Eye movements, search and crowding

Oogbewegingen, zoeken en ‘crowding’

(met een samenvatting in het Nederlands)

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Contents

Chapter 1

Introduction

This thesis is about the interplay between visual perception and eye movements. Why is this interesting? As we all know, visual perception is important for humans as well as for most other animals. Our senses provide our brain with information, and further processing will eventually result in an internal representation of the outside world. This information is subsequently used by observers to interact with the environment. In order to supply our brain with high quality information, we move our body, our head as well as our eyes. For good reasons! High quality visual information is only available from a rather limited part of the visual field. This information enters the visual system through the center of the retina: the fovea. Relative to other retinal areas, a large part of the information processing power of the visual system is devoted to foveal visual information (Rovamo & Virsu, 1979; Virsu & Rovamo, 1979). Stronger, a massive part of our visual cortex is devoted to the processing of information coming form the central parts of our retina. In order to acquire visual details from a large part of the visual field, eye movements are required. Eye movements direct the fovea, and as such the part of the retina with the highest spatial resolution at interesting locations quickly and accurately. Yet, vision also controls eye movements. The processed visual information forms a basis upon which decisions are made concering when to move the eyes (e.g., Greene & Rayner, 2001; Hooge & Erkelens, 1998; Jacobs, 1986; Rayner & Pollatsek, 1981) and where to move the eyes (e.g., Bertera & Rayner, 2000; Hooge & Erkelens, 1999; Jacobs, 1986; Motter & Belky, 1998a).

How do we move our eyes? Before the 19th century, it was thought that for activities like reading the eyes move around in a smooth manner (Wade, Tatler & Heller, 2003). In the 19th century Javal first reported that the eyes move in a jerky way. He termed these movements saccades. But, it was Lamare, one of Javal's lab members, who actually observed these movements first. He later reported that these saccades could be felt 'with a finger over the lid of a closed eye' [Lamare, 1892, page 357, adapted from Wade et al. (2003)].

Saccades are ballistic, stereotyped movements produced at a rate of 2 to 5 per second. During saccades the eye reaches peak velocities over 500°/s (Collewijn, Erkelens & Steinman, 1988). Although observers are usually not aware of it, visual information that falls on the retina during a saccade is mostly suppressed (Matin, 1974; Thiele, Henning, Kubischik & Hoffmann, 2002).

Between saccadic eye movements, visual information is taken in by the eyes for further processing. These periods, in which the eyes are more or less stationary are called fixations. That is, the eye is fixating a location or an object in the scene. According to Viviani (1990), a least three processes are assumed to take place during a fixation: The 'analysis of the visual stimulus in the foveal field, the sampling of the peripheral field, and the corresponding planning of the next saccade' (p. 360). In tasks like reading, fixation durations typically range between 200 ms and 300 ms (see Rayner, 1998).

Visual span

In a landmark study, Jacobs (1986) hypothesized that eye movements are directly governed by the 'spatial visibility limits'. Central in this idea is that during a given fixation only a limited part of the visual scene can be inspected with a given accuracy. Jacobs (1986) termed this part the visual span. The visual span covers the fixation location and a part of the area surrounding this fixation location. For a given stimulus, the size of the visual span is ultimately limited by the sensory acuity limitations of the retina. Towards the periphery, details are harder or impossible to resolve (Anstis, 1974; Curcio & Allen, 1990; Rovamo & Virsu, 1979; Virsu & Rovamo, 1979).

Jacobs' hypothesis (1986) has particularly strong predictions concerning the saccade amplitude. The saccade amplitude refers to the step size or distance between two successive locations of fixation. Jacobs stated that "each saccade should bring the eye to a zone where new information can be gathered. That is, the limit of the visual span" (pp 47 - 48). Accordingly, stimulus factors that change the size of the visual span should evoke a parallel change in the saccade amplitude. For the fixation duration, Jacobs did not derive a clear-cut prediction. He suggested to take the following factors into account: (1) fixation duration can increase with decreasing span size, because sensory processing is harder; (2) fixation duration can remain the same, because saccade amplitude is correctly adjusted; and (3) fixation duration can increase with span size because more elements are processed.

Indeed, evidence has accumulated that changes in the visual stimulus that affect the visual span also affect the fixation duration and saccade amplitude. In a search task, Jacobs (1986) himself showed that saccade amplitude decreased with increasing target-distracter similarity using alphanumerical search elements. Others confirmed this finding both with alphanumerical elements (Rayner & Fisher, 1987a, 1987b) as well as figurative search elements (Cornelissen, Bruin & Kooijman, 2005). Similarly, it has been reported that lowering luminance contrast leads to a decrease in saccade amplitude (Näsänen, Ojanpää & Kojo, 2001). Fixation duration has been found to increase both with target-distracter similarity and with decreasing contrast, (Cornelissen et al., 2005; Jacobs, 1986; Näsänen et al., 2001; Rayner & Fisher, 1987a, 1987b).

More insights are provided by the moving window paradigm (Bertera & Rayner, 2000; Cornelissen et al., 2005; McConkie & Rayner, 1975; Rayner & Fisher, 1987a, 1987b). This paradigm was adopted from eye movement studies in reading. The technique consists of

Figure 1. A demonstration of the crowding phenomenon. If you try to identify the upper letter while fixating the upper dot on the left and if you then try to identify the lower middle letter while fixating the lower dot, you may experience that the flanked letter is harder to identify.

gaze contingent visual stimulus changes. With this technique, subjects only have access to the search display area that surrounds the point of fixation (the moving window) because the search display outside the window is masked. As subjects change their gaze direction, the window remains centered around the gaze location. The experimentally interesting aspect of the moving window paradigm is that it provides a controlled way to artificially limit the visual span. For example, in case the window is smaller than the subjects' visual span, the moving window basically forms the visual span. Using this technique it was discovered that the saccade amplitude indeed decreased with decreasing window size. Fixation durations were affected as well. However, contrary to what was expected, the duration of a fixation increased with decreasing window size, that is, a decrease in the number of elements that are processed per fixation came with longer fixation durations. Thus, Jacobs' intuition turned out to be right. Although the saccade amplitude was highly related to the visual span, the relationship between the fixation duration and the visual span appeared to be more complicated.

