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Optimal exploration strategies in haptic search

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Abstract. In this study, we have investigated which strategies were optimal in different haptic search tasks, where items were held in the hand. Blindfolded participants had to detect the presence of a target among distractors while using predetermined strategies. The optimal strategy was determined by considering reaction time and error data. In the search for salient targets, a rough sphere among smooth or a cube among spheres, parallel strategies were optimal. With non-salient targets, the results were different. In the search for a sphere among cubes, a parallel strategy was effective, but only if the fingers could be used. In the search for a smooth sphere among rough, only a serial strategy was successful. Thus, the optimal strategy depended on the required perceptual information.

Keywords: Haptic search, Exploratory movements, Psychophysics

1 Introduction

In haptic search, many possible exploration strategies can be used to detect a target among distractors. In general, a division between parallel and serial strategies is made based on the change in reaction times (i.e., the time to detect a target) with the number of stimuli. In a parallel strategy, multiple items can be perceived at the same time, so the reaction time will not increase with more items. On the other hand, in a serial strategy, the items are explored one by one, so the reaction time will increase. This reaction time measure stems from visual research [4, 8] and is also most often used to infer the strategy used in haptic search.

There are only a few studies that used motion analysis to examine strategy use in haptic search in a 2D task (i.e., stimuli presented on a display). When the exploratory movements are examined, strategy differences have been found in the search for roughness [3] and movability [5, 6]. When a salient target needed to be detected among distractors, movements were shorter, faster and more fluent than in the search for a non-salient target. Specifically, if movements were divided into qualitative categories, different movement types were dominant depending on the target that was to be searched for [5]. For example, a salient target could be detected with only a sweep over the display. These observations indicate that humans adapt their behaviour to the difficulty of the task.

These studies investigated set-ups where the items were placed on a display (2D task). In situations where the stimuli are held in the hand (3D task), less is known about the exploration movements that are made. It has been reported that items are more often dropped out of the hand in difficult searches [3, 7]. This behaviour is intentional, to explore the items in a serial manner. However, in these studies it was only counted whether items were dropped or not and this measure gives only limited information about the strategy that can be used.

In the explorations of single objects, it seems that participants choose the optimal exploratory procedure to perceive a specified object property [1]. The question is whether they also choose an optimal strategy in a search task. We wanted to examine which strategy would be optimal in different search tasks. Therefore, we restricted participants to the use of a single strategy that was determined beforehand. These strategies differed in the use of the fingers and a parallel or serial nature. In this way, we could examine whether parallel or serial strategies can be used in the search and whether sensitive parts of the hand (i.e., the fingertips) should be used.

2 Methods

2.1 Participants

Nine participants (5 males) with a mean age of 20±2 took part in the study. They all reported to be right-handed. Before the start of the experiment, participants gave their informed consent. The study was approved by the Ethics Committee of the Faculty of Human Movement Sciences, VU University Amsterdam.

2.2 Apparatus

The same stimuli as in [7] were used: rough spheres, smooth spheres and smooth cubes. The spheres had a diameter of ~ 15 mm and the cubes had an edge length of ~ 12 mm, making the volumes (~ 1.7 cm^3) and weights (~ 1 g) approximately equal. The stimuli were all made of wood and the rough spheres were made rough by gluing small pieces of sandpaper on them. Strings were glued to the stimuli and bundles of 7 items were made, which was the maximum number of items that can be held comfortably in the hand. The same experimental set-up as described in [7] was used. A bundle of items was hung from a tripod that was placed on a weighing scale (Mettler Toledo SPI A6). When the items were touched, a weight change induced the start of the reaction time measurement. The end of the reaction time was determined by a vocal response from the participant, recorded with a microphone of a head-set. The weighing scale had a delay of 90 ± 20 ms [6], which was added to the raw data.

2.3 Task and Procedure

The experimental design consisted of four search tasks and three movement strategies. The search tasks were the search for a rough sphere (*rough*) among smooth spheres and vice versa (*smooth*) and the search for a smooth cube among smooth spheres (*cube*) and vice versa (*sphere*). The names of the tasks correspond to the target property that is searched for.

The three movement strategies were called *grasp*, *rub* and *drop*. In the *grasp* strategy, the whole hand was used to squeeze the stimuli. The fingers must not be used separately and stimuli should not be felt between the fingers. Multiple grasps were allowed and all items must be held in the hand. In the *rub* strategy, only the fingers were used to feel the stimuli and not the hand palm. The hand was allowed to rest on the table. The final strategy was the *drop* strategy. Here, all items must initially be held in the hand and subsequently dropped out of the hand one by one with the thumb or fingers.

The strategies were presented in a blocked design and approximately counterbalanced across participants. Within the strategy blocks, the order of the tasks was varied, but the texture searches (smooth and rough) and the shape searches (cube and sphere) were always grouped together. This was done to keep strategy and property changes minimal for participants. Ten target-present and ten target-absent trials were randomly presented in each condition. Erroneous answers where repeated at the end of each condition. To avoid endless repetitions of errors, the condition was terminated once 10 errors were made.

