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RESEARCH ARTICLE

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Saccadic search performance: the effect of element spacing

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Abstract In a saccadic search task, we investigated whether spacing between elements affects search performance. Since it has been suggested in the literature that element spacing can affect the eye movement strategy in several ways, its effects on search time per element are hard to predict. In the first experiment, we varied the element spacing (3.4°–7.1° distance between elements) and target–distracter similarity. As expected, search time per element increased with target–distracter similarity. Decreasing element spacing decreased the search time per element. However, this effect was surprisingly small in comparison to the effect of varying target–distracter similarity. In a second experiment, we elaborated on this finding and decreased element spacing even further (between 0.8° and 3.2°). Here, we did not find an effect on search time per element for element spacings from 3.2° to spacings as small as 1.5°. It was only at distances smaller than 1.5° that search time per element increased with decreasing element spacing. In order to explain the remarkable finding that search time per element was not affected for such a wide range of element spacings, we propose that irrespective of the spacing crowding kept the number of elements processed per fixation more or less constant.

Keywords Visual search · Saccade · Crowding

Introduction

The goal of search tasks in daily life is often to find a specific target as fast as possible. A factor that affects the time it takes to find the target is the oculomotor strategy. In the case that a visual scene exceeds the area that can be inspected within a single glance, eye movements are required to find the target (We refer to such search tasks as saccadic search tasks to distinguish them from the many search tasks that can be accomplished without making eye movements.). This search time is roughly equal to the number of eye movements multiplied by the average fixation duration. So, in order to find the target as fast as possible, it is of importance not to make too many eye movements, nor to fixate too long on a single location.

However, fixation duration and the number of fixations required to find the target are not independent. Moffitt (1980) conducted a meta-study on the effects of several search task manipulations on the oculomotor strategy that were assumed to affect the difficulty of the search task (for example, varying the target–distracter similarity). Fixation duration was expected to increase when the search task was more difficult. Surprisingly, in many of the reviewed studies, the fixation duration was not affected at all. Instead, Moffitt (1980) found that the number of fixations required to find the target increased. He attributed this result to a decrease in the number of elements inspected during a single fixation. Apparently, oculomotor behavior can be adjusted to the demands of a new search task applying a strategy that lies in between two extremes (Fig. 1a, b): at the one extreme, fixation duration can be adjusted (it can either increase or decrease, depending on the search task) to such an extent that the number of elements inspected per fixation remains the same and thereby the number of fixations required to find the target. At the other extreme, the number of elements inspected per fixation is sufficiently adjusted to maintain fixations at the same duration. As a result, the number of fixations varies as well.

The number of elements that can be inspected per fixation has been investigated under several conditions. Rather than referring to the number of elements inspected per fixation, many researchers refer to the size of the area surrounding the point of fixation in which

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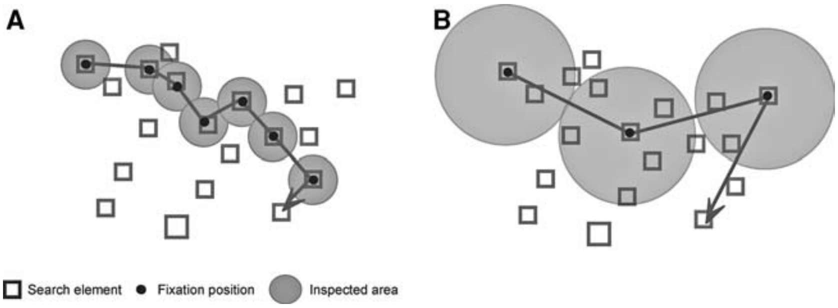


Fig. 1 Illustration of the relationship between the number of saccades and fixation duration according to Moffit (1980). Drawing (**a**, **b**) are examples of the two extreme strategies. Fixation positions and the areas inspected per fixation are represented. In (**b**) fixations are longer and more elements are inspected per fixation than in (**a**). Therefore, fewer fixations are required to find the target

elements are inspected. An increase in the size of this area would then be similar to an increase in the number of elements inspected during a single fixation. There are several names for this area, such as the visual span (e.g., O'Regan et al. 1983; O'Regan 1990), the perceptual span (e.g., Rayner and Fisher 1987a; Bertera and Rayner 2000), conspicuity area (e.g., Engel 1977), zone of focal attention (Motter and Belky 1998a) and the visual lobe (e.g., Widdel and Kaster 1981). Although their definitions differ slightly, they all boil down to the same concept of an area in which elements are inspected during a fixation. Here, we refer to this area as the visual span.

Research concerning the visual span shows that the size of the span, the number of fixations required to find the target, and the fixation duration are not independent of each other. The number of fixations required to find the target is often found to decrease with an increase in the size of the visual span (relative to the distance between elements) (Rayner and Fisher 1987a, b; Motter and Belky 1998a; Bertera and Rayner 2000). Motter and Belky (1998a) took the probability of detecting the target on the subsequent fixation as a function of the distance between the point of fixation and the target position as a measure for the span (they called it the zone of focal attention). Search displays that gave rise to a shift of this curve towards lower eccentricities (i.e., smaller span) also required more fixations. This means that the number of fixations increased when the size of the span decreased.

Moreover, the decrease in the number of fixations required to find the target when the visual span size increases implies that saccade amplitudes become larger. Indeed, in a one-dimensional search task, Jacobs (1986) varied target–distracter similarity and showed that with decreasing target–distracter similarity, both the visual span size and saccade amplitudes increased. 80% of the variability in saccade amplitudes could be explained by means of the size of the visual span. This increase in saccade amplitude with increasing visual span has been replicated several times (Rayner and Fisher 1987a, b; Bertera and Rayner 2000; Näsänen et al. 2001).

There are several indications that there might be a relation between fixation duration and the visual span size (for a given processing time per element). Some indications come from eye movement research. It has been found that an increase in fixation duration is associated with an increase in the number of elements inspected during a fixation (Mackworth 1976; Salthouse and Ellis 1980; Scialfa and Joffe 1998). Nattkemper and Prinz (1987) found that increasing fixation duration is correlated with an increment in saccade amplitude, which is an indication for an increase in the visual span size. Other indications stem from research in which search displays were presented while subjects were required to maintain fixation. Below the duration of a typical fixation (<250 ms), the number of elements inspected depends on the duration of the search display presentation (e.g., Sperling et al. 1971; Carrasco et al. 1995). Interestingly, towards the visual periphery, elements are inspected later (eccentricity effect, Carrasco et al. 1995; Wolfe et al. 1998). However, this relationship between fixation duration and the size of the visual span is not undisputed. An opposite relationship has been found in studies that applied the moving window technique. This technique involves the masking of the search display outside a predefined area that is contingent on the eye movements—the moving window (McConkie and Rayner 1975). Research that involves this technique shows that when the moving window is small (and there is less information to process), fixation durations tend to be longer (Bertera and Rayner 2000; Rayner and Fisher 1987a, b).

In summary, there appears to be a relation between fixation duration and the number of fixations mediated by the size of the visual span. This relation is similar to the relation between fixation duration and the number of fixations found by Moffitt (1980) mediated by the number of elements inspected per fixation. For example, other things being equal, an increase in fixation duration may be accompanied by an increase in the size of the visual span. An increment in the size of the visual span is related to a decrease in the number of fixations required to find the target. These interdependencies offer several possible oculomotor strategies to adopt.

In his meta-research, Moffitt (1980) showed that it is particularly in dense displays (small element spacings) that the oculomotor strategy is hard to predict. In this study, we report how element spacing affects search time and oculomotor behavior for a wide range of elements spacings (from 0.8° to 7.1°). In the present experiments the distance between elements was varied by varying the number of elements in the display while keeping the display size constant.

