence) repeated measures ANOVA on the percentage of trials on which an item was released showed significant main effects for target shape [$F(2,18) = 14.8$, $p < .001$, $\eta_p^2 = .6$] and target presence [$F(1,9) = 54.7$, $p < .001$, $\eta_p^2 = .9$]. The factor of distractor shape did not reach significance. However, the interaction between distractor shape and target shape [$F(1.3, 11.7) = 43.5$, $p < .001$, $\eta_p^2 = .8$] and the interaction between distractor shape and target presence [$F(1,9) = 11.3$, $p < .01$, $\eta_p^2 = .6$] were significant.

For both the search slopes and the percentages of item releases, an interaction was found between target presence and distractor shape. In Figure 4, it can be seen that the ratio between target-absent and target-present search slopes varied for the different conditions. Also, the ratio between the percentage of item releases between target-absent and target-present trials varied over the conditions. There was a significant positive relationship between the search slope ratios and the item release ratios ($r = .38$, $p < .001$, two tailed).

Discussion

The slopes from the different conditions cover a large range of values, and search efficiency ranged from highly efficient (25 msec/item) to quite inefficient (703 msec/item). Note that search efficiency for a certain target depended heavily on the identity of the distractor items. For instance, search for an ellipsoid among cubes was

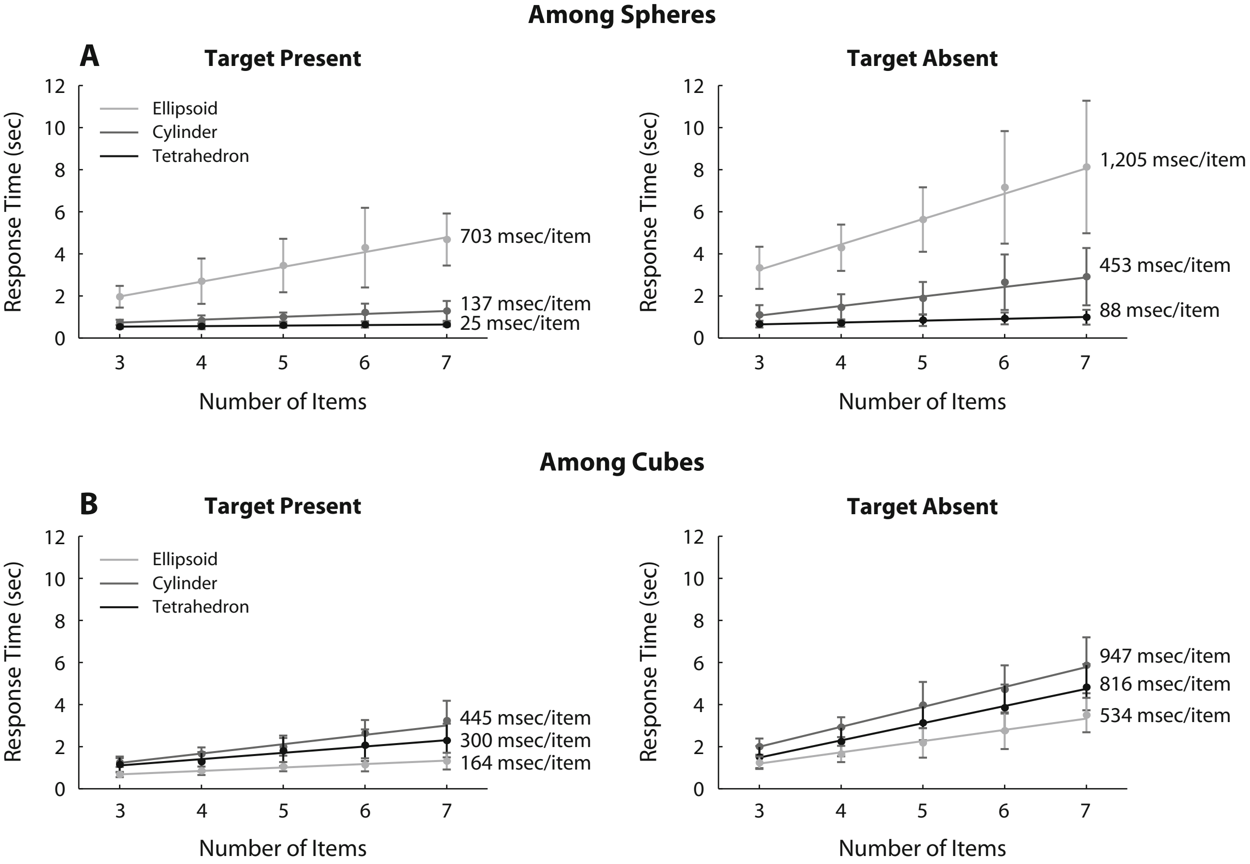

Figure 3. Response times averaged over subjects as a function of the number of items for each of the target items. The error bars indicate the standard error. The left panels show target-present trials, and the right panels show target-absent trials. The solid lines represent linear regression to the data, and the slopes are indicated in the figure. Distractor items were spheres (A) or cubes (B).

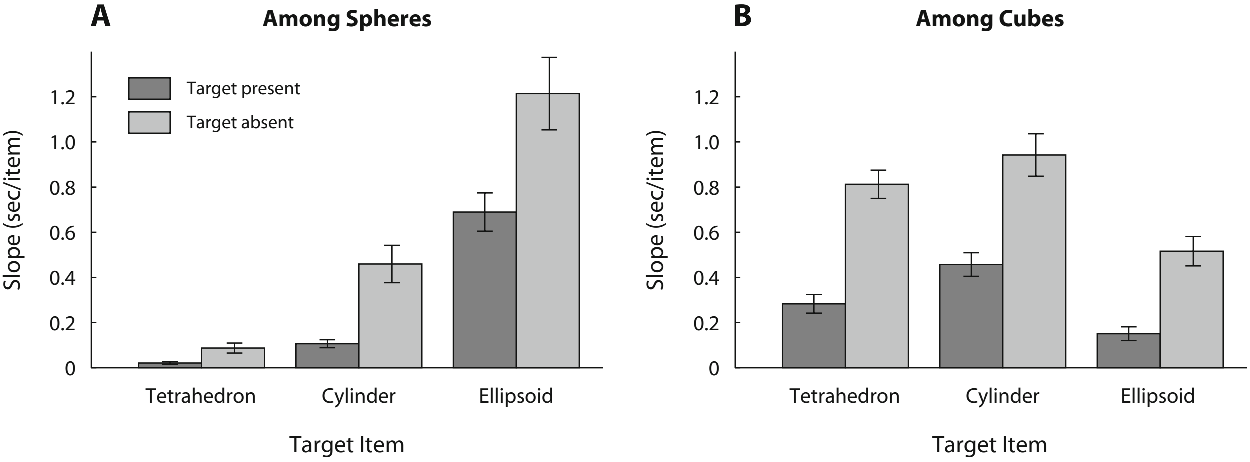

Figure 4. Bar charts of the averaged slopes from regression to the individual subject's data for each of the target items. The error bars indicate the standard error. Distractor items were spheres (A) or cubes (B).

