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Haptic pop-out in a hand sweep

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ABSTRACT

Visually, a red item is easily detected among green items, whereas a mirrored S among normal Ss is not. In visual search, the former is known as the pop-out effect. In daily life, people often also conduct *haptic* (tactual) searches, for instance, when trying to find keys in their pocket. The aim of the present research was to determine whether there is a haptic version of the pop-out effect. Blindfolded subjects had to search for a target item which differed in roughness from the surrounding distractor items. We report reaction time slopes as low as 20 ms/item. When target and distractor identities were interchanged the slopes increased indicating a search asymmetry. Furthermore, we show that differences in search slope were accompanied by search strategy differences. In some conditions a single-hand sweep over the display was sufficient, while in others a more detailed search strategy was used. By relating haptic search slopes to parallel and serial search strategies we show, for the first time, that pop-out effects occur under free manual exploration.

1. Introduction

Everyday we reach into our pocket to take out our keys or we try to find a light switch in the dark. These are some common examples of the haptic searches humans conduct. Like in visual search, some haptic searches are much easier than others. Visual search tasks have been researched extensively over the years. Typically, the task is to find a certain target item among a varying number of distractor items. This can yield large differences in response times among tasks. Models of visual search try to explain these differences. However, relatively little is known about haptic search.

Treisman and Gelade (1980) proposed the Feature Integration Theory (FIT). This theory distinguishes between processing of visual information at the 'pre-attentive' stage and at the 'attentive' stage. They suggested that searches for basic features, the so-called 'visual primitives' (e.g. colour) can be processed at the pre-attentive level. At the pre-attentive level information is processed in parallel, which means that response times are independent of the number of distractor items and the target item is said to 'pop-out'. Searches at the attentive level (e.g. an 'S' among mirrored 'S's) are processed serially and the response time increases linearly with the number of items in the display. However, in practice this division between parallel and serial searches is not as rigid as suggested by this theory. Many conjunction searches, e.g. a red vertical bar among red horizontal and blue vertical bars, are processed more efficiently than the purely serial processing predicted from the Feature Integration Theory. Therefore, another theory of visual search, the 'guided search model', was proposed (Wolfe, Cave, & Franzel, 1989). This model suggests that the efficiency differences between visual search tasks can be explained from variations in the extent to which pre-attentive parallel processes can be used to guide attention in the attentive stage. One way of guidance is 'bottom-up' guidance, where attention is guided to a salient feature. In the case of a conjunction search there is 'top-down' guidance, which means that at the pre-attentive stage all red bars and all vertical bars, for instance, could be located and through feature binding this information could be used to make a single object representation and find the item that is both red and vertical. This could be an explanation for the fact that many conjunctions searches are performed more efficiently than predicted when the search would be performed serially.

In previous research on haptic search tasks, target and distractor items were usually pressed onto the fingers of human test subjects (e.g. Lederman, Browse, & Klatzky, 1988; Lederman & Klatzky, 1997; Purdy, Lederman, & Klatzky, 2004). Exploratory movements are then confined to small finger movements and the number of items that can be presented is limited to the number of fingers. The advantage of presenting haptic items to the fingers, on the other hand, is that all items are presented simultaneously. Since it can be expected that the information processing on a neurological level is similar to that in vision, visual search models may be easily extrapolated to haptic search tasks in which items are

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presented in this manner. However, these results cannot readily be generalised to haptic search under free exploration conditions. Although in case the items are randomly distributed on a display, the presentation of the items is similar to how this is generally done in vision, the way in which the information is extracted haptically can be considered quite different. In the haptic case subjects will always have to move their hand over the display, which introduces a serial component, but most importantly, they can adjust their exploratory strategy. Hand movements are not performed in the same way as eye movements which consist of saccades and fixations. Movement of the hand and probably the whole arm is relatively slow and this may have a large influence on haptic search times. If and how the haptic exploratory strategy of a display co-varies with difficulty of a search task has never been investigated. Note that while roughness perception is usually investigated in terms of cutaneous perception, under free exploration conditions, when items also vary in spatial location and hand and arm movements are made, proprioception also plays an important role. Hence such a task should be referred to as a haptic search task (a combination of cutaneous and proprioceptive perception) rather than a tactile search task.

In vision, the slope of the relationship between response times and the number of items in the display is used as a measure for the efficiency of a search. These slopes are referred to as search slopes. A serial self-terminating search is usually characterised by a 1:2 ratio between the search slopes of the target present and target absent trials, while the intercept is the same. For serial search in target present trials, subjects only search on average half of the items before they find the target, while they always search the whole display in target absent trials (hence the ratio 1:2). This might not be the case for haptic search, because it is difficult to determine whether the whole display was searched and subjects might search part of the display or possibly the whole display repeatedly. This might result in differences in intercept between target present and target absent trials. It also implies that the 1:2 ratio between the slopes may not be a suitable indication for haptic serial self-terminating search.

When trying to find our keys or switching on the light, we make hand movements and the item we are trying to find can make contact with any part of our hand. The type of hand movements made has been shown to depend on the type of haptic information that is to be extracted (Lederman & Klatzky, 1987). The natural exploratory movement for perceiving roughness, for instance, is a lateral motion. Perceiving thermal properties of a material, on the other hand, requires the skin to make contact with the material long enough to establish a certain amount of heat transfer. This is a relatively slow process which was also reflected in the results of Lederman and Klatzky (1997). Besides being relatively fast, roughness perception has been the subject of a considerable amount of research (e.g. Bergmann Tiest & Kappers, 2007; Goodwin & Wheat, 2004; Hollins & Risner, 2000; Johnson & Hsiao, 1992; Klatzky & Lederman, 1999; Lederman & Taylor, 1972). Lederman and Klatzky (1997) found that searches for material properties, like a rough target item among smooth distractor items, are relatively easy. In contrast, searches for relative orientation were shown to be more difficult and to depend strongly on the number of items. These results make some material properties, such as roughness, and good candidates as 'haptic primitives'. Therefore, we decided to have subjects haptically explore surfaces covered with patches of differing roughnesses as target and distractor items.