In addition to the distance between elements we also varied the target–distracter similarity. target–distracter similarity is known to strongly affect the size of the visual span (e.g., Jacobs 1986). Increasing the difference between target and distracters increases the visual span and, therefore, shortens the average search time that is required to find the target. In all of the conditions, eye movements were required to inspect the whole search display.

Experiment 1

Methods

Apparatus

An Apple G3 generated the stimuli, which were presented on a Sony Trinitron 19″ monitor (1,024×768 pixels). Eye movements were recorded using an SMI Eyelink I system (for details see Van der Geest and Frens 2002). A camera, attached to a headband, was placed in front of the left eye of the subject. Although viewing was binocular, only movements of the left eye were recorded. Stimuli were presented with Matlab for Mac OS running the Psychophysics Toolbox (Brainard 1997; Pelli 1997). Eye movement recording was controlled by means of the Eyelink Toolbox for Matlab (Cornelissen et al. 2002). The eye movement data were analyzed off-line.

Stimulus

A search display consisted of a closed square (the target) among squares with a gap in one of the four edges (the distracters), as shown in Fig. 2. The elements were purely defined by their edges. These edges were lines with a width of 1/12 of their length (0.475°). The size of all the elements (target and distracters) was 0.57°×0.57°. The elements were white and the background was black. The search elements were placed on a hexagonal grid in a 37° × 31° display. The target position was randomly chosen among these locations. The other locations were occupied by the distracters.

Procedure

The experiment consisted of 12 conditions: four element spacings in combination with three distracter gap sizes. The four different element spacings were created by putting different numbers of elements (36, 64, 100, 144) in the search display while keeping the display size constant. Accordingly, the center-to-center distance between elements in a display was either 7.1°, 5.2°, 4.1° or 3.4°. The three gap sizes measured 0.09°, 0.19° and 0.28° (‘small gap’, ‘medium gap’, and ‘large gap’, respectively). With decreasing gap size, the resemblance of a distracter to the target (gap size 0°) increases. All gap sizes were thus large enough for the target to be clearly discerned from a distracter when foveated. Distracters in a single condition all had the same gap size. Conditions differed in their number of trials. Prior to the experiment, we intended to acquire a more or less equal number of eye movements for each condition. The number of trials was determined at 100, 75, 50 and 25 for the 7.1°, 5.2°, 4.1° and 3.4° conditions, respectively. The conditions were presented in block.

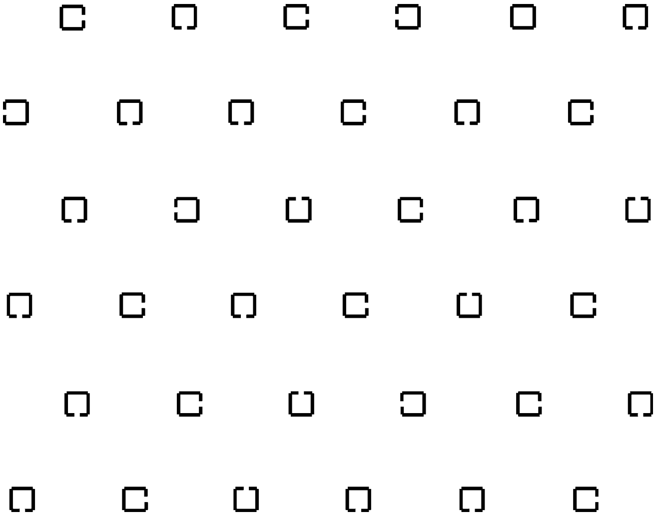


Fig. 2 An example of a search display of experiment 1. The target is the *closed symbol*. In the experiment, the elements were *white on a black background*

Subjects sat at 41 cm distance from the monitor; head movements were restricted by means of a chinrest. The room was dimly lighted. A block started with the calibration of the eye tracking system. Each trial started with a recalibration (‘drift correction’) of the eye tracker based on a single fixation to maintain accurate eye movement recording throughout the session. By pressing the ‘space bar’ drift correction was applied. Immediately after a successful drift correction the search display appeared. Since the fixation point of the drift correction was presented in the center of the screen, search always started in the center of the search display. Subjects searched the display until they found the target; there was no time limit. After they had found the target, subjects maintained their eyes fixated on the target while pressing the space bar to terminate the trial. The start of the fixation on the target was designated the end of the trial.

Eye movement analysis

Saccades were detected with a velocity threshold of 50°/s. After the detection of a saccade our Matlab program searched back and forth until the velocity was two standard deviations higher than the velocity during fixation (as in Van der Steen and Bruno 1995). Saccades with amplitudes smaller than 0.1° were removed from the analysis. If a small saccade was removed, fixations before and after this saccade were added together. Fixations shorter than 50 ms were removed from further analysis.

Subjects

Five subjects participated in all conditions. The authors (Björn N.S. Vlaskamp, Eelco A.B. Over and Ignace Th.C. Hooge) were three of the subjects (all male). The other two subjects (one male and one female) were naïve with respect to the goals of this experiment. All subjects were between 19 and 35 years old and had normal vision. The subjects gave their informed consent. The experiment was conducted in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki.

Results experiment 1

Here, we will report the average results across subjects. The accompanying figures will additionally contain the individual subject data.

Search time

The search time is a measure for search performance. Figure 3 shows plots of the mean search time averaged across all subjects. Mean search time is plotted as a function of the spacing in the display. Search time is defined as the period stretching from display onset until fixation of the target. As expected, there was a large decrease in search time with increasing element spacing due to the increasing number of elements in the display. Target–distracter similarity clearly affected the search. When the gap size was larger (less resemblance to the target), search time was shorter.

Search time per element

The search time as a function of spacing is confounded with the number of elements in the display. To gain better insight into the dependence of the search performance on spacing, search time per element (mean search time divided by the number of elements in the display) was calculated. This measure should not be confused with the actual rate of processing, because during search only a fraction (± 0.5 when search is systematic) of the elements is fixated. Mean search time per element is plotted in Fig. 4 as a function of element spacing. The element spacings of 7.1°, 5.2°, 4.1° and 3.4° relate to 36, 64, 100, and 144 elements, respectively, in the display. Element