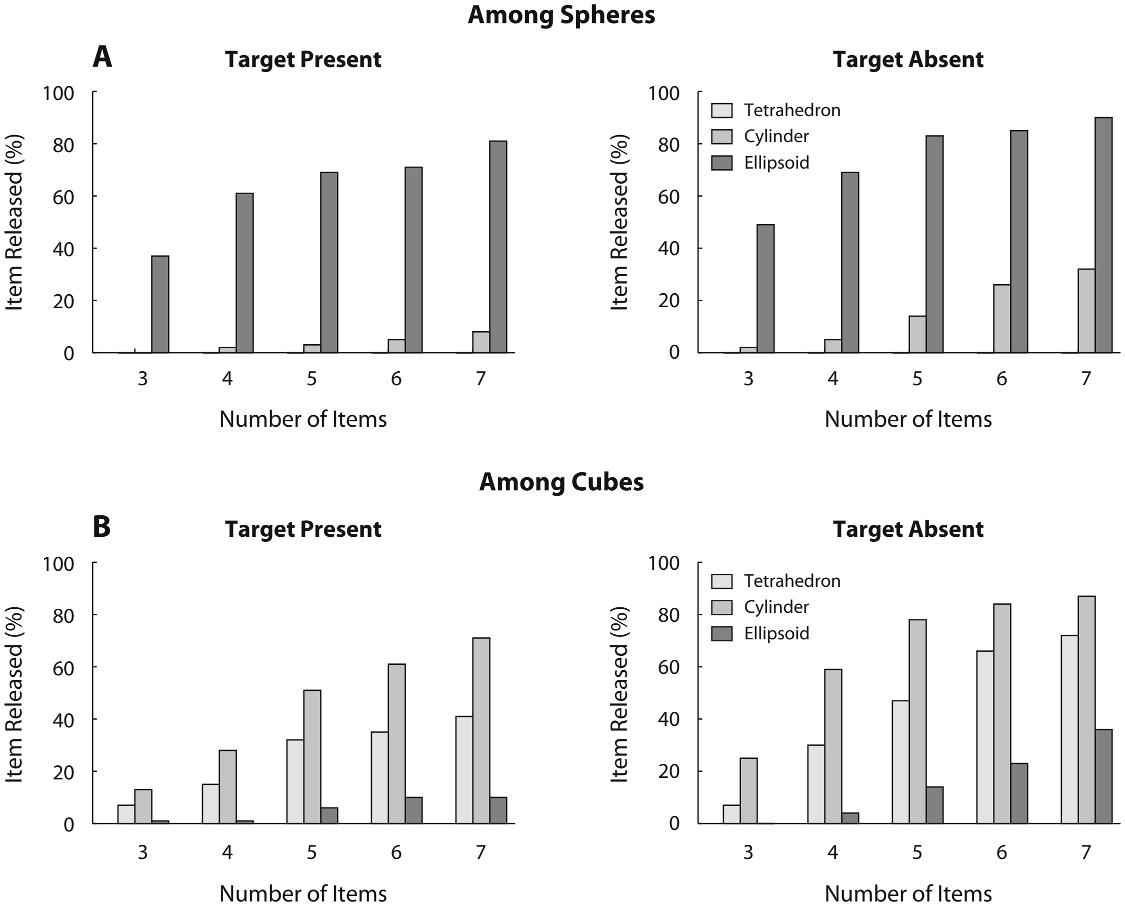

Figure 5. Percentage of trials on which an item was removed from the hand for each of the target items as a function of the number of items. The left panels show target-present trials, and the right panels show target-absent trials. Distractor items were spheres (A) or cubes (B).

relatively efficient, whereas, of all the conditions in the experiment, the ellipsoid-among-spheres condition had the least efficient search performance. The reversed result was found when the target was the tetrahedron. Search for the tetrahedron among spheres was performed more efficiently than was search in all the other search conditions in the experiment, but search for the tetrahedron among cubes was much less efficient.

These differences in search slopes were accompanied by differences in the percentage of trials on which an item was released from the hand. The conditions for which this percentage was high were also the conditions that yielded relatively large search slopes. This indicates that the search strategy that was adopted depended on the specific combination of target shape and distractor shapes. As was also found in Experiment 1, the subjects released items from the hand more often when the distractors were cubes than when the distractor items were spheres. Also, analysis of the slopes showed that search slopes were, on average, larger when the distractors were cubes. There are two possible explanations for this strategy difference. First, the relatively intense stimulation from the edges and vertices of the cubes may make it difficult to find a target among cubes, and as a consequence, subjects tend to remove an item from their hand more often. Another explanation mentioned earlier suggested that the difference between cubes and spheres as distractors is due to the physical interactions between the shapes when they slide along each other. Also, the interaction between distractor shape and target presence found in the analysis of the slopes, as well as the item release data, could be related to the sliding of the shapes along each other. A certain target shape might easily slide out from among the distractor items, but in target-absent trials this would not happen, and subjects would adopt a more serial search strategy. Both of these explanations are in agreement with the data, and it is possible that both effects played a role here.