A final issue concerning the relationship between the visual span and the saccade parameters is the anisotropy of the span. In other words, the extend to which the visual span is related to the movement direction of the eyes. From reading-studies it is known that the span is elongated along the axis along which the eyes move (Pollatsek, Raney, Lagasse & Rayner, 1993). It has also been reported that the visual span stretches in the direction of reading and is shortened in the opposite direction (Rayner, Well & Pollatsek, 1980). For example, English readers have a span that stretches to the right of the fixation location, whereas the span of Hebrew readers extends towards the left visual periphery (Pollatsek, Bolozky, Well & Rayner, 1981).

In summary, the visual span hypothesis appears to be a valuable for understanding eye movement strategies. It is in particular the saccade amplitude that is related to the visual span. As an illustration of this point, Jacobs (1986) showed that 80% of the variability in the saccade amplitude can be explained by the size of the visual span.

Crowding

If one fixates the upper dot on the left in figure 1, one will probably be able to identify the isolated letter on the right side. If one now fixates the lower dot on the left, the central item on the right is much harder to identify. Apparently, the two flanking items interfere with the perception of the target item. This is a demonstration of a phenomenon that is known as crowding or lateral masking (Bouma, 1970; Fine, 2004; Flom, Weymouth & Kahneman, 1963; Levi, Hariharan & Klein, 2002; Pelli, Palomares & Majaj, 2004; Toet & Levi, 1992; Tripathy & Cavanagh, 2002). Jacobs (1986) suggested a role for crowding in the control of eye movements (see also O'Regan, 1990); he suspected that crowding is a potential limit on the size of visual span. But why would one suspect such a role for crowding? Since crowding becomes stronger towards the visual periphery (Bouma, 1970; Jacobs, 1979; Strasburger, Harvey & Rentschler, 1991; Toet & Levi, 1992), there may be an eccentricity at which the identity of the individual items becomes imperceptible due to crowding. If this eccentricity is the ultimate eccentricity at which items can be identified, crowding forms the limit on the visual span.

Moreover, crowding is a surprisingly strong suppressor as was demonstrated by Bouma (1970). He conducted a simple experiment in which the observer had to identify a single letter. This target letter was presented at several eccentricities. Bouma added other letters and determined the distance to the target at which they interfered with target perception. Bouma revealed a general rule: the threshold distance scales linearly with target eccentricity. This result was later confirmed in several other studies, (see Chung, Levi & Legge, 2001 for an overview). The spatial extent over which crowding occurs turned out to be remarkably large: Even items halfway the fixation location and the peripheral target interfered with target perception. Yet another remarkable finding was the fact that items on the peripheral side of the target cause stronger crowding than items closer to the fovea.

Since the spatial extent of crowding may be that large, it seems likely that the oculomotor system takes crowding into account. Some results from eye movement research indicate that this is indeed the case. For example, similarity between target and distracters increases the effect of crowding (Kooi, Toet, Tripathy & Levi, 1994; Nazir, 1992). Accordingly, it is known that the visual span size decreases with target-distracter similarity (Jacobs, 1986; Rayner & Fisher, 1987a, 1987b). With this decrease in span size, fixation duration increases while saccade amplitude decreases (Jacobs, 1986; Rayner & Fisher, 1987a,b).

However, at this time it may not be fully fair to conclude that crowding influences oculomotor behavior. One potential problem is that crowding is confounded with the spatial resolution across both the retina and cortex. Since spatial resolution is lower towards the periphery, items are more difficult to discern in the periphery as compared to areas closer to the fovea. If target-distracter similarity increases, differences between target and distracters are even harder to resolve. Thus, results that are attributable to crowding may also be explained, or partly be explained, by the distribution of spatial resolution.

In addition, it is still unclear to what extend crowding actually blocks information from further processing. Research by He, Cavanagh & Intriligator (1996) raised questions concerning this issue. They asked their observers to judge the orientation of a target gabor patch. This patch was located above a fixation dot and surrounded by two more gabors, one above and one below the target patch. Subjects performed at chance level, hence they did not consciously perceive the target orientation. This orientation judgment was followed by another experiment with interesting results. The target patch and the flanking patches were removed and a test patch was placed at the target item position. The task of the observers was to judge the orientation of this patch. The results showed that the perceived patch orientation was influenced by the orientation of the target patch in the preceding crowded stimulus (measured by the tilt after effect). This study shows that even though crowded information is not available consciously, it is processed by the brain nevertheless, at least up until a certain point along the pathways of visual information processing.

A study by Parkes et al. (2001) also demonstrated that crowded information may still be available for use. They presented a Gabor patch at 2.5° eccentricity. Subjects had to judge the orientation of this Gabor patch (clockwise vs. counterclockwise). This target patch was surrounded by 8 other Gabor patches , which were oriented horizontally. The target tilt threshold was higher with the surrounding patches than without (one of the subjects did not even perform above chance level). This implies crowding. Interestingly, the threshold decreased linearly with the number of surrounding patches that had an orientation similar to the target orientation. It appears that crowded, individual item information is not lost, but can for example be used to estimate average orientation.

Thus, crowding may act as a bottleneck on the visual span size and may consequently affect the eye movements. However, the latter cannot be concluded on the basis of the literature. The crowding literature is mostly concerned with describing and modeling crowding based on data from psychophysical threshold measurements during continuous fixation. This thesis addresses the questions whether and how crowding influences oculomotor behavior.