We set out to find a haptic version of the pop-out effect under free exploration conditions by exploring search efficiency differences. We did this in terms of response times as a function of the number of items and in terms of exploratory strategy, i.e. movement track over a display. In analogy with visual search tasks, response times were measured while varying the number of items on the surfaces. We asked blindfolded subjects to freely explore the surfaces with their dominant hand. As there was no reason to expect otherwise, we assumed a linear relationship between response time and the number of items. In visual parallel search, all items on the display are perceived simultaneously and search times are independent of set size. In contrast with visual searches, subjects had to move their hand over the surface and therefore not all items were perceived simultaneously. All displays were of the same size and the target item could be placed anywhere on the display. Thus, set size by itself could not influence the response time. A search slope deviating from zero would therefore, like in the visual case, be caused by the influence of the distractor items. Slope differences between different conditions could be caused by differences in the haptic information processing mechanism, but also by the subjects' exploratory movements. Pilot experiments suggested that some haptic search tasks could be performed by a single-hand sweep, while others required the subjects to visit each item with their fingers. The first method enables a more parallel intake of information than the second. Since the natural exploratory movement for perceiving roughness is a lateral motion, the most efficient way to explore the presented surfaces would be to sweep the hand over it. If the target item pops-out and distractor items have little or no influence it can be expected that subjects just sweep their hand across the surface once in order to detect a target item.

From visual experiments it is known that interchanging target and distractor identity can also cause differences in search slopes, an effect labelled 'search asymmetry'. These asymmetries can be caused by differences in processing of the items, but also by an asymmetry in the design of the stimulus (e.g. Rosenholtz, 2001). Search asymmetries in touch were already reported by Lederman and Klatzky (1997). In the present research, we investigate whether they occur under active exploration and if an asymmetry in response times is accompanied by an asymmetry in exploration strategy.

Two experiments were conducted. Experiment 1 was a 'classic' search experiment in which subjects had to search for a single target item among a varying number of distractor items, while response times were measured as a function of the number of items. Two control experiments were conducted to assess that all items could be detected accurately. In Experiment 2, we partially repeated Experiment 1 while tracking the subjects' hand position on the display. Again a control experiment was conducted, this time to investigate whether the different types of items were detected using different exploratory strategies.

2. Experiment 1: Response times

In this experiment, subjects actively searched a display with target and distractor items on it to investigate how efficient they can perform such a task. Furthermore, we compared different conditions to assess the effect of different types of target and distractor items. To investigate the effect of decreasing intensity contrast between target and distractor items, we compared a condition where the target item was rough while the distractor items had a finer texture with a condition where the target item was replaced by a somewhat less rough texture. We also included a condition in which the identities of the target and distractor items were interchanged, i.e. a fine textured target item among rougher distractor items. To investigate how well each of the types of sandpaper could be detected, we performed also two control experiments.

2.1. Method

2.1.1. Participants

Eight paid undergraduate students (3 females, 5 males; mean age = 20 ± 2 years) participated in each of the experimental conditions. All subjects were right-handed according to Coren's test (Coren, 1993). They gave their informed consent and were treated in accordance with the local guidelines.

2.1.2. Stimuli and apparatus

Fig. 1 shows a schematic representation of one of the stimuli. The set consisted of 20×20 cm^2 displays, made out of Medium Density Fibre (MDF) board with a smooth surface into which 3 cm diameter holes had been drilled. There were 3, 5, 7, 9 or 11 holes and they were distributed randomly over the display at least 2 cm from the edges of the display. The rims of the holes were at least 1 cm apart. Two different displays were made for every number of holes. Plugs with sandpaper on them could be fitted into the holes, such that the surface of the sandpaper was at the same level as the MDF surface. This allowed for items to be placed on the displays. Three types of sandpaper were used as items: fine (Siawat P360), medium rough (Sianor J P120) and rough (Sianor P60). These type codes indicate a mean particle diameter of 28.8 μm, 116 μm and 269 μm, respectively, according to the Federation of European Producers of Abrasives (FEPA) 'P' standard and in this case the particles were silica.

For response time measurements, the stimuli were placed on a computer-interfaced precision scale (Mettler Toledo SPI A6). Measurements were started when a weight change was detected due to a subject touching the stimulus. The scale had a time delay of 70 ms and this was added to the raw data. Measurements terminated with a verbal response registered using a headset microphone. The height of the scale remained stable upon pressure.

2.1.3. Task

The experiment consisted of three conditions in which subjects had to search for a target item among distractor items. Subjects had to say whether the target item was present or absent by calling out the Dutch equivalents of 'yes' and 'no', respectively. In the first condition, the target item was the rough sandpaper and the distractor items were fine sandpaper (condition 1). In the second condition, the target item was replaced by the medium rough sandpaper (condition 2) and in the third condition, the target item was fine sandpaper and the distractor items were made of medium rough sandpaper (condition 3).

2.1.4. Procedure

The blindfolded subjects were instructed to determine in the shortest possible time whether a target item was present, but it was also emphasised that they had to be correct. Incorrect trials were repeated at the end of the block so the average response time for each number of items was based on the same number of trials. Subjects used their dominant hand to explore the displays. Control experiments with and without earplugs did not reveal any difference in performance; therefore, to increase their comfort, subjects did not wear earplugs. Before a trial started, subjects placed their dominant hand on a hand rest. Since all subjects were right-handed the rest was always located on the right-hand side of the stimulus. The rest was levelled with the height of the stimulus so subjects could easily slide their hand from the rest onto the stimulus.

Each block of trials was preceded by a training session. During training, stimuli were presented until the subject was comfortable with the task and subjects were encouraged to find the fastest strategy. Then, trials were continued until 10 in a row were correct before the actual experiment began. Throughout the training and the experiments, subjects received feedback as to whether their answers were correct.

The experiments were divided into blocks of approximately 45 min each and subjects performed no more than one block on the same day. The three conditions consisted of 150 trials each (30 trials for each number of items and in half of these trials the target was present). Each condition was divided into two blocks. The order in which the different conditions were performed was counterbalanced over the subjects. For each number of items there was one display with a target item and one without. The display that had a target item on it was interchanged between the two blocks and the position of the target item was randomised. After each trial, the display was rotated 90° to maximise the number of different displays available. Recorded response times that differed by more than three times the standard deviation from the mean were excluded from the raw data.