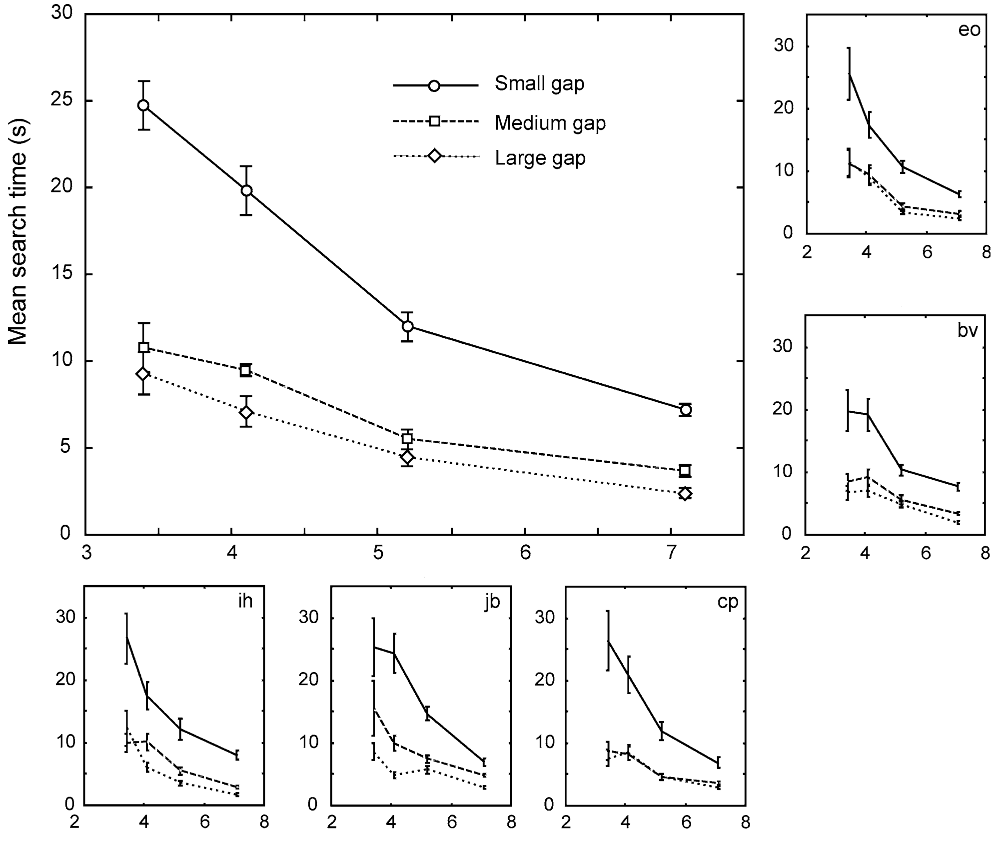


Fig. 3 Search time versus element spacing. The *large panel* shows the mean across all subjects. The *small panels* represent data of individual observers. *Error bars* represent standard errors of the mean. *Dotted line* denotes gap size 0.27°; *dashed line* denotes gap size 0.19°; *solid line* denotes gap size 0.09°

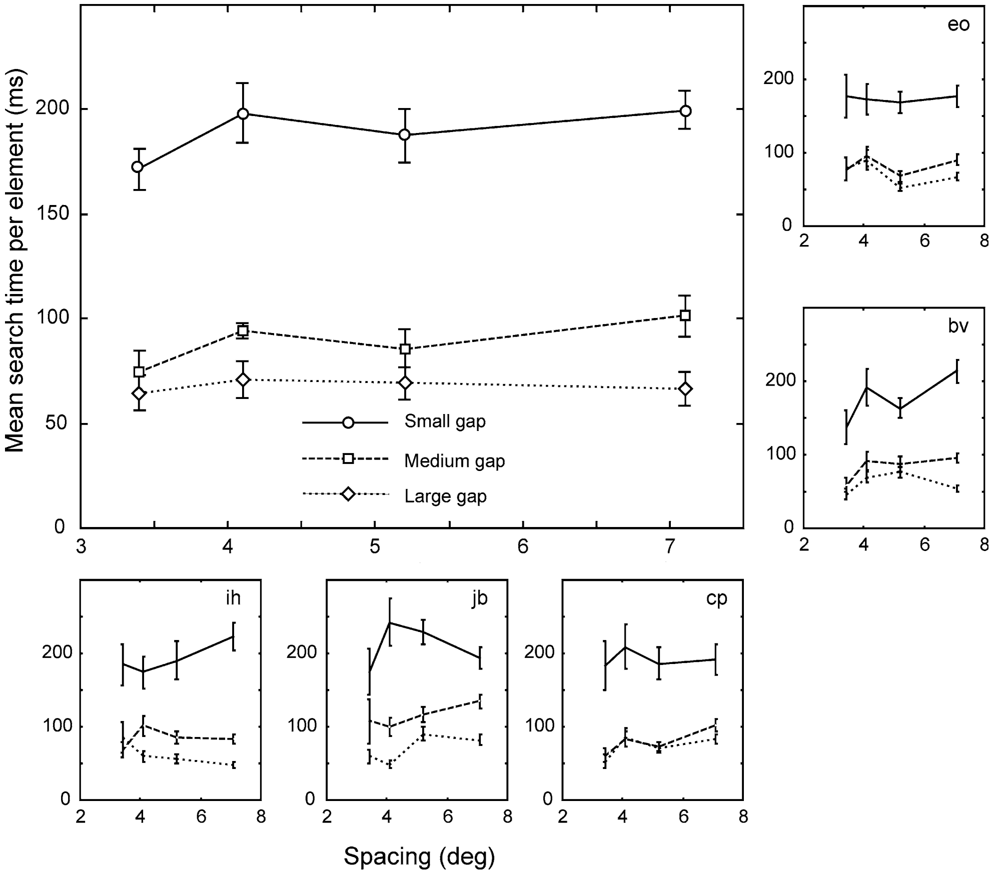


Fig. 4 Mean search time per element versus element spacing. The mean search time per element is defined as the mean search time divided through the number of elements in the search display. *Error bars* represent standard errors of the mean. The *large panel* shows the mean across all subjects. *Dotted line* denotes gap size 0.27°, *dashed line* denotes gap size 0.19°, *solid line* denotes gap size 0.09°

spacing affected search time per element [$F(3,12) = 3.64$, $P = 0.045$]. The search times per element decreased with decreasing spacing. However, the effect of spacing on the search time per element was only small compared to the effect of gap size. Whereas the maximum difference in search time per element between spacings within a single gap size level was 28 ms (small gap), gap size effects within a single spacing level were between 107 ms (spacing 3.4°) and 133 ms (spacing 7.1°). Increasing gap size facilitated search: search times decreased. This effect was highly reliable [$F(2,8) = 241.67$, $P < 0.001$]. The facilitation of search by decreasing target–distracter similarity is in agreement with other reports (e.g., Jacobs 1986; Rayner and Fisher 1987a, b; Hooge and Erkelens 1996). There was no interaction between spacing and gap size [$F(6,24) = 0.71$, $P = 0.64$]. Thus, the search time per element improved with decreasing spacing. However, the effect of spacing was relatively small in comparison to the effect of gap size. The effect of gap size was four times as large as the effect of spacing.

Number of fixations per element

A possible limitation on the search performance is the amount of information that is inspected per fixation. A measure to reveal whether the amount of information is the same across conditions is the number of fixations divided by the number of elements in the display. A decrease in this measure denotes an increase in the number of elements that is inspected per fixation.

The number of fixations per element increased with spacing [$F(3,12) = 6.00$, $P = 0.012$]. However, as with the search time per element this effect was only minor in comparison to the effect of gap size on the number of fixations per element. The effect of gap size on the number of fixations per element was several times larger (see Fig. 5). Gap size produced a highly reliable effect on the number of fixations per element [$F(2,8) = 354.98$, $P < 0.001$]. Spacing and gap size did not interact on the number of fixations per element [$F(6,24) = 1.09$, $P = 0.40$]. Thus, the number of fixations per element was mainly affected by gap size. Spacing also affected the number of fixations per element, but the magnitude of the effect was considerably smaller than the effect of gap size (collapsed across gap sizes it roughly amounted to less than a fifth of the effect of target–distracter similarity collapsed across gap sizes).