Overview of the thesis

It should be clear by now, that the relation between crowding and eye movements is the central topic of this thesis. More specifically, we examined eye movement behavior while several aspects of crowding were manipulated. Moreover, we investigated the role of eye movements and how these affect the perception of a crowded stimulus. In our experiments we mostly use search tasks where we record the movements of the eyes.

Saccadic search

We used saccadic search tasks, which are visual search tasks for which saccades are required if observers want to perform well. This task provides an ideal tool to investigate eye movements with regard to our research questions. It is also a valid task because our observers engage in a task that people commonly do in the natural world. Think about searching a desk for a pencil, a computer desktop for a specific icon or your favorite soup in a supermarket. Sometimes these tasks are even more crucial, especially when the factor time plays an important role. Think about radar technicians looking for airplanes on collision course, doctors searching for cancer on a mammography, soldiers searching for hidden or camouflaged enemies and security personnel at airports looking for weapons on the images from scanners. These tasks can often not be performed without making eye movements. This makes it tempting to conclude that laboratory search tasks have much in common with search tasks in natural environments, also when accuracy as well as speed is stressed and as a consequence results acquired from experimental search tasks are easier to generalize to search in everyday life (e.g., Wolfe, Horowitz & Kenner, 2005).

Our search displays contain abstract search elements and a solid background. Still, why use such stimuli if one could also use more natural images and pictures? The answer is that we wanted to be able to relate the eye movements to the contents of the search display. The information content of pictures is harder to determine and control than of displays with abstract elements. In the literature many of these ‘simple’ search stimuli can be found. For example, letters (e.g., Bertera & Rayner, 2001; Gilchirst & Harvey, 2001; Jacobs, 1986; Rayner & Fisher, 1987a, b), simple forms with openings at different locations like Landolt C’s (Cornelissen et al., 2005; Hooge & Erkelens, 1996; Hooge & Erkelens, 1998; Hooge & Erkelens, 1999), discs (Engel, 1977; Mackworth, 1976), Gabor patches (McSorley & Findlay, 2003), and simple lines (Motter & Belky, 1998a, b; Scialfa & Joffe, 1998)]. The investigator has many possibilities to selectively manipulate the search items. Depending on the items used, this includes color, contrast, size, spatial frequency, and orientation. It is also possible to change display background characteristics, like luminance and noise level, and of course the dimensions of the search area. In our experiments observers were asked to search an O amongst Cs. With these elements it is possible to manipulate the difficulty of the search task. For example, Cs with a small gap are harder to distinguish from Os than Cs with large gaps. This difficulty is reflected in the time required to find a specific item.

Many studies have been conducted in which a visual search paradigm was used. In such experiments, 'target present' trials are interleaved with 'target absent' trials. The subject's task is to respond whether there is a target in the search display. The relevant measures are the reaction time and the proportion correct answers. Typical visual search tasks are designed such that targets can be found without the use of eye movements. Hence, the number of search studies that take eye movements into account is very limited (Rayner, 1998). So, visual search researchers seldom measure eye movements. But to us this appears unwarranted: People are used to making eye movements especially when searching. Stronger, Findley and Gilchrist (1998) have shown that observers make eye movements in visual search tasks even if they would perform better without making an eye movement. In order to contrast our experimental paradigm where eye movements are a central part with the traditional visual search literature, we will not use the term 'visual search', but use 'saccadic search' instead.

Experiments

In the last 4 years, we have conducted many experiments. Five of these studies are presented in this thesis. show how I have worked in those four years. The questions addressed in the distinct studies are obviously connected to each other and as a result the reader might find some overlap between the chapters. This is due to the fact that the chapters are written to be published as separate articles.

Chapter 2 is based on work by Moffitt (1980). He suggested that humans may set their eye movement parameters in different ways as function of the spacing between search elements in a search display. That is, eye movement parameters may differ when the elements are far apart or close to each other. These different strategies may imply that the number of elements inspected per fixation differ. In this study, we examined the eye movement strategy along a wide range of element densities (7.1° - 0.8° distance between elements). Surprisingly, the number of elements inspected per fixation roughly remained the same across densities. We suggest that the results can be explained if it is assumed that the visual span (the part of the search display that can be inspected with a given accuracy) is limited by crowding.

In **Chapter 3**, we tested whether crowding limits the visual span and whether the eye movements take crowding into account. The search display was designed in such a way that the degree of crowding was manipulated without changing the density of the search elements. The crowding manipulation was confirmed using a threshold measurement. The results showed that the eye movements were adjusted to the level of crowding: Saccade amplitude decreased, fixation duration increased, and the number of fixations required to find the target increased with increased crowding. Furthermore, search times increased with 76%. This study shows that crowding should be taken into account if one wants to understand eye movements in tasks that require the active exploration of the visual scene.

In **Chapter 4**, we explored fixation duration. We elaborated on a finding presented in the second chapter. There, we found that fixation duration increased dramatically in very high density displays (when the distance between elements is 1.5° or smaller). The increase in fixation duration appeared not to be attributable to the number of elements inspected per fixation. We present evidence that fixation durations are long in high element densities because the visual analysis time of a single element increases with when neighboring items are close by. We suggest that oculomotor factors may also play a role: When there is much information present at the fovea, the time required to initiate a saccade increases.

In **Chapter 5**, we turn to the benefits of making a saccade to a crowded item. A first benefit is that a saccade aims the fovea at the item. This 'breaks' crowding. We demonstrate another benefit: the perceptibility of a crowded saccade target is increased already during saccade preparation. Observers were required to discriminate a crowded item in the visual periphery. They either made a saccade towards the item or allocated their attention covertly. If the target was presented during saccade preparation and removed before the saccade landed at the target, subjects identified the target correctly more often then when they allocated attention covertly (i.e., without making an eye movement). Clearly, more attentional resources are allocated during saccade preparation than when attention is allocated covertly.