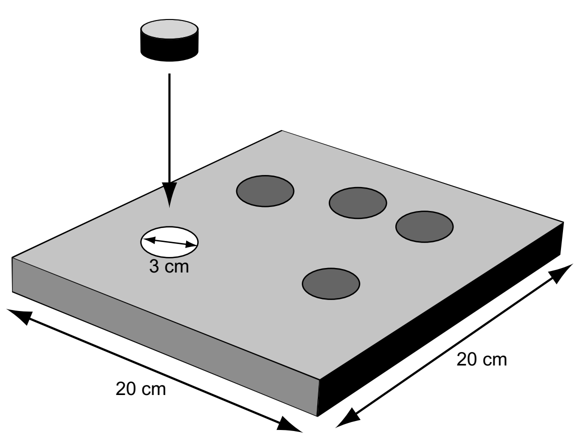

Fig. 1. Schematic drawing of the display with five items. Plugs could be fitted into the holes to place the items on the display.

2.2. Results

For each number of items the response times averaged over all subjects are shown in Fig. 2a for the target present trials and for the target absent trials in Fig. 2b. The lines represent linear regression to the data. The values of the slopes and intercepts of the regression lines are indicated by s and y_0, respectively. Error rates did not exceed 5% in any of the conditions. Note that for all conditions the target absent trials yielded larger slopes and intercepts than the target present trials. The search slopes varied between the different conditions. For condition 1 it was rather shallow, while the search slope for condition 2 was somewhat steeper and for condition 3 the slope was quite steep.

For every subject in each condition, linear regression to the data from the target present and the target absent trials provided slopes and intercepts. Two separate 3 (condition) $\times$ 2 (target presence) repeated measures ANOVAs (analysis of variance) with planned comparisons were performed on the slopes and the intercepts. For the slopes this showed significant main effects for condition ($F(2,14) = 28.40$, $p < 0.0005$) and target presence ($F(1,7) = 6.92$, $p = 0.034$). Also the interaction term was significant ($F(2,14) = 4.34$, $p = 0.033$). The main effects for the intercepts were also significant (condition $F(1.11,7.77) = 16.61$, $p = 0.003$, target presence $F(1,7) = 31.68$, $p = 0.001$, interaction term $F(1.03,7.21) = 15.09$, $p = 0.006$). The effect of target presence was analysed further with paired samples t-tests. For each of the separate conditions, the effect of target presence on the slopes was significant ($t(7) \leqslant -2.5, p \leqslant 0.040$) except in condition 2. For the intercepts, the difference between target present and absent trials was significant in all conditions ($t(7) \leqslant -4.2, p \leqslant 0.004$).

Planned comparisons between conditions 1 and 2 showed significant differences for the slopes ($F(1,7) = 6.36, p = 0.002$) as well as the intercepts ($F(1,7) = 15.71$, $p = 0.005$). So decreasing the contrast between the target and distractor items increased both

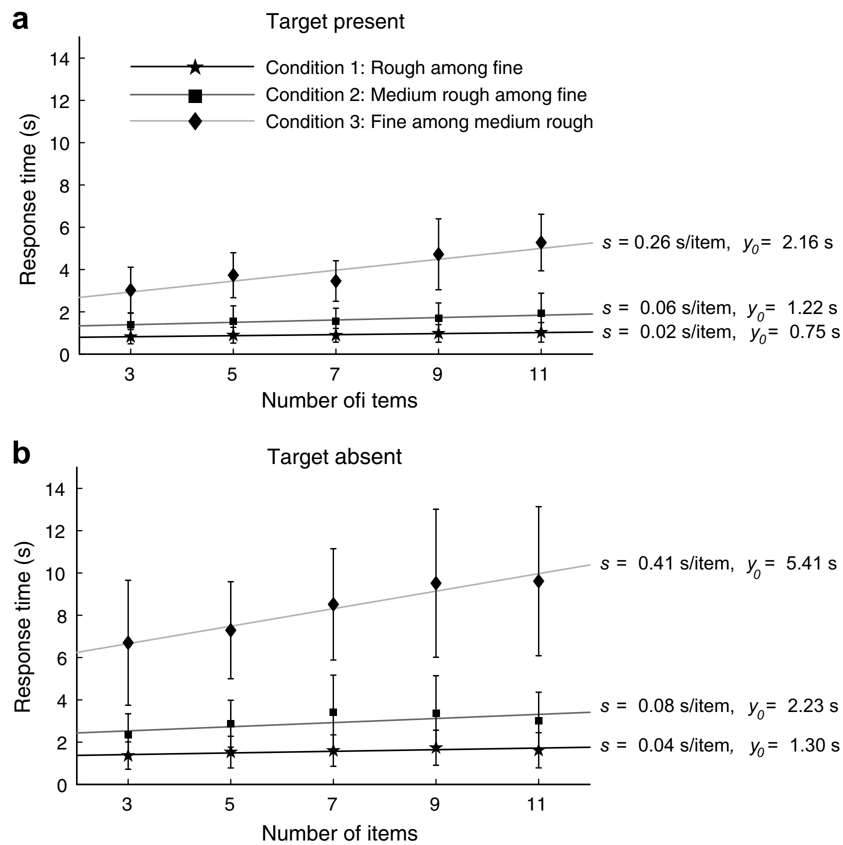

Fig. 2. Experiment 1: Subjects had to search for a target item among varying numbers of target items. The different conditions are indicated in the figure. Response times for each condition are shown, averaged over all subjects ($N = 8$) as a function of the number of items. (a) represents target present trials and (b) the target absent trials. The error bars represent the standard error of the mean and the lines represent linear regression to the data, where s represents the slope and y_0 the intercept.

the intercept and the slope. The contrast between conditions 2 and 3 was also significant for both the slopes and the intercepts ($F(1,7) = 25.23$, $p = 0.002$ and $F(1,7) = 12.71$, $p = 0.009$). This means that interchanging target and distractor identities caused an increase in both the slopes and intercepts.

2.3. Discussion

Compared to the other conditions, the search slope for condition 1 is rather shallow. Also, the intercept of less than a second is surprisingly low considering the fact that mechanical action is involved. If all items had to be found one by one to decide whether it was a target item, we would have expected much higher search times and slopes. Furthermore, in all conditions the intercept is larger for the target absent trials than for the target present trials. The intercept would be expected to be the same if the only difference between target present and absent trials is that subjects search on average only half of the display. The increase in intercept could be explained by subjects searching part of the display more than once in the target absent trials because they are uncertain of whether they did search the whole display.

The significant difference in slope between conditions 2 and 3 indicates a search asymmetry. A search asymmetry for rough and smooth items was also reported by Lederman and Klatzky (1997). They suggested that the search asymmetry is caused by the ends of a given continuum not being equally perceptually accessible. A rough patch would therefore be processed earlier than a fine patch. An alternative explanation could be that attention is guided by rough items more strongly than by less rough items, which would relate to Wolfe's guided search model (Wolfe et al., 1989). To investigate the origins of the differences in search slopes between the conditions we investigated detectability in Control Experiments 1.1 and 1.2.