A difference in strategy between target-present and target-absent trials can explain a large ratio between the associated slopes. The results showed that when there was a large difference in search slope between target-present and target-absent trials, there was also a large difference between the percentages of item releases for target-present and target-absent trials. This suggests that a large difference in search slope between target-present and target-absent trials may indeed have been caused by a change in search strategy. Strategy differences also explain why the general range of search slope values that was found is so large. When items are released from the hand, the extra search time per item is considerable, and this will result in a search slope that is much larger than that for conditions in which no items were released. Therefore, haptic search slopes from different conditions of one experiment can span a much larger range than is usually found in vision. This is especially true under conditions of free exploration, in which subjects actively explore the stimulus.

RELATIONSHIP BETWEEN SHAPE FEATURES AND SEARCH EFFICIENCY

To investigate which specific features of 3-D shape were the most salient, the slopes from Experiments 1 and 2 were included in one analysis. The shape features that were taken into account were edge acuteness, vertex acuteness, edge length, maximal curvature, length of the longest axis, surface area, aspect ratio, the number of edges, and the number of vertices. Note again that the volume was the same for all of the shapes. The values of these parameters for the different shapes are summarized in Table 1. Because search efficiency depended on the specific combination of target and distractor shapes, the absolute difference between the values of the parameters of the target shape and those of the distractor shape were taken for each of the conditions in Experiments 1 and 2, designated by Δ parameter. Linear regression was then performed on the target-present search slopes as a function of these absolute differences. For each of the parameters, this is shown in Figure 6.

In the set of shapes that was used, edge acuteness and vertex acuteness were highly correlated, as were the number of edges and the number of vertices (Pearson's $r > .9$). To avoid collinearity problems for the pairs of correlated features, the feature with the smaller R^2 value was not taken into the multiple regression analysis. This means that edge acuteness and number of edges were taken into the analysis and vertex acuteness and number of vertices were not. A