Chapter 6 presents a study that was explorative and meant to derive a description of strategies that are used in search. We deployed complex stimuli that allow a more complete description of strategies applied in search than the simple displays that we used in previous chapters and even more complete than 'natural' images. We choose to investigate search with displays that vary in target detectability across the display (as often is the case in natural images due to background variations). Target detectability was manipulated by the search element luminance (target and distracters alike). Some strategies concerned the immediate setting of the saccade parameters: We found that fixation duration decreases with increasing element luminance, but that saccade amplitude is not affected (both in uniform and mixed displays). We conclude that varying element luminance does not affect target conspicuity and that visual analysis times increase with decreasing luminance. We also found long term strategies that ultimately stretch from the start until the end of the search. Two main long term strategies emerged: Observers search areas with high target detectability first and they have a strong preference to search in a horizontal direction.

Conclusion

In the literature, descriptions and models about crowding have been derived from research using psychophysical methods (e.g., Bouma, 1970; He et al., 1996; Toet & Levi, 1992). Three crowding 'rules' have emerged: Crowding becomes stronger as objects (1) are situated closer to each other (e.g., Bouma, 1970; Toet & Levi, 1992), (2) are moved further into the visual periphery, (3) are more similar to each other (Kooi et al., 1994; Nazir, 1992). Yet, psychophysical measurements may not suffice to answer the question whether crowding influences eye movement behavior. Crowding researchers have conducted threshold measurements under highly controlled conditions in which subjects were not allowed to make eye movements. However, in daily life, the threshold range is mostly avoided. Who crosses a street with a chance level of 99% to reach the other side? In this thesis, we investigated whether the knowledge about crowding that has been gathered through psychophysical measurements is predictive for eye movement behavior.

In order to study eye movement behavior, we have used search tasks. Since search is a common activity in daily life, search tasks may be a good model for tasks in the world outside the laboratory. Our studies show that crowding is a limiting factor when exploring the visual environment and eye movements serve to overcome this limit (this has recently also been confirmed by Wertheim et al., in press). We have studied the relationship between crowding and eye movement behavior in detail. Our studies show that the strength of crowding has a specific effect on eye movement parameters: with increasing crowding, saccade amplitudes decrease and fixation durations increase. These findings are in accordance with the 'direct control' hypothesis of Jacobs (1986). According to this hypothesis, the size of the area within which objects can be recognized with a certain accuracy is taken into account when making eye movements. This area, known as the visual span, has a size that is reduced when the strength of crowding increases. We found that the saccade amplitude scales with the visual span size. In addition, we found that the fixation duration becomes longer with increasing crowding. This may indicate that an eye movement strategy is applied in which the time for visual analysis is increased in order to counteract the reduction of the visual span size due to crowding. Clearly, crowding plays a critical role when and where to move the eyes because it is a bottleneck on the size of the visual span. The crowding 'rules' may therefore be applied to construct predictions about the saccade amplitude and the fixation duration. Thus, the scope of the crowding rules can now be extended to eye movement behavior.

The crowding rules have been derived from visibility studies during continuous fixation and yet they predict eye movement behavior. Does this mean that the accuracy of peripheral object recognition during continuous fixation equals that of a fixation in between saccades? This thesis demonstrates that there is a subtle difference between the two. The discrimination performance of a peripheral object is 10% higher when this object is a saccade target too. This suggests that the size of the visual span as measured during continuous fixation (Geisler & Chou, 1995; Jacobs, 1986; Vlaskamp & Hooge, 2006) may be a slight underestimation of the visual span size during search with eye movements.

Chapter 2

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° to 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.

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, fixation duration was not affected at all. Instead, Moffitt 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 (Figure 1A and 1B): 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. For 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 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, Lévy-Schoen,& Jacobs, 1983; O'Regan, 1990), the perceptual span (e.g., Bertera & Rayner, 2000; Rayner & Fisher, 1987a), conspicuity area (e.g., Engel, 1977), zone of focal attention (Motter & Belky, 1998a) and the visual lobe (e.g. Widdel & 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

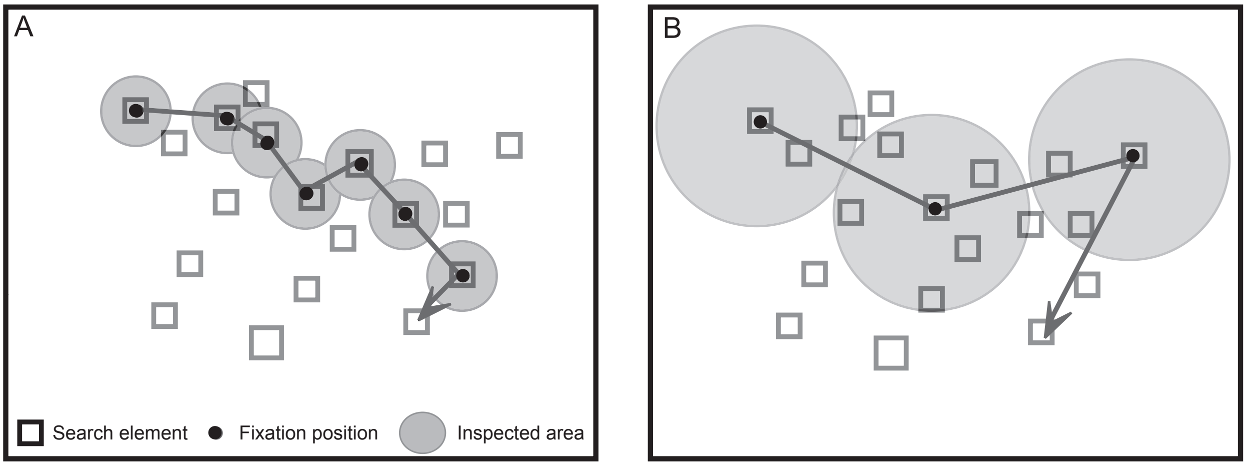

Figure 1. Illustration of the relationship between the number of saccades and fixation duration according to Moffitt (1980). Drawing (A) and (B) are examples of the two extreme strategies. Fixation positions and the areas inspected per fixation are represented. In (B) fixations are longer and more elements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

of fixations required to find the target and 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)(Bertera & Rayner, 2000; Motter & Belky, 1998a; Rayner & Fisher, 1987a,b). Motter & 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 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 (Bertera & Rayner, 2000; Näsänen, Ojanpäa,& Kojo, 2001; Rayner & Fisher, 1987a,b).