2.4. Control Experiment 1.1

In vision, search asymmetries are often caused by an asymmetrical design of the experiment (Rosenholtz, 2001; Rosenholtz, Nagy, & Bell, 2004). The search asymmetry reported in the previous experiment could thus be caused by an asymmetry in our experimental design. This might be due to detectability differences between the types of sandpaper. To investigate how accurate and how fast the three types of sandpaper were perceived a detection experiment was performed.

2.4.1. Method

The same subjects that participated in Experiment 1 also participated in this experiment. The set-up, procedure and also the stimulus design were the same, only this time there were just four displays: one blank display and three displays with a single item. The item could be any of the three types of sandpaper and subjects only had to say as fast as possible whether or not there was an item present. Each subject performed 60 trials; 15 trials for each type of sandpaper and for the blank display.

2.4.2. Results

Fig. 3 shows the response times averaged over all subjects for the four conditions in the detection experiment. Response times were below 1 s for displays with an item on them. The large standard error for the no item case was due to one subject having a

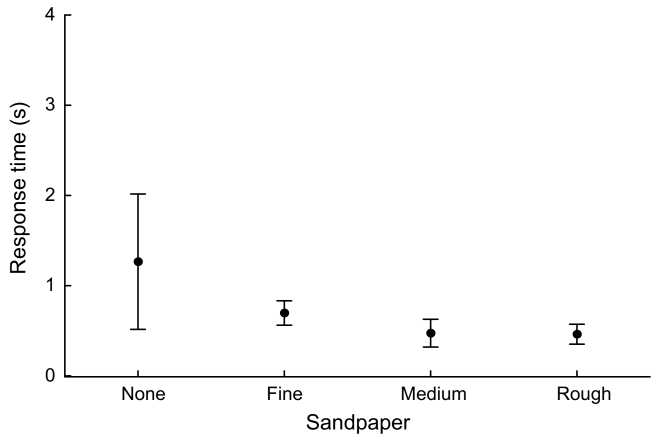

Fig. 3. Control Experiment 1.1: Subjects had to say whether an item was present on the display. The graph shows response times averaged over all subjects ($N = 8$) for the three types of sandpaper and an empty display. The error bars indicate the standard error of the mean.

much longer response time in this condition than the other subjects. For displays with the medium rough or rough sandpaper, no incorrect answers were given, while for the displays without sandpaper and with the fine sandpaper error rates were 0.83% and 3.3%, respectively. This indicates that all types of sandpaper were detected accurately. Response times for the rough and medium rough sandpaper were shorter than for the fine sandpaper and the no item case. A repeated measures ANOVA showed a significant main effect for the type of sandpaper, $F(1.057, 7.402) = 8.68$, $p = 0.019$. Pairwise comparisons with Bonferroni correction yielded significant differences in response time for the fine and the medium rough sandpaper ($p = 0.045$), as well as for the fine and the rough sandpaper ($p = 0.008$). These results show that all types of sandpaper were detected relatively fast, but the rough and medium rough sandpaper were detected significantly faster than the fine sandpaper.

2.4.3. Discussion

These findings indicate that the rough sandpaper had a higher contrast with the smooth background of the display than the fine sandpaper. This could be the reason for the slope difference between the search for a fine item among medium rough distractors and a medium rough item among fine distractors. However, it could also be that the differences between the different numbers of items were not perceived when the distractors consisted of the fine sandpaper. This would mean that the distractor items did not distract and therefore yielded the relatively shallow lines in the rough or medium rough target item among fine distractor items conditions. To be certain that differences between different numbers of items were perceived, Control experiment 2 was conducted.

2.5. Control Experiment 1.2

We conducted an experiment in which the subjects had to judge the number of items in the display to confirm that the differences between the varying numbers of distractor items in Experiment 1 were perceived. If subjects could judge the different numbers of items accurately then the differences between the varying numbers of items were perceived and their use as distractor items was justified.

2.5.1. Method

Again the subjects from Experiments 1 and 2 participated and the set-up and procedure of Experiment 1 were used. We took a subset of the displays from Experiments 1 and 2. Subjects were presented with displays having 0, 1, 3 or 5 items on them and they had to respond how many items were on the display. This experiment was done with both the fine and the medium rough sandpaper, which were used as distractor items in Experiment 1. Each subject performed 60 trials per type of sandpaper.

2.5.2. Results

Fig. 4a shows the response times averaged over all subjects, as a function of the number of items for the fine sandpaper and Fig. 4b for the medium rough sandpaper. It can be seen that response times did not vary systematically with the number of items and response times are in the same range for both types of sandpaper. A 4 (number of items) × 2 (type of sandpaper) repeated measures ANOVA on the response times did not show a significant main effect. On average the subjects were able to maintain an accuracy above 95% correct answers for both types of sandpaper. For the fine sandpaper the incorrect answers per number of items ranged from 0.83% to 10% and for the medium rough sandpaper from 0% to 7%. In both conditions the error rate increased with the number of items.

2.5.3. Discussion

The low error rates indicate that differences between the varying numbers of items could be perceived accurately. Numerosity