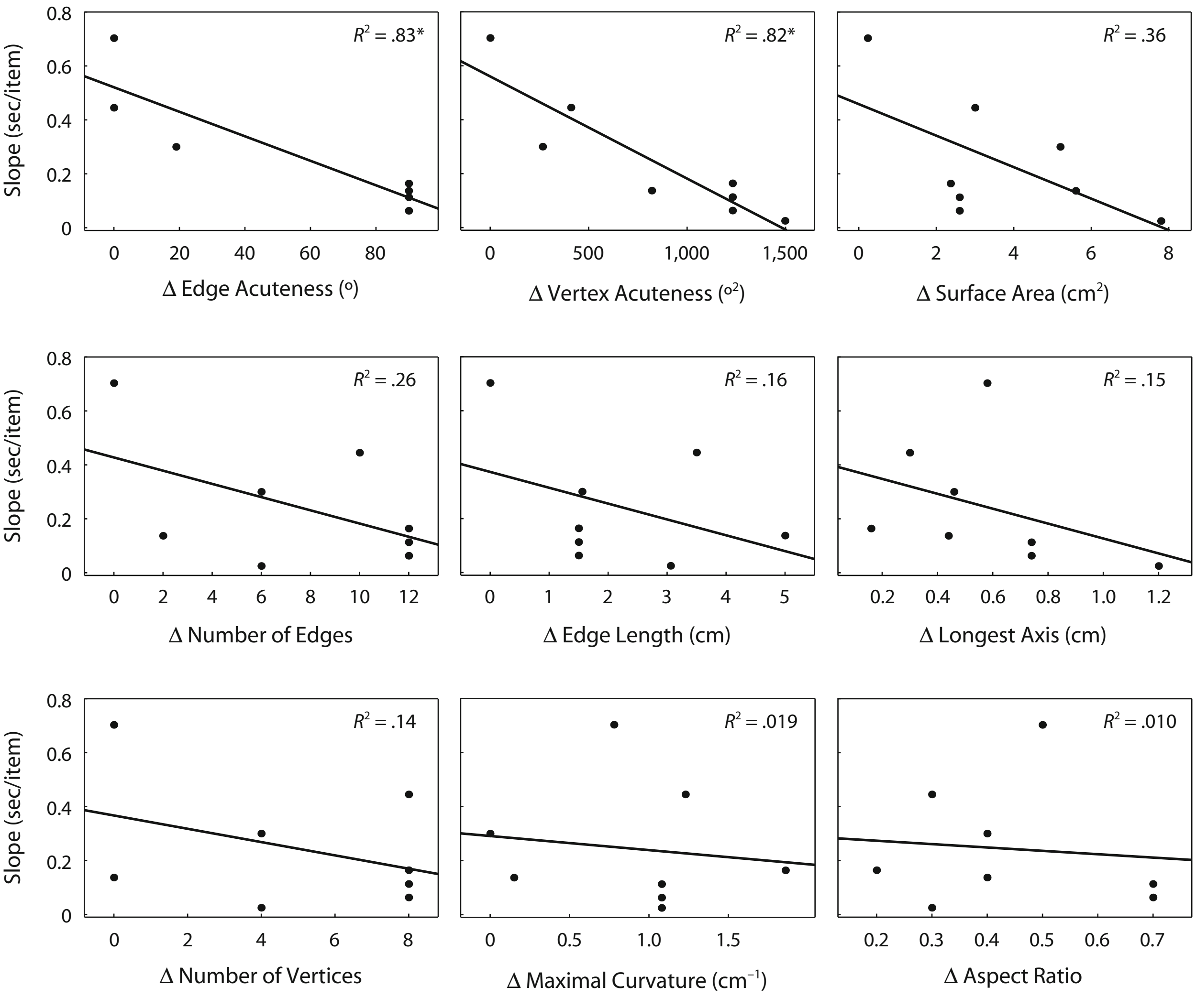

Figure 6. Target-present search slopes as a function of the absolute difference between target and distractor shapes for several parameters of the shapes. These parameters were edge acuteness, curvature, longest axis, surface area, aspect ratio, and number of edges. An asterisk indicates that the relationship was significant ($p < .05$). Note that this was the case only for edge acuteness and vertex acuteness.

multiple regression analysis with stepwise variable entry was performed on the aforementioned parameters, with target-present slopes as the dependent variable. The regression analysis showed that only acuteness of the edges improved the model significantly ($R^2 = .91, p = .002$). This indicates that this was the dominant parameter for search efficiency. Note that because edge acuteness and vertex acuteness were highly correlated, we cannot distinguish between these two features. Therefore, we conclude that edges and vertices are the most salient features in haptic perception of 3-D shape. Search is most efficient when the target shape has edges and the distractors do not or vice versa. Number of edges, however, did not show a significant relationship with the search slopes. Of course, if both target and distractors do or do not have edges, search efficiency will depend on other parameters, and these results do not mean that other features cannot be used for haptic shape recognition. These results could be interpreted in terms of similarity between target and distractor items. In vision, it has been proposed that the difficulty of a search task increases with increasing similarity between target and distractor items (Duncan & Humphreys, 1989). In relation to this, it has also been shown that the saliency of a target item increases when there is a feature contrast between the target and the distractors in several dimensions (Nothdurft, 2000). If we extrapolate this to our study, this would indeed predict that a cylinder among cubes is more salient than a tetrahedron among cubes, since the cylinder differs from the cube in both edge acuteness and curvature, whereas the tetrahedron mainly differs only in edge acuteness.

GENERAL DISCUSSION

It has been shown that haptic object recognition can be very fast and accurate (Klatzky & Lederman, 1995; Klatzky, Lederman, & Metzger, 1985). To mediate fast object recognition, there must be certain object features, such as shape, that are extracted and processed very efficiently. Unfortunately, only a few studies are available on haptic perception of 3-D shapes. The studies that are available were concerned mainly with the comparison between haptic and visual shape perception. One of these studies, in which subjects had to haptically explore solid shapes and then recognize the felt shape visually, showed that this task could be performed fairly well (Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004). This suggests that there is some shared underlying representation of shape for both modalities. However, in this study, differences were also found between the modalities. When the shapes were first presented visually and had to be recognized haptically, the authors found that shapes with similar *global shape* tended to be confused. This could have been due to a difference in weighing of global and local shape features between the haptic and the visual modalities. It has indeed been shown that such a difference exists. Lakatos and Marks (1999) showed that, in vision, global shape properties were weighed more heavily than local shape properties. In the haptic modality, on the other hand, global and local shape properties were weighed equally.