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, 1963; Salthouse & Ellis, 1980; Scialfa & Joffe, 1998). Nattkemper & Prinz (1987) found that increasing fixation duration is correlated with an increment in saccade amplitude, which is an indication for an increase in 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., Carrasco, Evert, Chang,& Katz, 1995; Sperling, Budiansky, Spivak,& Johnson, 1971). Interestingly, towards the visual periphery, elements are inspected later (eccentricity effect, Carrasco e.a., 1995; Wolfe, O'Neill,& Bennett, 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 & 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 & Rayner, 2000; Rayner & 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 (1024 x 768 pixels). Eye movements were recorded using an SMI Eyelink I system (for details see Van der Geest & 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, Peters, & Palmer, 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 figure 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° x 0.57°. The elements were white and the background was black. The search elements were placed on a hexagonal grid in a 37° x 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 distance between elements (center-to-center) 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° (we will refer to these as ‘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 that the target could clearly be 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.

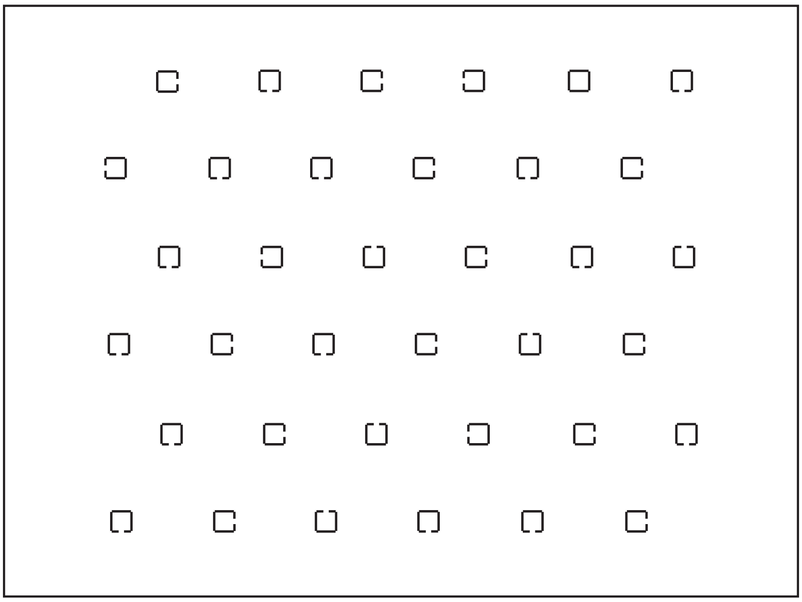

Figure 2. An example of a search display of experiment 1. The target is the closed symbol. In the experiment, the elements were white on a black background.

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 & 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 (bv, eo and ih) 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 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 figure 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 in the display. Element 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 in 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. Hooge & Erkelens, 1996; Jacobs, 1986; Rayner &