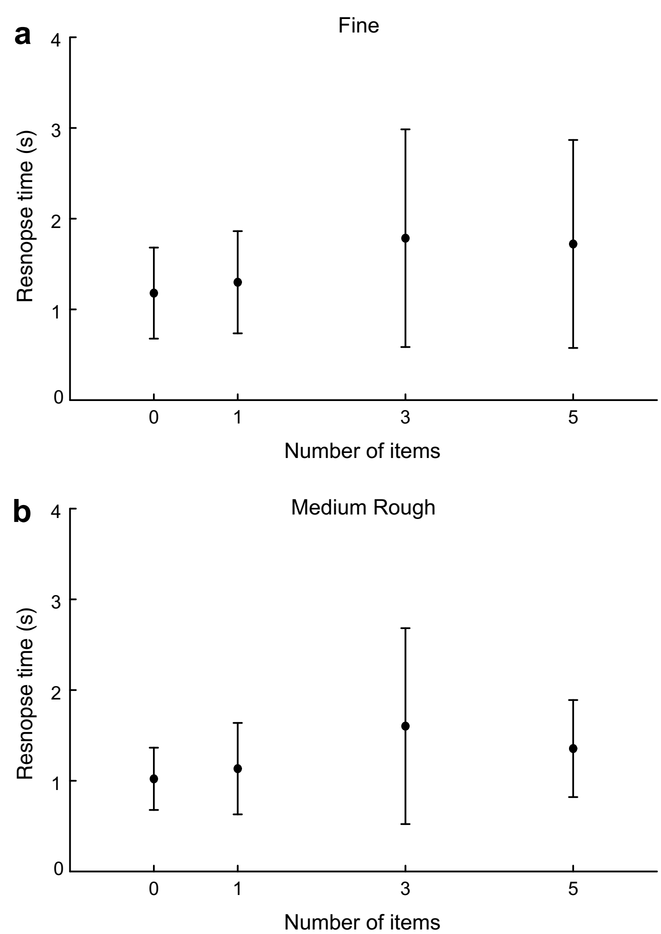

Fig. 4. Control Experiment 1.2: subjects had to judge the number of items in the display. The graphs show the response times, averaged over all subjects ($N = 8$), as a function of the number of items. The error bars indicate the standard error of the mean. Items on the display were fine sandpaper (a) and medium rough sandpaper (b).

judgements for the medium rough sandpaper, however, were not significantly faster than for the fine sandpaper. These results show that subjects could accurately estimate the number of items on a display of up to five items.

2.6. Conclusions

The search slopes show that when the target item was rough among fine distractor items, search slopes were relatively low. Since haptic exploration involves hand and arm movements, much higher slopes would be expected if the display would be scanned serially. When the roughness difference between target and distractor items was reduced both the slope and the intercept increased. The slope increase indicates that the influence of the distractors was larger when the roughness difference was smaller. The increase in intercept indicates that exploration speed decreased independently of the number of items on the display. Furthermore, there was an increase in slope and intercept comparing search for a rougher target item among finer distractor items with search for a finer target item among rougher distractor items, indicating a search asymmetry. The control experiments show that all types of sandpaper could be detected accurately (control 1.1) and also that the differences between different numbers of items could be detected (control 1.2). This means that all types of sandpaper used in this experiment could indeed act as target and distractor items. The differences in search slopes between the conditions were therefore caused by the differences in target and distractor identity and not merely detectability differences.

3. Experiment 2: Exploratory strategy

The differences in intercept and slope values between the conditions in Experiment 1 could be caused by subjects simply moving slower over the surfaces or by a shift in search strategy. To investigate whether a strategy shift occurred we repeated Experiment 1 in part while tracking the subjects' hand movements. Also a control experiment was performed to investigate whether the different types of sandpaper were detected through different exploratory strategies.

3.1. Method

Eight new paid subjects (6 females, 2 males; mean age = 22 ± 2 years) participated in this experiment and all of them also performed the control experiment. All subjects were right-handed according to Coren's test (Coren, 1993) and gave their informed consent. None of them had any known hand deficits. The response time measuring set-up and stimuli from Experiment 1 were adopted. The subject's hand position was recorded using a movement tracking system (NDI Optotrak Certus). A marker consisting of an infra-red LED was placed on the nail of the index finger of the subjects' dominant hand and the marker position was recorded at a rate of 100 Hz. In Experiment 1, it was observed that subjects always moved over the surface with a flat hand and they did not spread their fingers and just moved their whole hand. They only rotated the hand with respect to the wrist when moving over the displays. Therefore, one marker was sufficient to detect strategy differences. As all subjects were right-handed they all entered the display from the right-hand side where they placed their hand on a rest before the trial started as they did in Experiment 1. This means they always entered the display from the same side, but the displays were rotated to randomise item positions as this was also done in Experiment 1.

The instructions were identical to those in Experiment 1. Each subject performed two target absent and two target present trials for each number of items in each of the three conditions from Experiment 1, totalling 60 trials. The order of the different conditions was counterbalanced over subjects.

3.2. Results

The response times in these experiments were similar to those found in Experiment 1 and therefore, these results can be extrapolated to what we found in Experiment 1. A representative selection of the tracks over the stimuli from one subject is shown in Fig. 5. The squares represent the display and the solid line marks the track of the subjects index finger over the display. The subject entered the display from the right-hand side. It can be seen that in all experimental conditions the track tended to be longer in the target absent trials. Note that as the position marker was on the index finger sometimes tracks will extend across the display edges, but the subjects hand would then still be on the surface. Furthermore, between the different conditions the length of the track and the scale of the movements varied. In condition 1 the target present trials generally show only one sweep over the surface, whereas the tracks over the displays in condition 3 show a far more complicated movement profile. In Fig. 6 a selection of tracks from one subject in conditions 1 and 3 is given, now with the position of the items indicated. A grey filled disk marks the position of the target item. Note that in condition 1 the subjects did not necessarily have to move their fingers over the target item, they also used other parts of the hand. In condition 3 the movements concentrated on the areas with items present, while this is not apparent in condition 1. Furthermore, the length of the track of the target present trials varied markedly in condition 3, because it was highly dependent of the location of the target. If a subject happened to start searching near the target item the track was much shorter than when it was further away.

For a more quantitative analysis the length of the tracks and movement speed were analysed. First the length of the track was calculated from the position data. The track lengths were averaged over all numbers of items tested (3, 5, 7, 9, 12) for the target present and absent trials in each of the three conditions. Fig. 7a shows the distance travelled across the display averaged over subjects for the target present and absent trials in the three conditions. In the target present trials from condition 1 the length of the track was approximately 20 cm, which equals the width of the displays and suggests a single-hand sweep was performed. Also the average speed at which subjects moved over the displays in the different conditions was calculated. The averaged speed is represented in Fig. 7b. From this figure it can be seen that in each condition the average speed in the target present trials was slightly smaller than in the target absent trials.

A 3 (condition) × 2 (target presence) repeated measures ANOVA with planned comparisons on the track length showed significant main effects for condition and target presence ($F(2,14) = 18.2$, $p < 0.0005$ and $F(1,14) = 21.3$, $p < 0.002$). Planned comparisons showed that the difference between conditions 1 and 2 was significant ($F(1,7) = 18.2$, $p = 0.004$), as well as the difference between condition 2 and 3 ($F(1,7) = 5.9$, $p = 0.045$). In each of the conditions the averaged total track over the display was significantly longer in the target absent trials than in the target present trials (paired samples t-test, $t(7) \leqslant -3.2, p < 0.0151$).