For haptic perception of global and local shape properties, different types of exploratory procedures (EPs) have been identified (Lederman & Klatzky, 1987). The typical EP for global shape is enclosure, whereas for local shape, the EP is contour following. In the aforementioned study by Lakatos and Marks (1999), subjects wore (splinted) gloves to force them to explore the shape through enclosure alone, in an attempt to bias them toward global shape properties. However, this did not produce different similarity ratings between the objects, as compared with when the objects were explored without the glove. In their article, they suggested that hand movements are not as specialized as is sometimes thought. It could be that some information about local shape also can be extracted through enclosure. Global and local shape properties can also be identified in the present study. The global shape can be interpreted as the shape of the cluster of the individual shapes when grasped together in the hand. Local shape properties are then the shape features of the individual shapes.

In our study also, different exploratory strategies were used. When search was performed efficiently, no items were released from the hand, and the target could be detected through enclosure (e.g., tetrahedron among spheres). Note that the global shape of the cluster of items was the same for target-present and target-absent trials. So, in this case, local shape properties could be detected through an EP that has been associated with global shape. Since the subjects were instructed to perform the task as quickly as possible, this suggests that speed can be a factor in selecting an EP. Lederman and Klatzky (1990) showed that there is a typical two-stage sequence for haptic object exploration, consisting of initially grasping (enclosing) the object, followed by a more specialized EP, if necessary. In the present study, enclosure was not sufficient in all of the search conditions for finding the target. In some, less efficient conditions, the individual shapes were explored through a serial strategy, and items were removed from the hand (e.g., ellipsoid among spheres). This suggests that the most salient local shape features can be perceived through enclosure, whereas less salient local shape features cannot be perceived this way.

Our results show that edges and vertices are very salient features of 3-D shape. Search was performed efficiently if the target shape had edges but the distractor shapes did not or vice versa. Efficiency of search for an edge has been studied before (Lederman & Klatzky, 1997). In that study, items were presented by pressing the surface onto the subjects' individual fingers. This could, then, be a continuous flat surface or a flat surface with a raised edge on it. In that study, no asymmetry was found between search for an edge among no-edge items and the other way around. However, the comparison between the results from that study with those from the present study is not straightforward. The exploratory movements in the present study were very different from the small finger movements that can be made when surfaces are pressed onto the fingers. Moreover, in the present study, the items consisted of solid 3-D shapes, and in such shapes, many features are present simultaneously and can also be interrelated. For instance, a closed 3-D shape that does not have edges must necessarily have curvature. The asymmetry between search for a cube among spheres and search for a sphere among cubes that was found in Experiment 1 of the present study can be interpreted in two ways. It could be interpreted as meaning that search for the presence of an edge is more efficient than search for the absence of an edge or as meaning that search for an edge is more efficient than search for curvature. The last interpretation is supported by the results from Experiment 2, which showed that search for a cylinder among cubes was less efficient than search for a tetrahedron among cubes, although a cylinder has curvature and cubes and tetrahedrons do not.

Haptic shape perception has often been studied by studying perception of isolated cues. Examples are research into the saliency of isolated shape features, as in the study of Lederman and Klatzky (1997), or measurements of perceptual thresholds for, for instance, curvature (Goodwin et al., 1991; Gordon & Morison, 1982; Pont, Kappers, & Koenderink, 1997; Van der Horst & Kappers, 2007). Although these studies have provided important information regarding the perception of shape features, in 3-D shapes many shape features are present simultaneously, and they are often related. It is not clear a priori how these different features are combined, and therefore, the present study, in which these features were combined, is very valuable. Furthermore, free exploration, as used in the present study, allows the subjects to optimize their perception (Lederman & Klatzky, 1987) and facilitates comparison with haptic exploration in daily life. Moreover, differences in exploratory movements across search conditions can provide information on the saliency of a target item. We have suggested before that the use of global exploratory movements combined with high search efficiency may be a useful definition for a haptic version of the pop-out effect (Plaisier et al., 2008a). According to that definition, edges and vertices would certainly qualify as shape features that pop out.

AUTHOR NOTE

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