Fixation duration

As has been mentioned before, in the search for which eye movements are required to inspect the whole display, the distance between elements might not only affect the number of fixations, but the fixation duration as well. Therefore, in order to gain insight into the search strategy we also discuss fixation duration. In the

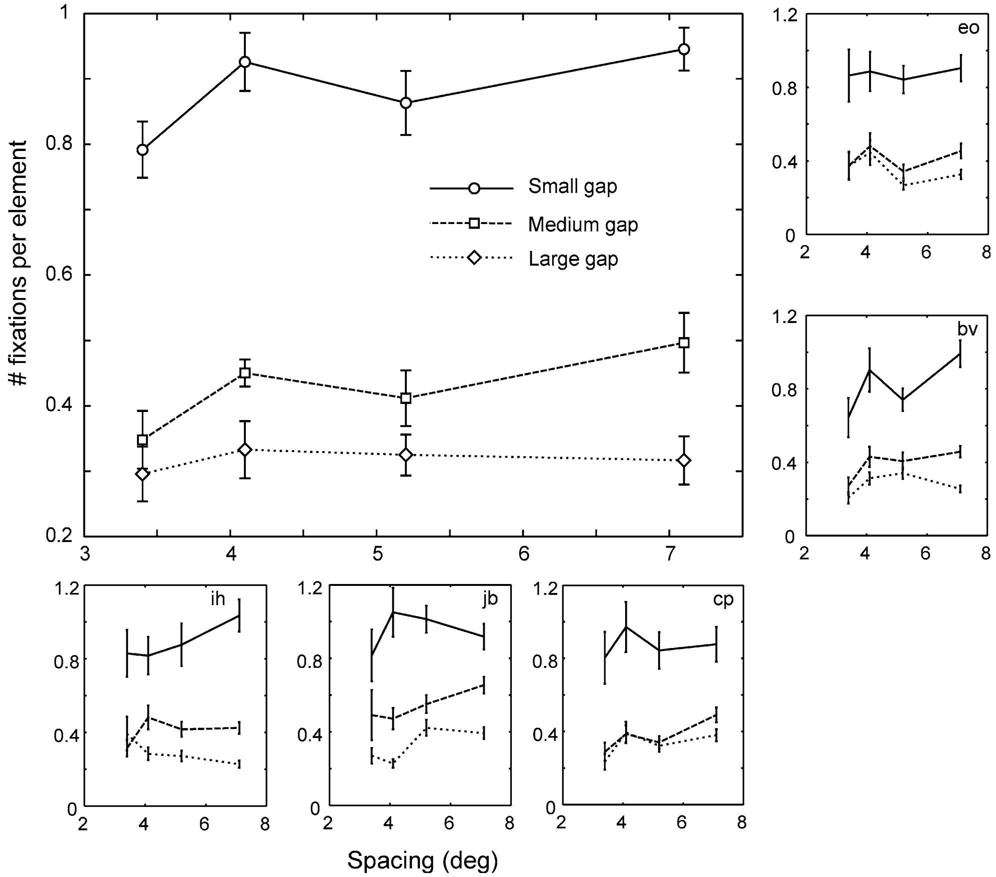


Fig. 5 Mean number of fixations per element versus element spacing. This measure is the number of fixations that were required to find the target divided by the number of elements in the search display. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean. *Dotted line* denotes gap size 0.27°, *dashed line* denotes gap size 0.19°, *solid line* denotes gap size 0.09°

calculation of the average fixation duration all fixations are included except the first and the last fixation in a trial. In Fig. 6 the mean fixation duration is plotted against element spacing. Fixation duration was shorter when the distance between two neighboring elements was large. This effect was significant [$F(3,12) = 21.05$, $P < 0.0001$]. The size of the effect was small. Maximum difference in the fixation duration between element spacings amounted to 13 ms (small gap), 16 ms (medium gap) and 23 ms (large gap). Gap size also affected fixation duration [$F(2,8) = 9.10$, $P < 0.01$]. Smaller gap size increased fixation duration. The effects were in a range similar to the effects of spacing (12, 10, 21 and 16 ms in the 3.4°, 4.1°, 5.2° and 7.1° spacings, respectively). The effect of gap size on the fixation duration with increasing target–distracter similarity (here, smaller distracter gap size) is in accordance with prior research on saccadic search (e.g., Jacobs 1986; Hooge and Erkelens 1996). Clearly, fixation duration is affected by the distance between elements as well as by gap size. There was an interaction effect of spacing and gap size on the fixation duration [$F(6,24) = 2.85$, $P = 0.03$].

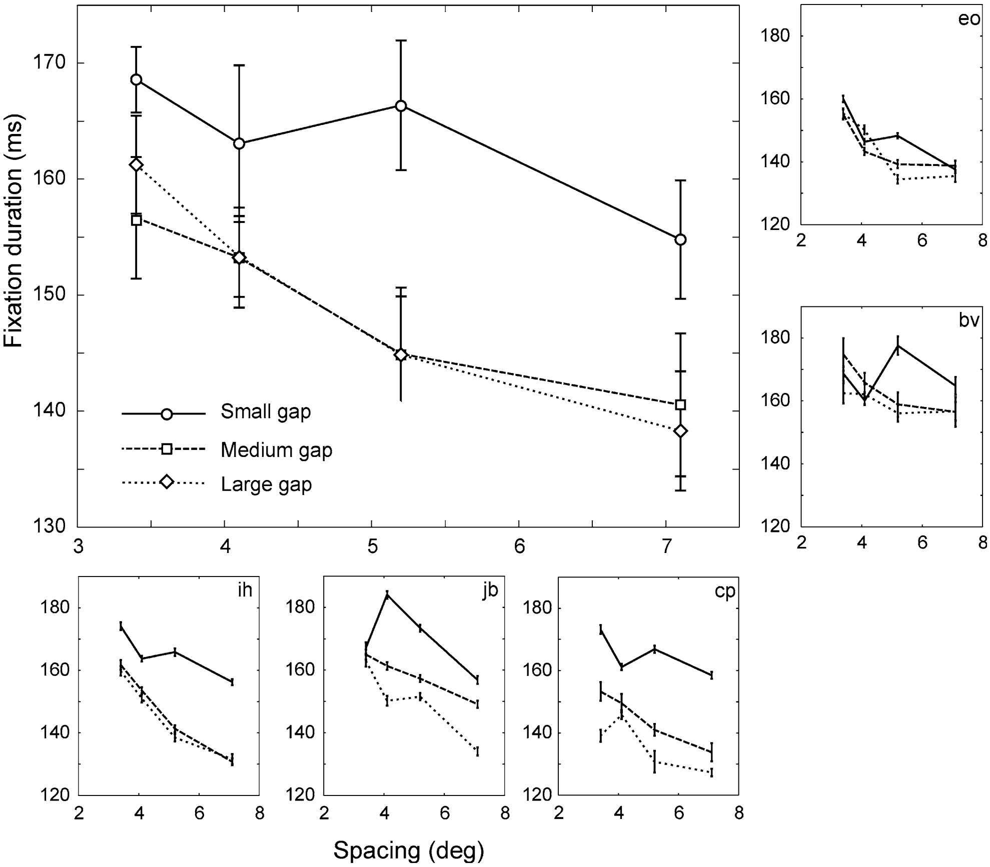
Saccade amplitude

Saccade amplitudes are displayed in Fig. 7. Mean saccade amplitude increased with increasing element spacing [$F(3,12) = 71.84$, $P < 0.001$]. In the small gap conditions, saccade amplitude increased from 5.1° at element spacing 3.4°–8.3° at 7.1°. In the medium gap size condition, saccade amplitude increased from 7.4° to 10.6° at element spacings of 3.4° and 7.1° respectively. Finally, in the conditions with the largest gap size, saccade amplitude increased from 8.2° to 12.3°. Gap size also affected the saccade amplitude. Saccade amplitude increased with increasing gap size [$F(2,8) = 67.00$, $P < 0.001$]. The effects were as large as 3.0° in the 3.4° spacing condition, 3.2° in the 4.1° condition, 4.0° in the 5.2° spacing condition and 4.0° in the spacing 7.1° condition. Saccade amplitude was not affected by an interaction between spacing and gap size [$F(6,24) = 1.24$, $P = 0.32$].