In Fig. 7b the average speed across the displays is shown. The average speed was highest in condition 1 and lowest in condition 3. Repeated measures ANOVA showed significant main effects for condition and target presence ($F(2,14) = 33$, $p < 0.0005$ and $F(1,14) = 26.8$, $p = 0.001$). For each of the conditions the difference between target present and absent trials was significant (paired samples t-test, $t(7) \leqslant -2.4, p < 0.049$). Planned comparisons revealed significant differences between conditions 1 and 2

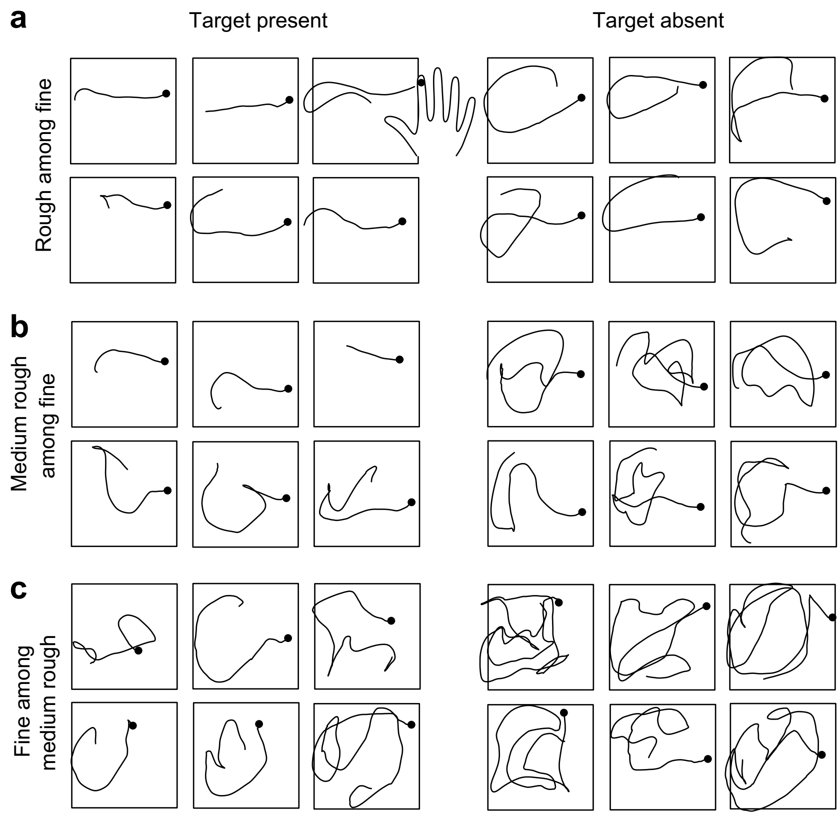

Fig. 5. Experiment 2: Subjects had to search for a target item among varying numbers of distractor items while the movement over the surface was recorded. A selection of tracks across the displays from a single subject is shown. The squares indicate the edges of the displays and the hand indicates the subjects' hand entering the display from the right side. The dot on the index finger depicts the position marker. The starting point of each track is marked with a dot. For each display the total number of items is indicated in the lower right corner. (a) Rough target item among fine distractor items (condition 1). (b) Medium rough target item among fine distractor items (condition 2) and (c) Fine target items among medium rough distractor items (condition 3).

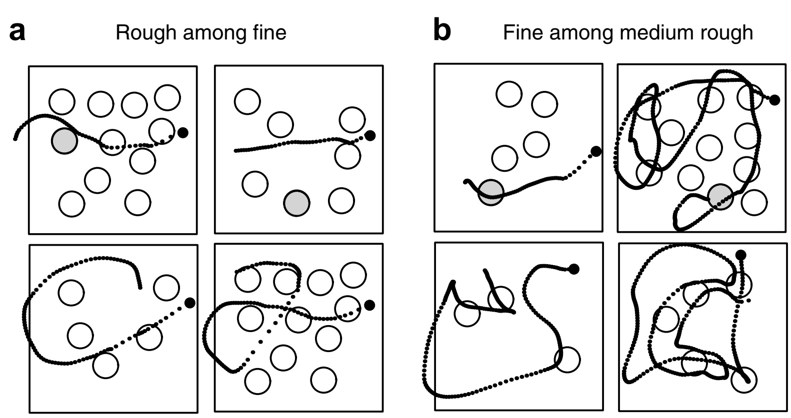

Fig. 6. Experiment 2. Tracks across the displays from the same subject as in Fig. 5 are shown with the position of the items indicated. A filled circle indicates a target item. The dots indicate the subsequent positions of the marker which was sampled at a rate of 100 Hz. A larger black dot indicates the starting position of a trial. (a) Condition 1 and (b) condition 3.

($F(1,7) = 14$, $p = 0.007$) and between conditions 2 and 3 ($F(1,7) = 18.2$, $p = 0.004$). This shows that interchanging target and distractor identity caused subjects to switch to exploration movements at a lower average speed, but also to make longer exploratory tracks over the display surfaces.

3.3. Discussion

These results show that subjects performed a hand sweep across the displays in condition 1, while in condition 3 they switched to searching the displays at a smaller scale and at a lower speed. The search strategy in condition 2 was an intermediate between a hand sweep and the strategy in condition 3. This suggests that in condition 1 the search had a parallel character in which the target could be found through a hand sweep. In condition 3 the search had a far more serial character in which items were examined sequentially. Summarising, subjects adjusted their search strategy to a more parallel or a more serial model depending on the contrast between target, distractor and background.