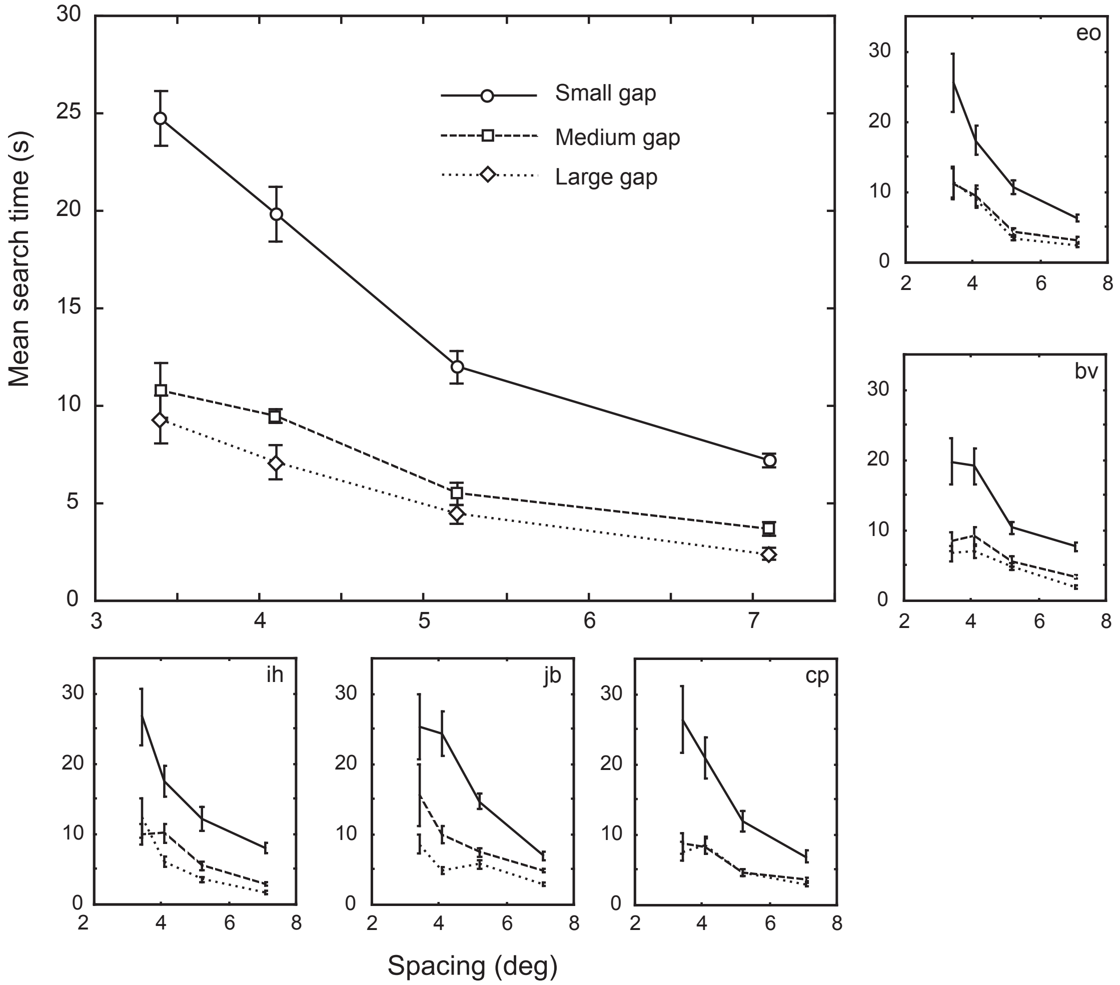

Figure 3. Search time vs. element spacing. The large panel shows the mean across all subjects. The small panels represent data of individual observers. Error bars represent standard errors of the mean. Dotted line denotes Gap size 0.27°; Dashed line denotes Gap size 0.19°; Solid line denotes Gap size 0.09°.

Fisher, 1987a,b). 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,

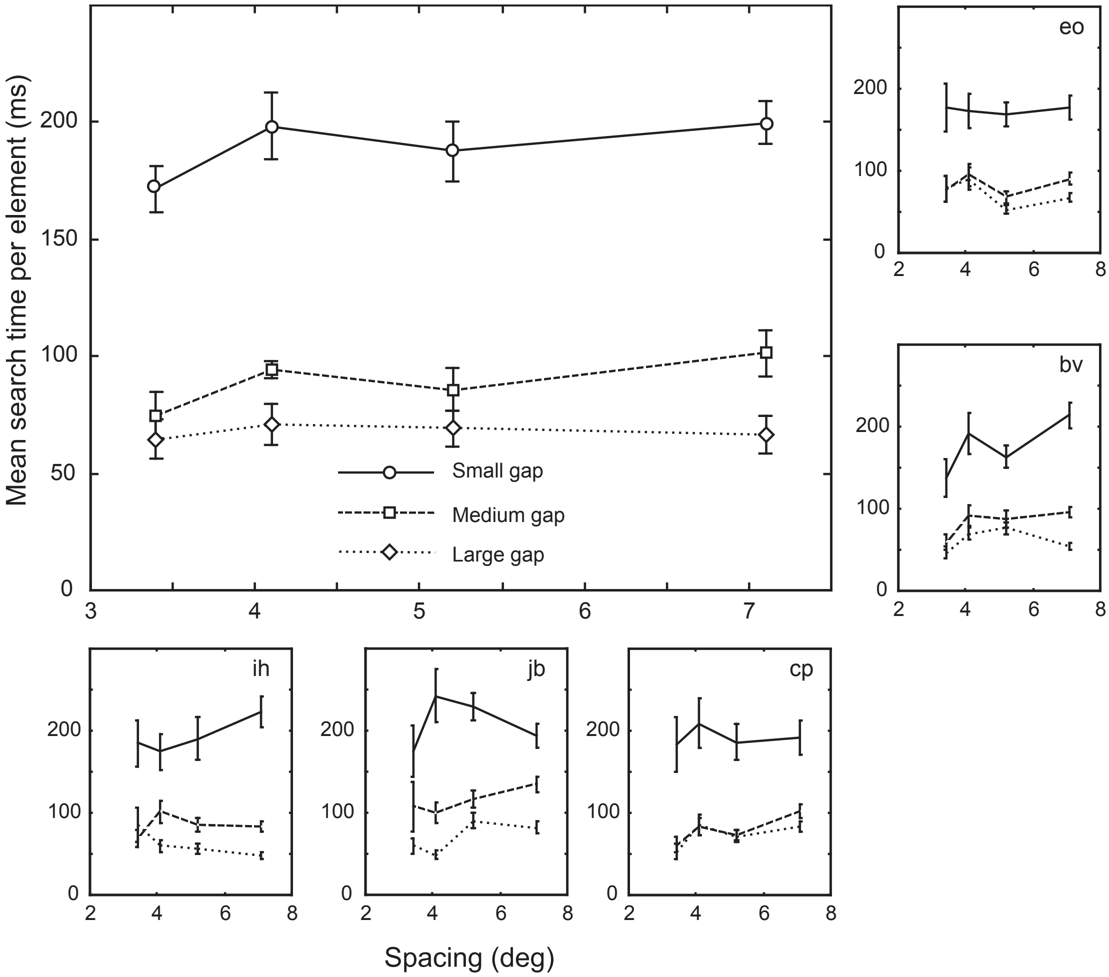

Figure 4. Mean search time per element vs. element spacing. The mean search time per element is defined as the mean search time divided through the number of elements in the search display. Error bars represent standard errors of the mean. The large panel shows the mean across all subjects. Dotted line denotes Gap size 0.27°; Dashed line denotes Gap size 0.19°; Solid line denotes Gap size 0.09°.

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 figure 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).