Discussion experiment 1

Search performance was studied as a function of the spacing between elements and target–distracter similarity. The measure for search performance, the search time per element, was affected by both the spacing and the target–distracter similarity. However, the effect of spacing was remarkably small in comparison to the effect of target–distracter similarity. Whereas the search time per element decreased with maximally 28 ms (a decrease of 14%) with decreasing spacing, gap size was found to roughly affect the search time per element four

Fig. 6 Mean fixation duration versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean. *Dotted line* denotes gap size 0.27°, *dashed line* denotes gap size 0.19°, *solid line* denotes gap size 0.09°



times as much, up to 133 ms (a decrease of 67%). Put in other words, the amount of information acquired per second was reliably influenced by spacing. Yet, the rate of information acquisition appears to be mainly determined by target–distracters similarity.

The number of fixations per element, which served to indicate whether there were differences across conditions in the amount of information acquired per fixation, showed a significant but small decrease with decreasing spacing. In contrast, increasing target–distracter similarity strongly increased the number of fixations per element. Thus, the amount of information acquired per fixation was affected by spacing. However, its effect was considerably smaller than the effect of gap size. Conceivably, the area that is inspected during a fixation roughly scales with the spacing. This is also reflected in the saccade amplitude, which roughly scales with the distance between elements.

Spacing affected the search time per element and the number of fixations per element, but only to a minor extent. Element spacing perhaps should be even smaller to achieve a larger effect on any of these two measures. At the retina, the highest resolution processing is achieved at the center (fovea) and it degrades towards the periphery. A similar distribution of resolution processing is found in the brain. Here, central vision receives more cortical processing than peripheral vision (as reflected by the cortical magnification factor). The fovea only extends 1° of visual angle into the visual periphery, whereas the minimum distance between elements in experiment 1 is 3.4°. Therefore, elements adjacent to the fixated elements might still not have been close enough to the fovea to benefit from the higher spatial resolution in and close to the fovea (parafovea).

Experiment 2

In order to investigate search time per element and oculomotor behavior when element spacings are even smaller than the spacings in the first experiment, we conducted a control experiment. In this experiment elements were placed closer to each other than in the previous experiment with center-to-center distances between neighboring elements as small as 0.8°. This way, elements adjacent to the fixated element fall within the parafovea (spacings roughly smaller than 2.5°) and in the conditions with the smallest spacings even within the fovea (spacings smaller than 1°).

Methods experiment 2

Apparatus

Stimuli were generated by an Apple G4 computer and presented on a LaCie Electronblue III 22″ monitor (1,600 × 1,200 pixels). The heads of the subjects were

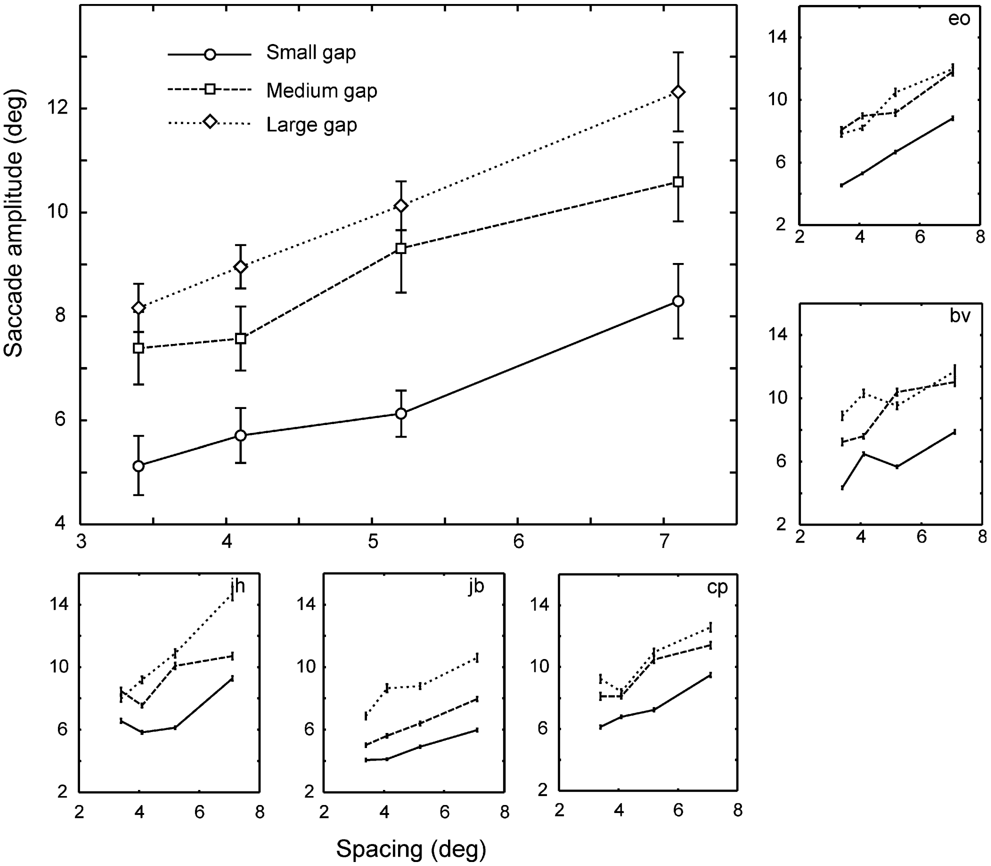


Fig. 7 Mean saccade amplitude versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean. *Dotted line* denotes gap size 0.27°, *dashed line* denotes gap size 0.19°, *solid line* denotes gap size 0.09°

stabilized by means of a bite board at 64 cm distance from the monitor. Movements of the left eye were recorded with the SMI Eyelink I eye tracker. One of the Eyelink cameras was placed on a stand close to the left eye of the subjects. Only movements of the left eye were recorded even though the search was binocular. Data were analyzed off-line in the same way as in the first experiment.

Stimulus

The search display size subtended 17° × 14°, which was smaller then the display in the first experiment. Search elements and search display were similar to experiment 1. Element luminance was 35.0 cd/m^2 and background luminance was 3.5 cd/m^2.

Procedure

The experiment consisted of eight conditions. Since there was no interaction between spacing and gap size in experiment 1 on the search time per element and the number of fixations per element, conditions only differed in the element spacing. It was varied by means of the number of elements in the search display. The display contained 36, 49, 64, 100, 144, 256, 400, or 576 elements, which agreed with element center-to-center spacings of 3.2°, 2.7°, 2.4°, 1.9°, 1.5°, 1.1°, 0.9°, 0.8°, respectively. This range of element spacings complemented the range of element spacings of experiment 1, which ranged from 3.4° to 7.1°. The size of an element was 0.44°×0.44° and the size of the gap was 0.18° in all conditions. Conditions were presented in block. The number of trials differed per condition: 36 elements → 90 trials, 49 elements → 80 trials, 64 elements → 50 trials, 100 elements → 40 trials, 144 elements → 30 trials, 256 elements → 20 trials, 400 elements → 20 trials, or 576 elements → 20 trials. The experiment was carried out in the same way as in experiment 1. The eye movement analysis was performed similarly as well.

Subjects

Five subjects participated in all conditions (age 22–26). Two of the subjects (Björn N.S. Vlaskamp and Eelco A.B. Over) are authors. The other subjects were naïve with respect to the goal of the study. All subjects had normal or corrected to normal vision. The subjects gave their informed consent. The experiment was conducted in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki.