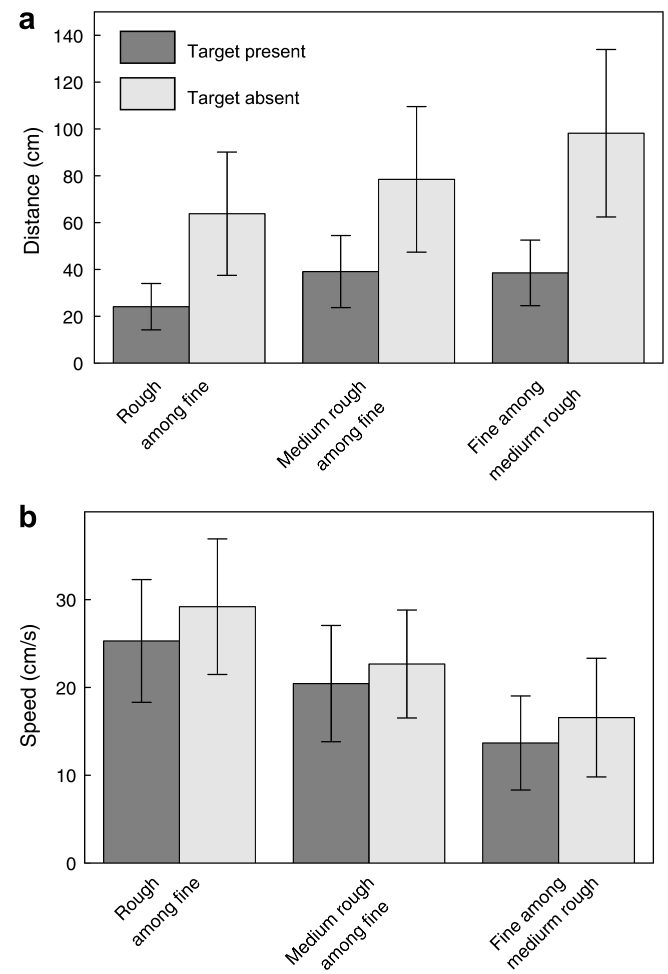

Fig. 7. Experiment 2. (a) The distance that subjects moved over the display and (b) the speed at which they did this averaged over all subjects ($N = 8$) for the three conditions. The dark bars indicate target present trials and the light grey bars the target absent trials. Error bars indicate the standard error of the mean.

3.4. Control Experiment 2.1

In Control Experiment 1.1 it was already found that all types of sandpaper were detected accurately. In the present control experiment we investigated whether there is a strategy difference between detecting different types of sandpaper. If it is found that all types of sandpaper are detected through the same exploratory strategy, we can conclude that the strategy differences found between the conditions in the search task must have been caused by the presence of distractor items. To investigate this we repeated Control Experiment 1.1 while tracking the subjects' hand position.

3.4.1. Method

The stimuli and instructions were the same as in Control Experiment 1.1. The subjects performed four trials for each type of sandpaper and the empty display. Since the displays were rotated 90° for each trial, the location of the sandpaper was roughly homogeneously distributed over the four quadrants of the display.

3.4.2. Results

A selection of tracks for the different types of sandpaper and the empty display and shown in Fig. 8. It can be seen that the empty display was searched more extensively than the other displays. All displays with sandpaper were searched with one sweep over the surface and subjects did not have to move their fingers over the item but could use any part of the hand to detect it. The average distance travelled over the displays and average speed are shown in Fig. 9 and it can be seen that for all sandpaper present trials the length of the track roughly equals the width of the display. Repeated measures ANOVA on the distance data showed a significant main effect of the four possible displays ($F(1.1, 7.9) = 9.4$, $p = 0.014$), but pairwise comparisons did not show any significant differences between the different displays. A planned comparison of the length of the tracks over the sandpaper present displays against track length over the empty display showed that the track length was significantly longer when no sandpaper was present ($F(1, 7) = 10$, $p = 0.016$). Analysis of the speed data did not show a significant main effect.

3.4.3. Discussion

These results show that all types of sandpaper were detected using a similar exploration strategy and that subjects could use any part of the hand. There were no significant differences in average speed of track length between the types of sandpaper.

3.5. Conclusions

The results show that different exploration strategies were used in the three conditions. They ranged from a parallel strategy (hand sweep) to a more elaborate serial strategy. There were no strategy differences in detection of the types of sandpaper and therefore we can conclude the strategy differences between the conditions were caused by the identity of target and distractor items.

4. General discussion

The results from Experiment 1 show that there were large differences in search slopes between the three conditions. The difference between conditions 2 and 3 indicated a search asymmetry. In Experiment 2 it was shown that different exploratory strategies were used in the different conditions. When searching for a rough target item among fine distractor items (condition 1) subjects generally performed a hand sweep over the surface, while search for a fine target item among medium rough distractor items (condition 3) was performed through a more complex track of movements over the surface. Not only was the exploratory trajectory over the display longer in condition 3, but also the speed was lower. Search for a medium rough target item among distractor items (condition 2) was performed through a strategy in between that of conditions 1 and 3. The control experiments showed that both the differences in search slopes and exploratory strategies were not caused by detectability differences. Therefore, these were truly effects of the target and distractor identities.

The difference between conditions 2 and 3 in search slopes (Experiment 1) accompanied by differences in search strategies (Experiment 2) indicate a search asymmetry. Finding a patch of rough sandpaper among fine sandpaper was easier than the reversed case. If the hand is moved along a textured surface there is cutaneous texture information, but there is also a frictional force. Note that the frictional forces are directly related to the roughness of the items. When moving the hand over a rough patch on a surface there will be local stretch of the skin because of higher friction and this friction is also likely to exert strain on the wrist. These cues can be used to efficiently determine whether a rough item is present among less rough items by just sweeping the hand over the display. In the reversed situation, on the other hand, subjects are searching for an item that is less rough and in that case the target item will not exert higher friction on the skin and joints than the distractor items. This could be an explanation why subjects had to switch to a more serial search strategy in this case. Lederman