The task and procedure were explained to the participants before the start of the experiment. They where told what to search for and the required strategy was explained and demonstrated by the experimenter. Next, the blindfolded participants performed 10 practice trials, to get acquainted with the strategy. The correct use of the strategy was monitored by the experimenter during the practice and the experiment. They were instructed to determine whether a target was present or not and they had to do this as fast as possible, but also as accurately as possible. Once they knew a target was present or not, they called out 'yes' or 'no'. Feedback about the correctness of their answer was provided.

2.4 Analysis

Only correctly answered trials were included in the reaction time analysis. Because in some cases the condition was terminated early, not all conditions included 20 correctly answered trials. However, in all conditions more than 83% of the data could be included. A 3 (strategy) $\times$ 4 (task) $\times$ 2 (target presence) repeated measures analysis of variance (ANOVA) was performed on the reaction time data. If Mauchly's test of sphericity was violated, a Greenhouse-Geisser correction was applied. Post-hoc tests were performed using paired-sample t-tests with a Bonferroni correction. In the comparisons between the conditions, only conditions with the same property (texture or shape) were compared.

The number of errors was counted and expressed in percentage of the total number of performed trials in a condition for target-present and target-absent trials separately. The influence of the strategies on the number of errors was of main interest to be able to investigate which strategy was optimal. Therefore, separate Friedman ANOVAs were performed for each task to examine the effect

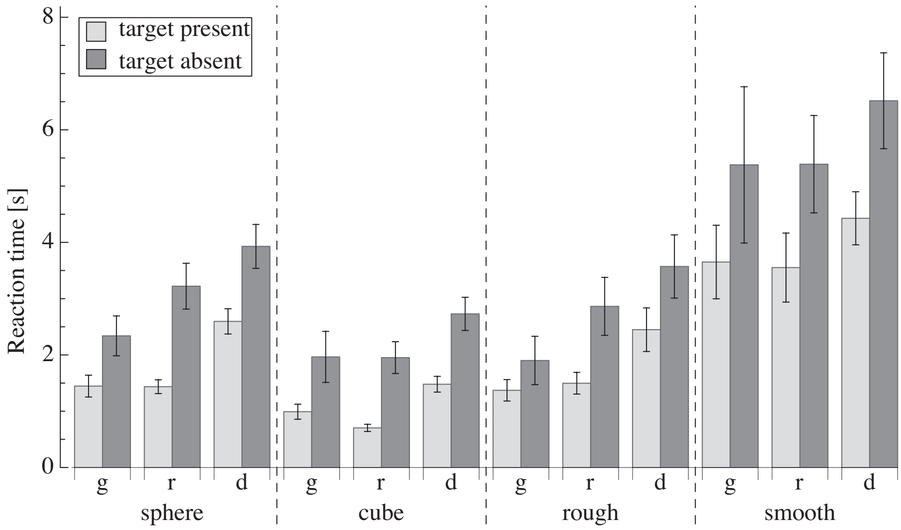

Fig. 1. The reaction times for each strategy (g=grasp, r=rub, d=drop) and each task. Error bars represent standard errors.

of strategy. Wilcoxon signed rank tests with a Bonferroni correction were used for post-hoc comparisons.

3 Results

The reaction time data are illustrated in Fig. 1. The ANOVA on the reaction times revealed main effects of strategy ($F_{2,16} = 9.5$, $p = 0.002$), task ($F_{1.1,8.9} = 23.9$, $p = 0.001$) and target presence ($F_{1,8} = 20.4$, $p = 0.002$). With the strategies grasp and rub, participants were faster than with the drop strategy (grasp: $p = 0.031$, rub: $p = 0.028$). The post-hoc tests of the condition effect indicated that reaction times were longer in the the smooth condition than the rough condition ($p < 0.001$). In addition, the sphere condition had longer reaction times than the cube condition ($p < 0.001$). The effect of target presence showed that reaction times were higher in target-absent trials compared with target-present trials. The interaction of condition × target presence ($F_{1.2,9.7} = 6.8$, $p = 0.023$) revealed no new interpretations. No increase in performance or learning effects were observed over the course of the trials.

More errors were made in target-present trials than in target-absent trials, as seen in Fig. 2. This is a common finding in search literature, indicating that it is more likely to miss a target than perceiving one that is absent. Because the number of errors was so small in target-absent trials, further analysis on the error data was performed on target-present trials only.