Results experiment 2

Search time per element

Mean search time per element was similar for a wide range of element spacings (Fig. 8). Even though there

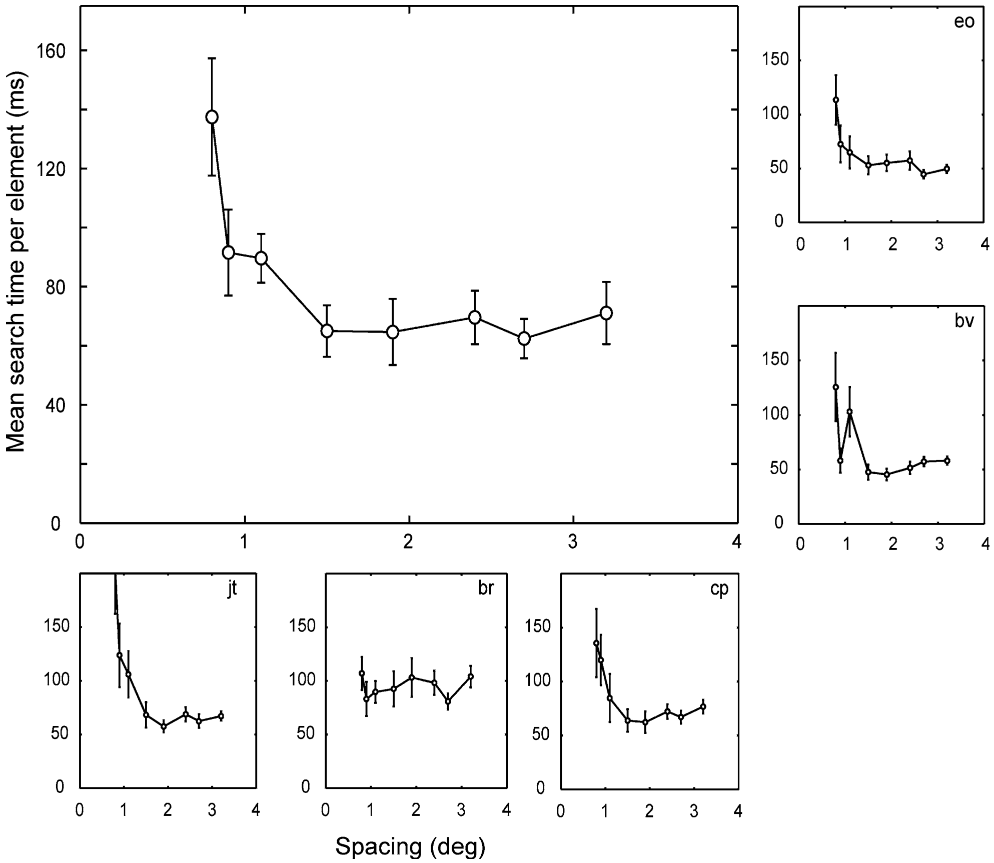


Fig. 8 Mean search time per element versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean

was a significant effect of element spacing on search time per element [$F(7,28) = 8.21$, $P < 0.001$], the figure suggests that the effect resides in element spacing smaller than 1.5°. Indeed, a one-way ANOVA on the spacings from 1.5° to 3.2° revealed that these search times per element did not differ significantly [$F(4,16) = 1.88$, $P = 0.16$]. Element spacings ranging from 0.8° to 1.5°, including 1.5°, were dependent upon element spacing [$F(3,12) = 9.06$, $P < 0.01$]. The independence of search time per element for element spacings from 1.5° to 3.2° corresponds to what we found in the first experiment. At element spacings smaller than 1.5° mean search time per element was affected, but oppositely to the effect of spacing found on search time per element in the first experiment. Search times per element increased dramatically. At element spacing 1.5°, mean search time per element was 65 ms. Mean search time per element at the smallest element spacings (0.8°) more than doubled to 137 ms. In comparison, the largest difference in search time per element found from 1.5° to 3.2° was 8.7 ms.

Number of fixations

Figure 9 shows the mean number of fixations per element as a function of the element spacing. The number of fixations increased as element spacing decreased [$F(7,28) = 4.71$, $P < 0.01$]. However, this effect mainly stems from element spacings from 1.5° and smaller (see Fig. 9). Even though there was a reliable effect for element spacings from 1.5° and larger [$F(4,16) = 4.28$, $P = 0.015$] as well as for spacings smaller than and including 1.5° [$F(3,12) = 8.21$, $P < 0.01$], the effect at the larger spacings was quite small in absolute numbers. Whereas the number of fixations per element increased 0.18 fixations per element when element spacing was decreased from 1.5° to 0.8°, there only was a maximum difference of 0.05 fixations per element for 1.5° spacings and larger. As in the previous experiment, mean number of fixations per element seems to reflect the search time per element to a great extent. This is in agreement with previous experiments (Motter and Belky 1998a; Näsänen et al. 2001).

Fixation duration

Eye movement parameters were affected by the distance between elements. Fixation duration (Fig. 10) decreased with increasing element spacing over the whole range of element spacings measured in this experiment [$F(7,28) = 48.39$, $P < 0.001$]. The figure shows that particularly spacings smaller than 1.5° affect fixation duration. At elements spacings between 0.8° and 1.5° distance there was a maximum difference in fixation duration of 49 ms. At spacings between 1.9° and 3.2° fixation duration differed 26 ms.

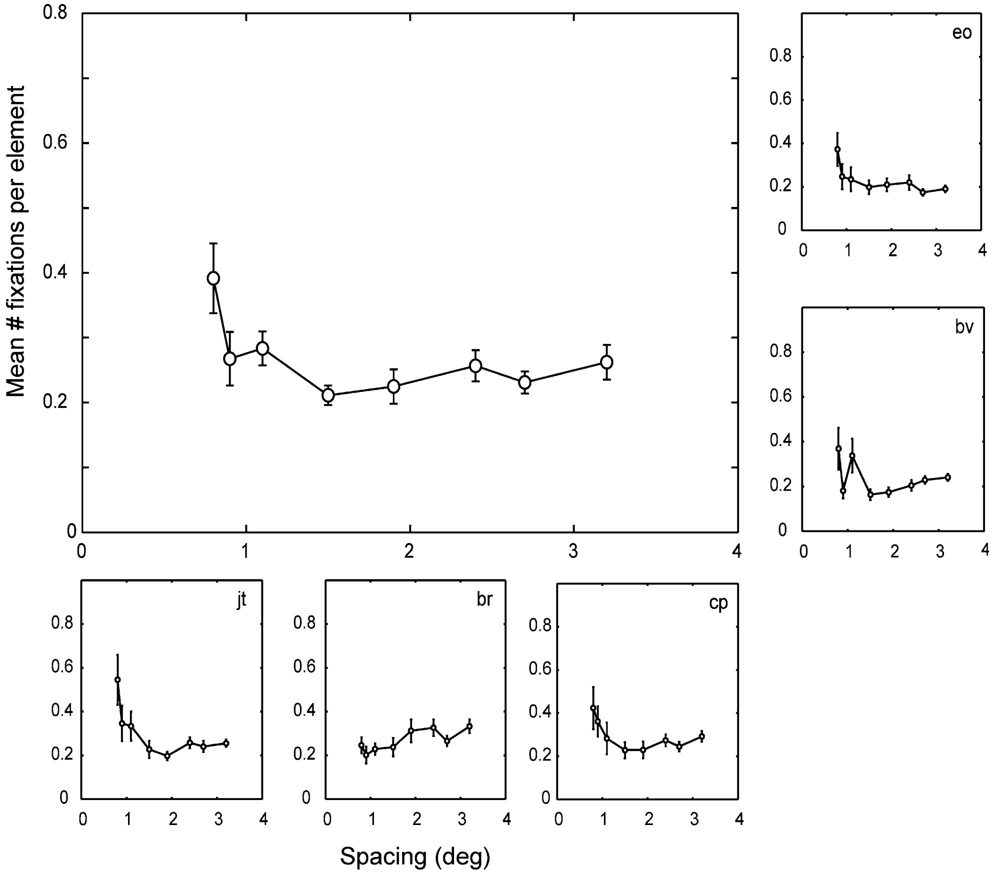


Fig. 9 Mean number of fixations per element versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean

Saccade amplitude

Saccade amplitude decreased with decreasing element spacing (Fig. 11) [$F(7,28) = 15.51$, $P < 0.001$]. Mean saccade amplitudes ranged from 2.9° at an element spacing of 0.8°–5.3° at 3.2° element spacing.