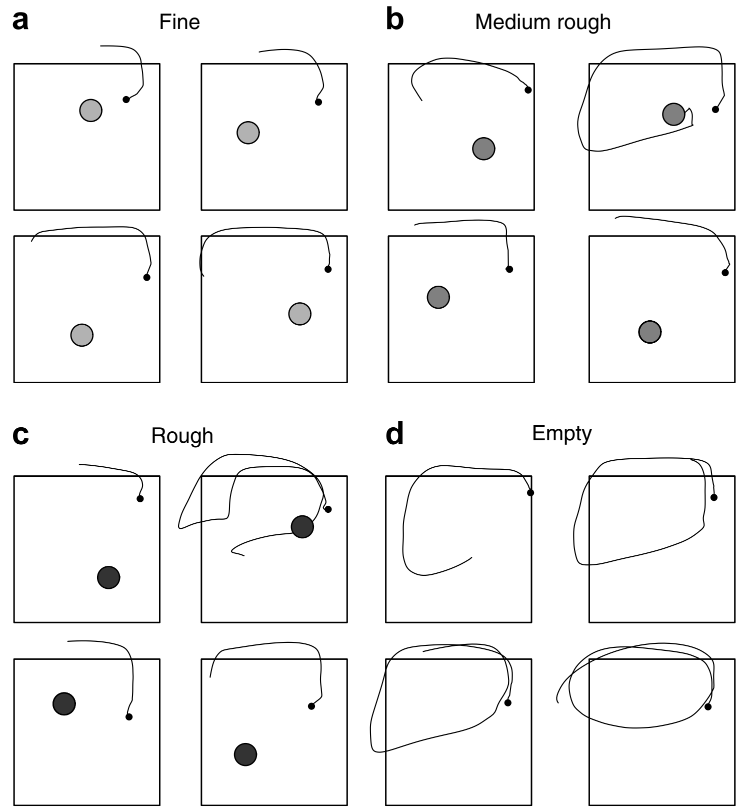

Fig. 8. Control Experiment 2.1: Subjects had to say whether an item was present on the display while the movement over the display was recorded. A selection of tracked movements over the displays from a single subject is shown. The grey disks indicate the item position and the items could fine sandpaper (light grey disk), medium rough sandpaper (intermediate grey disk) or the rough sandpaper (dark grey disk). The start of a track is marked with a black dot. The subjects responded whether there was an item present for fine sandpaper (a), medium rough sandpaper (b), rough sandpaper (c) and an empty display (d).

and Klatzky (1997) found the same asymmetry in their experiments. Although in their set-up items were pressed to the subjects fingers they could make finger movements and it could be that also in their case subjects found it easier to detect whether their was higher friction on one finger than lower friction on one of the fingers.

For visual search, Wolfe (1998) showed that there is no clear-cut distinction between parallel searches and serial searches based on response times alone. This is probably also the case for haptic searches. However, differences in the extent to which response times depend on the number of items between haptic search tasks do show that information processing in some tasks is more efficient than in others. This could be due to internal processing differences, but in this study using free exploration conditions, subjects also showed differences in their exploratory strategy. Our results show a shift from a very coarse and efficient search strategy (a hand sweep) to more detailed exploration movements on a smaller scale over three different search conditions. This suggests a gradual change from a search strategy with a 'parallel' character to a more 'serial' strategy. In vision it has been shown that eye movements can provide information on whether search is parallel or serial through the number of fixations and saccades (e.g. Zelinsky & Sheinberg, 1997). However, haptic exploratory movements are not readily comparable with eye movements. Saccades can be planned using information from peripheral vision, but in haptics an item can only be detected upon contact with it. This could be an explanation for the differences in search time between target present and target absent trials and the longer distance that subjects moved over the display. Subjects were very unsure whether they have truly searched the whole display. This also indicates that the criterion of a 1:2 ratio between search slopes in target present and absent trials is not appropriate to distinguish between serial and parallel search in this type of search tasks. Experiment 2 showed that when subjects performed a hand sweep they swept on average over the whole width of the display in target present trials, not just half of it. In target absent trials they swept the display more than once to be sure there was no target. The ratios between target absent and target present search slopes found in Experiment 1 for the rough among fine, medium rough among fine and fine among medium rough sandpaper were 0.5, 0.75 and 0.6, respectively. So, only for the rough among fine sandpaper condition, a ratio of 1:2 for the target present and target absent slopes was found. Experiment 2 shows that this was not because all items were visited sequentially, since the hand movement data clearly shows a parallel search strategy for this condition. Therefore, a ratio of 1:2 between target present and target absent trials does not correlate with a serial search strategy in a search task under free exploration conditions.

Our results show that there are haptic search tasks that can be performed markedly fast and efficient while others are more time consuming. We also showed that changes in search slopes between the different condition were accompanied by search strategy differences between the conditions. In this way we have shown for, the first time, a direct connection between search slopes and type of exploration strategy in haptic search. When search slopes were relatively shallow the search was performed through a strategy with a parallel character, while searches yielding a relatively steep search slope were performed through a more serial strategy. This is an important result, because it is difficult to directly relate haptic search slopes to visual search slopes or to haptic searches that were not performed under free exploration conditions. In visual search tasks, pop-out effect usually means that there is little influence of

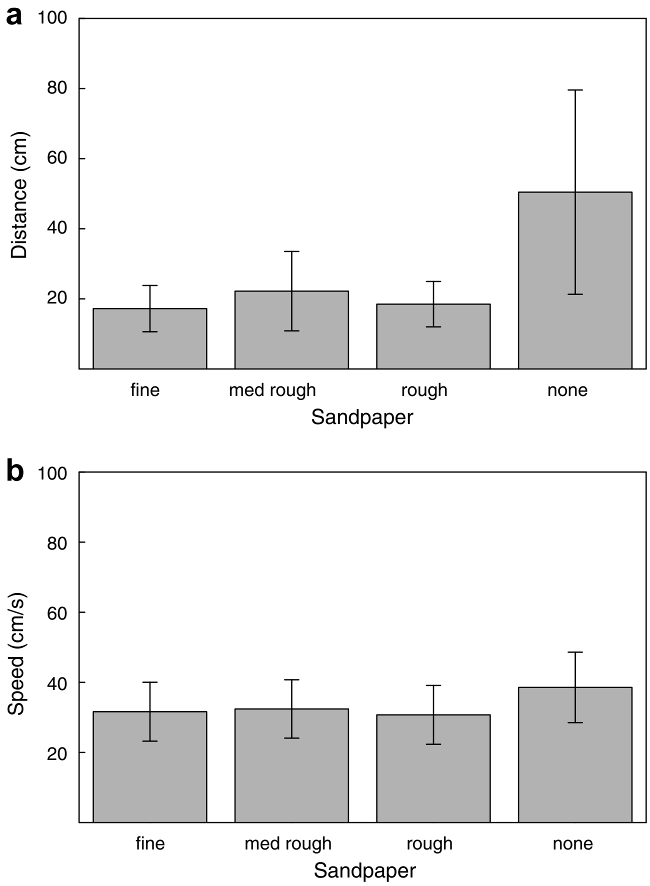

Fig. 9. Control Experiment 2.1. (a) The distance that subjects moved over the display and (b) the speed at which they did this averaged over all subjects ($N = 8$) for each of the types of sandpaper and the empty display. Error bars indicate the standard error of the mean.

the distractor items. As was already pointed out in Section 1, a single-hand sweep is the most efficient strategy possible to haptically explore a surface with rough items on it. If the target item can be detected through such a strategy this means that the distractor items have little or no influence. Our results show that when the target item was rough sandpaper and the distractor items were fine sandpaper, subjects used a single-hand sweep to search the displays. Therefore, we propose that this condition can be interpreted as a haptic version of the pop-out effect.

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