Friedman ANOVAs were performed on each condition to compare the error percentages of the different strategies. A significant effect was found in the search

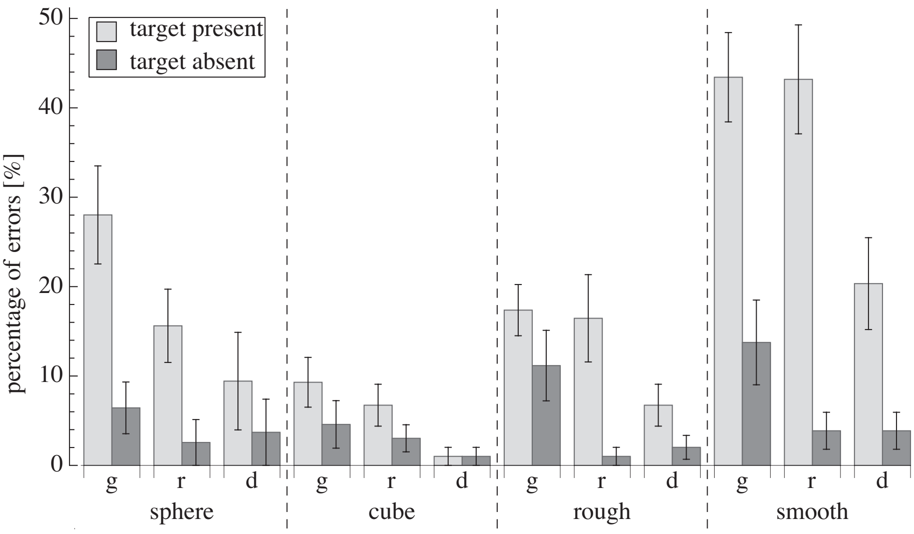

Fig. 2. The percentage of errors for each strategy (g=grasp, r=rub, d=drop) and each task. Error bars represent standard errors.

for a cube ($\chi^2{}_2 = 6.3$, $p = 0.042$) and in the smooth condition ($\chi^2{}_2 = 8.7$, $p = 0.013$). Post-hoc tests in the cube condition revealed no significant differences between the strategies. In the smooth condition, lower error percentages were found in the drop strategy than in the grasp strategy ($p = 0.045$). One-sample t-tests indicated that all conditions differed from chance (50%, ps < 0.01), except the grasp and rub strategies in the target-present trials in the search for a smooth target.

4 Discussion

The aim of this study was to investigate which strategies were optimal for different search tasks. An optimal strategy should not only produce low reaction times, but also keep the number of errors minimal. We defined three different strategies that participants had to use in four different search tasks. In the following session, we evaluate which strategy was optimal for each task.

With respect to reaction times, similar patterns were found for all conditions, where the parallel strategies (grasp and rub) were faster than the serial one (drop). However, this does not mean that a parallel strategy is better in all conditions, because the number of errors must also be taken into account. In the rough and cube conditions, no differences in the number of errors were found between the strategies. For the cube and rough conditions, error values were relatively low for all strategies. So, for both these conditions, a parallel strategy seems to be optimal. This is consistent with the notion that roughness and edges, which are present in the cubes, have been found to be salient features [2, 3], which can be explored in a parallel way. The search for these features is faster, which was also found in this study. The use of more sensitive (fingers) or less sensitive parts (hand palm) of the hand, did not seem to matter much in these conditions.

Although also no significant error percentage differences were found in the sphere condition, visual inspection of Fig. 2 suggests that the percentage of errors with the grasp strategy was quite high compared to the other strategies. Almost 30% of the answers were wrong. This gets close to guessing, which would be a percentage of 50%. Therefore, we suggest that the rub strategy seems to be optimal for the search for a sphere among cubes. Here, the error percentages and reaction times were both relatively low. Interestingly, the rub strategy is a parallel strategy. The notion that this is an optimal strategy contrasts previous research, where serial strategies (i.e., more often items dropped out of the hand) and an increase of the reaction time with the number of items were observed in the search for a sphere among cubes [3, 7]. Such a reaction time increase also suggests a serial strategy, but apparently a more parallel search is viable. It seems, however, that the more sensitive parts of the hand, the fingertips, needed to be used to detect the target in a more efficient way.

Significant differences in the number of errors between the strategies were found in the search for a smooth target among rough distractors. In Fig. 2 can been seen that both the grasp and rub strategies had very high error rates. When these parallel strategies were used, participants seemed to almost guess whether a target was present, since the values were not different from 50%. Thus, a drop strategy seemed to be optimal for the smooth condition, although reaction times were a bit higher here. In the search for a smooth item among rough, not only sensitive hand parts are necessary, but the items also need to be explored in a serial manner.

Although only a small number of strategies was investigated in this study, they were chosen to be distinct categories between the use of the fingers and the serial nature. Some conclusions about optimal strategies in 3D haptic search tasks can be drawn from the results. It seems that the saliency of the target mainly defines the optimal strategy for a search task. The differences between the property dimension that was searched for appears to have less influence. In searches for targets that are not salient, sensitive parts of the hand are necessary to explore the stimuli or items even need to be explored one by one. If the target is salient, a parallel strategy can be used. This suggests that humans adapt their behaviour to the required information and they do this in an optimal way. Such knowledge might also be useful in the development of haptic devices, which could incorporate optimal exploration modes into their design.

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