Discussion experiment 2

Experiment 2 was designed to investigate search time per element and oculomotor behavior in search displays with element spacings smaller than 3.4°. Remarkably, search time per element was still not affected for element spacings in the range of 1.5°–3.2°. This pattern of results was largely reflected by the number of fixations per element. Even though there was a difference between means on this measure at spacings between 1.5° and 3.2°, the difference found was only marginal in absolute numbers. With decreasing spacing, fixation duration increased and saccade amplitude decreased.

It is only at smaller spacings that search time per element was influenced. However, at first sight the direction of the effect here is rather counter-intuitive. Following the line of reasoning that more oculomotor strategy possibilities might arise with decreasing element spacing, one would expect that the most efficient strategy would be applied in the conditions with smallest element spacings. In contrast, the search time per element increased substantially. At smaller spacings the number of fixations per element also increased strongly with decreasing element spacing.

General discussion

The main finding of the experiments described above is that the spacing has only a relatively small effect on search time per element. At wide spacings (3.4°–7.1°) this effect was small in comparison to the effect of target–distracter similarity. At spacings between 1.5° and 3.2° spacing did not affect the search time per element at all. The number of fixations per element was similarly affected for both the spacings in experiment 1 and experiment 2. For the whole range 1.5°–7.1°, fixation durations increased slightly and saccade amplitude decreased with decreasing element spacing. For element spacings smaller than 1.5° the results changed dramatically. In this range, search time per element and the number of fixations per element increased with decreasing element spacing. Fixation duration became increasingly longer with decreasing element spacing and saccade amplitude decreased. Additionally, it was found in the first experiment that the relationship between element spacing and search time per element was not affected by target–distracter similarity. Target–distracter

Fig. 10 Mean fixation duration versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean

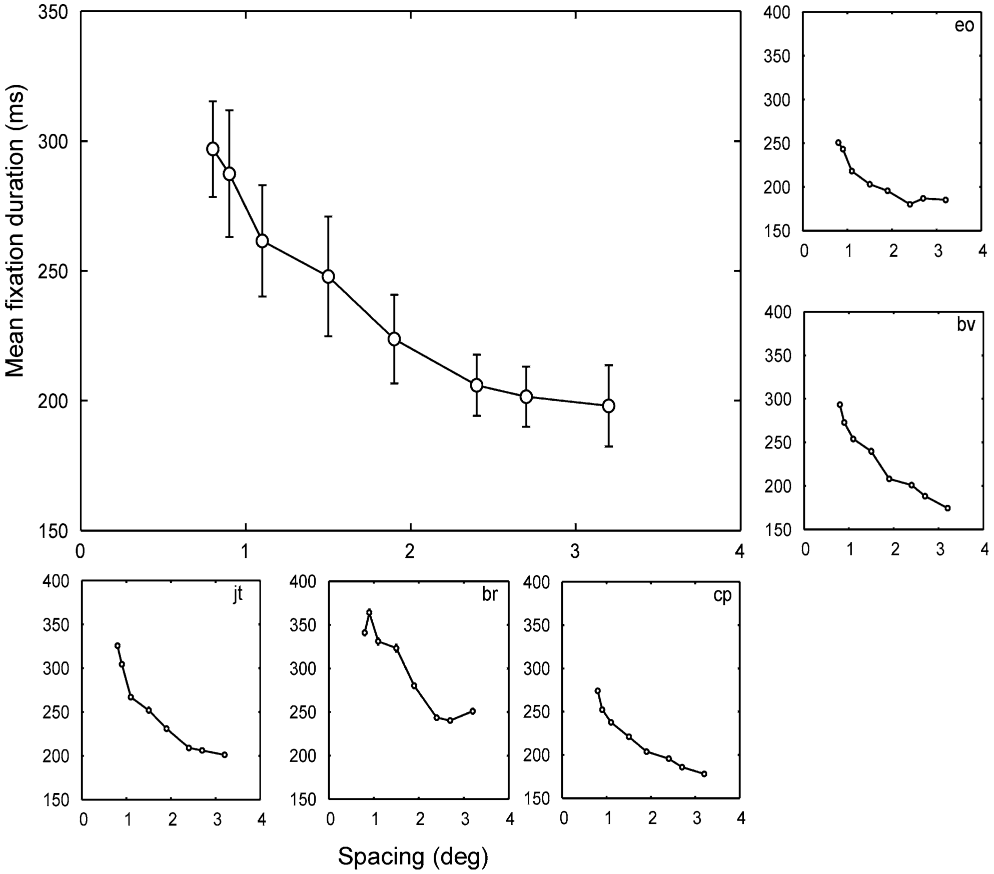
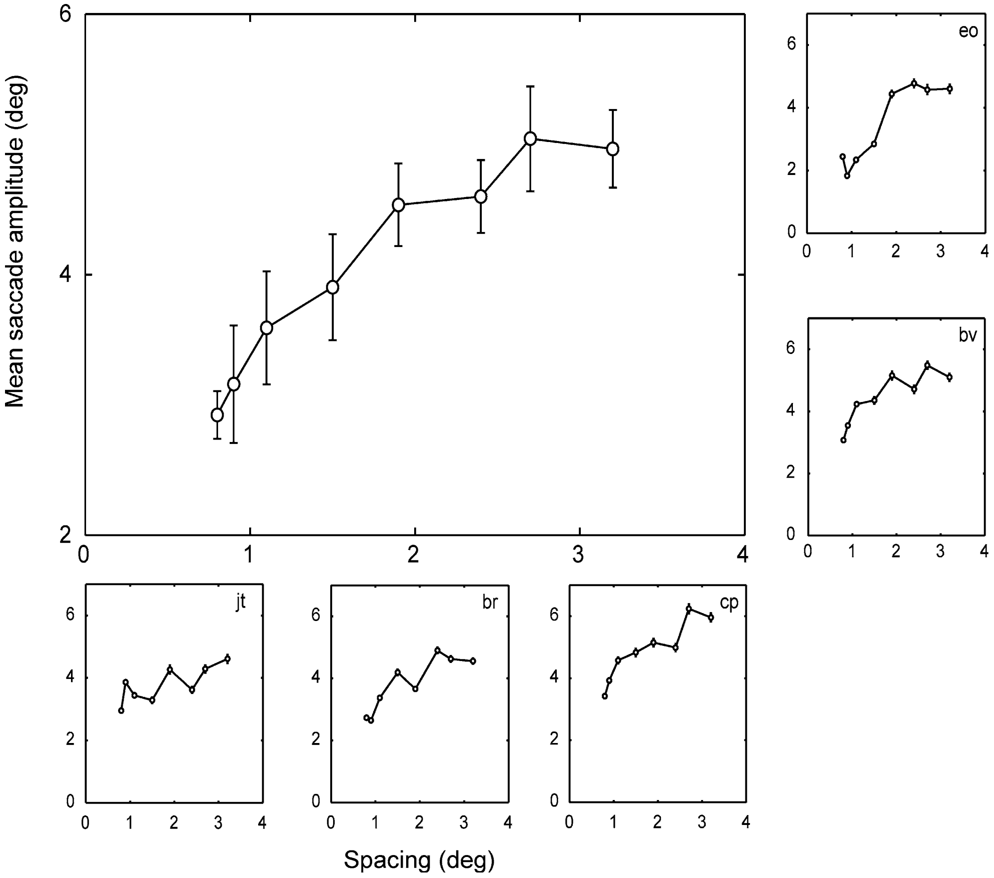


Fig. 11 Mean saccade amplitude versus element spacing. The *large panel* shows the mean across all subjects. *Error bars* represent standard errors of the mean



similarity by itself strongly increased search time per element, the number of fixations per element and fixation duration; it decreased saccade amplitude.