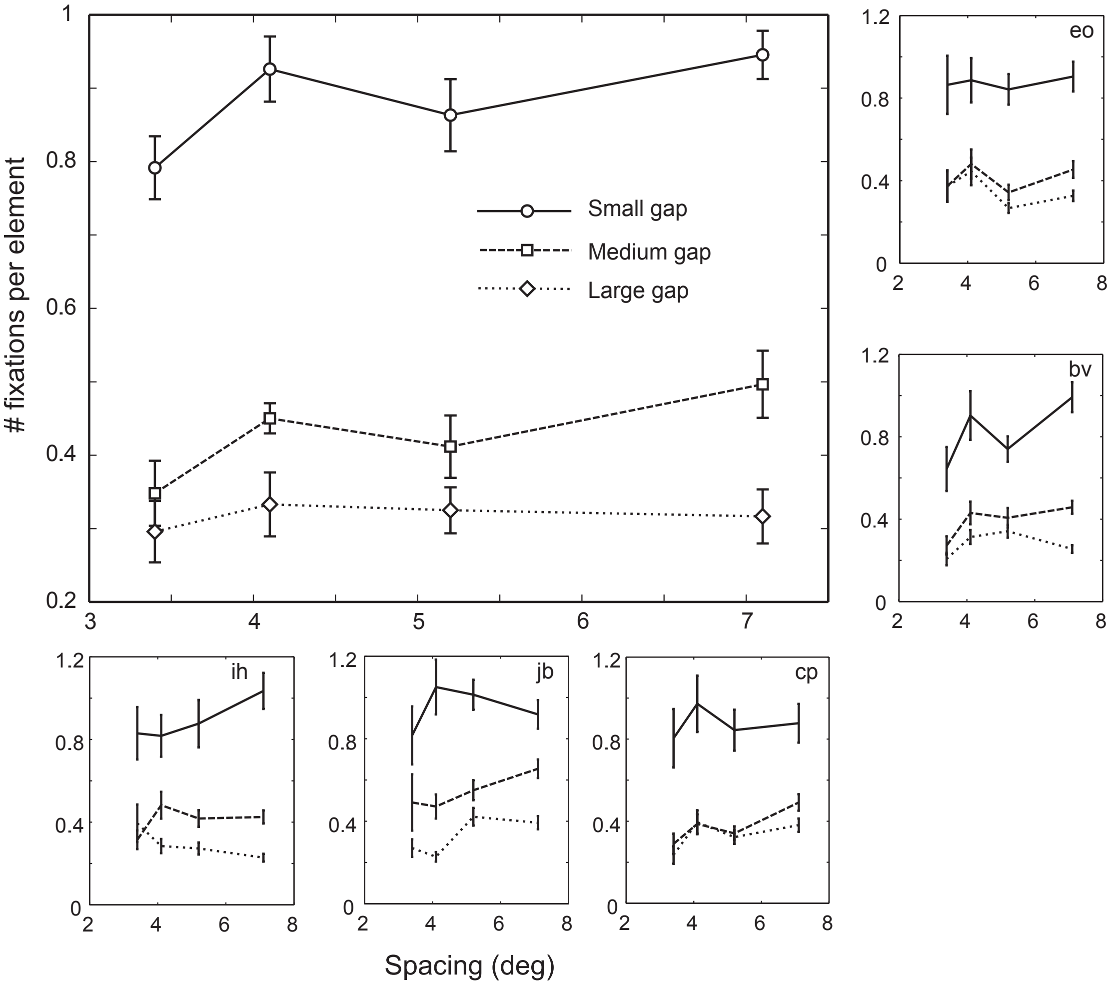

Figure 5. Mean number of fixations per element vs. element spacing. This measure is the number of fixations that were required to find the target divided by the number of elements in the search display. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean. Dotted line denotes Gap size 0.27°; Dashed line denotes Gap size 0.19°; Solid line denotes Gap size 0.09°.

Fixation duration

As has been mentioned before, in 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 fixation duration as well. Therefore, in order to gain insight into the search strategy we also discuss fixation duration. In the calculation of the average fixation duration all fixations are included except the first and the last fixation in a trial. In figure 6 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 < .0001]. The size of the effect was small. Maximum difference in fixation duration between element spacings amounted to 13 ms (small gap), 16 ms (medium gap) and 23 ms