Relation to previous research

The results of several other studies can be related to our data. Studies that have measured search performance report that the search time per element decreased as a function of the distance between elements (e.g., Rayner and Fisher 1987a, b; Bertera and Rayner 2000). In these studies, search displays differed to ours in several respects that possibly affect the eye movement strategy. For example, in our experiments all distracters in a single display were equally similar to the target. In the experiments of Bertera and Rayner (2000) and Rayner and Fisher (1987a, b) the distracters in a single display resembled the target to a different degree. It is likely that the uniformity of target–distracter similarity affects oculomotor behavior, since distracters are more likely to be foveated with increasing similarity to the target (e.g., Motter and Belky 1998b; Scialfa and Joffe 1998; Hooge and Erkelens 1999). Another difference between the current search displays and the ones used by Rayner and Fisher (1987a, b) and Bertera and Rayner (2000) is that they had placed the search elements at random positions, whereas our search elements were equidistantly separated from each other.

Special attention should be devoted to the research conducted by Motter and Belky (1998a, b). They investigated search in which eye movements were allowed to find the target across several element spacings. Instead of human subjects, two monkeys searched for the target. Another difference was that the search element positions were quasi-randomly chosen. As noted above, this might affect scanning behavior. At first sight, their data appear to be at odds with ours. They found that the search time per element decreased with decreasing distance between elements. However, they provided a measure for the visual span as well. This measure was the distance at which the target was detected, i.e., the distance from the target to the last fixation position before fixating the target. Motter and Belky (1998a) found that this target detection distance, normalized to the element spacing, remained unaffected. This corresponds with our finding that spacing had such a relatively small effect on the number of fixations per element, which is inversely related to the number of elements inspected per fixation.

Crowding

In our experiments, the number of elements inspected per fixation was affected to a relatively small extent for spacings between 1.5° and 7.1°. This suggests that the bottleneck on the number of elements inspected during a fixation is more or less the same for these spacings. Several factors can act as a bottleneck. For example, beyond a certain eccentricity it becomes impossible to resolve a search element as target or distracter due to the drop of spatial resolution from the retinal center to the periphery. However, the inhomogeneous distribution of spatial resolution was clearly not the bottleneck on the number of elements inspected per fixation in our experiments. For, decreasing the distance between elements did not affect the number of elements inspected per fixation.

An explanation on the computational level that fits the current results is the following. From psychophysical experiments it is known that the identification or discrimination of a target element is hindered by elements that surround it, particularly in the visual periphery—a phenomenon known as lateral masking or crowding (e.g., Bouma 1970; Wolford and Chambers 1983; Toet and Levi 1992; He, Cavanagh and Intriligator 1996). The extent of crowding is defined as the threshold distance between target and distracters at which the distracters interfere with the discrimination or identification of the target. It has been found to be as large as 0.5 times target eccentricity (Bouma 1970; see Chung et al. 2001, for an overview of the extents of crowding found in the literature).

In search, the crowding phenomenon potentially acts as a bottleneck on the number of elements inspected per fixation. The extent of crowding of an element increases with retinal eccentricity (Bouma 1970; Toet and Levi 1992). Elements that are situated beyond the eccentricity at which the extent of crowding of search elements is larger than the element spacing, cannot be discriminated as a target or distracter; surrounding elements affect their discrimination. Conversely, elements closer to the fovea have an extent of crowding that is smaller than the element spacing. They can be discriminated.

When crowding restricts the number of elements that are inspected during a fixation, element spacing is expected not to influence this number. When the distance between elements in the display is increased or decreased, the extent of crowding for each element also increases or decreases. In fact, the extent of crowding of each element might remain the same relative to the distance between two elements. On the one hand, elements should be easier to identify when the element spacing is decreased since they are closer to the fovea. On the other hand, elements should be harder to identify since they are closer to each other. Indeed, Bouma (1970) showed in a letter identification task that there is a linear relationship between the extent of crowding and target eccentricity. Therefore, the same number of elements is expected to be acquired from the search display per fixation, irrespective of element spacing.

We also reported that the search time per element increased with increasing target–distracter similarity and the number of elements inspected per fixation decreased. This is in accordance with the explanation that crowding limited the number of elements inspected per fixation. The extent of crowding depends on the similarity between target and distracters (Nazir 1992; Kooi et al. 1994). When target and distracters are more similar, the extent of crowding increases. As a result, fewer elements can be inspected per fixation.

Does the visual span size in the present experiment reflect the extent of crowding reported in the literature? In the literature, the extent of crowding has been reported to stretch up to 0.5 times the target eccentricity (Bouma 1970; Toet and Levi 1994; Kooi et al. 1994). For a search task, this means that elements at double element spacing from the point of fixation might be crowded by the elements that surround it (the surrounding elements are situated within 0.5 times eccentricity from elements at double spacing). A rough measure for the (uni-directional) extent of the visual span is the saccade amplitude. Jacobs (1986) found that visual span size and saccade amplitude are highly correlated. In the current experiments, the saccade amplitudes range from larger than the element spacing to over two times the element spacing. In the majority of the conditions, the saccade amplitudes were about two times the element spacing. Thus, the visual span appears to have a size that might well be limited by an extent of crowding that is roughly 0.5 times eccentricity.

Alternatively, is it possible that the number of elements that is inspected per fixation is restricted by a limited capacity for processing visual information? For example, the capacity for information that visual attention acts upon might be limited (Verghese and Pelli 1992). However, the amount of information processed does not depend only on the processing capacity, but also on the time available for the processing. Indeed, Verghese and Pelli (1992) also define the capacity limit of attention as the amount of information processed within ‘a single glimpse’. The number of elements inspected per fixation, then, would depend on the processing capacity, but also on the duration of fixation. Fixation durations vary within a broad range (e.g., consider the fixation durations in the present experiments. They range from about 140 to 300 ms). Therefore, stating that the number of elements inspected per fixation is limited due to a limited information processing capacity would merely shift the problem from the question, what limits the area inspected to what limits the time to inspect elements.

Element spacings smaller than 1.5°

When element spacing was decreased to 1.5° and smaller, search time per element as well as the number of fixations per element and fixation duration strongly increased. Among other possibilities, the change in search behavior at element spacings smaller than 1.5° might be in oculomotor limitations. To maintain an oculomotor strategy similar to the one applied at larger element spacings, saccade amplitudes have to be very small in the conditions with the smallest spacings. Perhaps amplitudes of voluntary saccades cannot be scaled to the spacing, forcing the adoption of a different and possibly less effective eye movement strategy. For example, if saccade amplitudes are larger than the visual span, the eye may jump over the target, increasing search time.

Conclusion

In this research the effect of element spacing, i.e., the distance between two neighboring elements, on the search performance was studied. It was reasoned that when element spacing is small, the number of possible oculomotor strategies might be larger (Moffitt 1980) than when the distance between elements is large.

We did not find different oculomotor strategies. We found one strategy, namely that saccade amplitude increased proportionally with spacing and fixation time decreased by a small amount with increasing spacing. This can be interpreted as that visual span roughly scales with element spacing. In other words, the number of elements processed per fixation is kept constant. An explanation that perfectly fits the results is that crowding limits the number of elements that is inspected per fixation. In fact this study shows that conclusions from psychophysical crowding experiments can be generalized to search with eye movements.

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