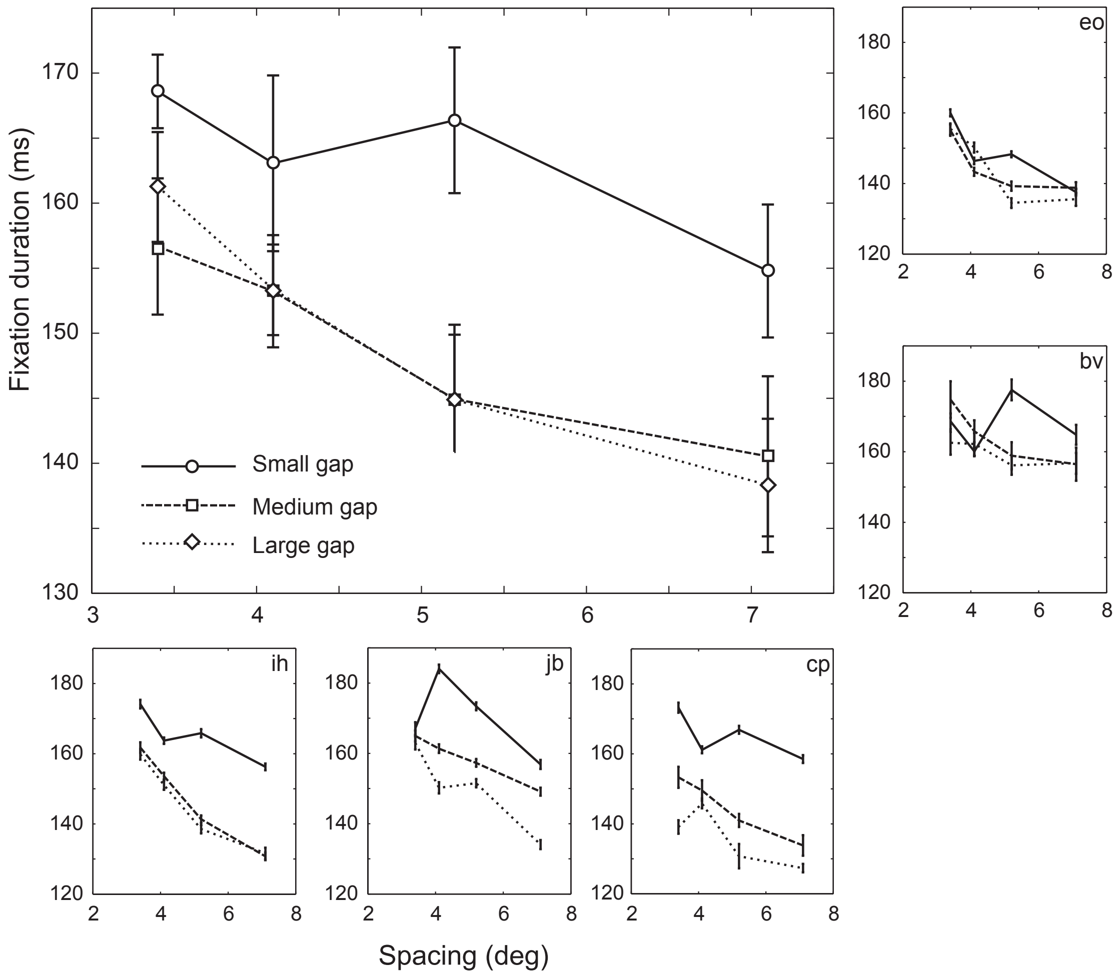

Figure 6. Mean fixation duration vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean. Dotted line denotes Gap size 0.27°; Dashed line denotes Gap size 0.19°; Solid line denotes Gap size 0.09°.

(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 ms, 10 ms, 21 ms and 16 ms in the 3.4°, 4.1°, 5.2° and 7.1° spacings respectively). The effect of gap size on 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 & 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 figure 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° to 8.3° at 7.1°. In the medium gap

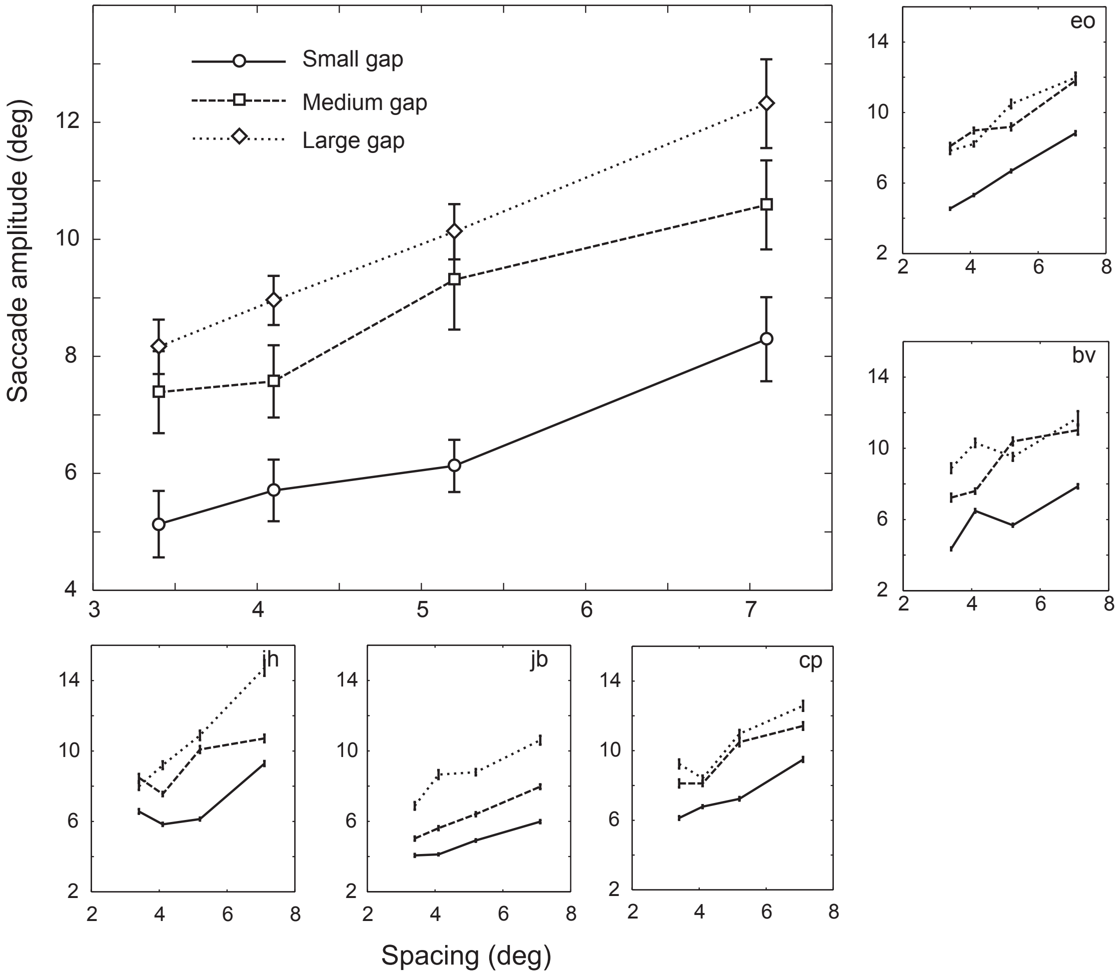

Figure 7. Mean saccade amplitude vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean. Dotted line denotes Gap size 0.27°; Dashed line denotes Gap size 0.19°; Solid line denotes Gap size 0.09°.

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 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. Maybe, element spacing should be even smaller to achieve a larger effect on any of these two measures. At the retina, 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 degree 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 adjacent to elements as small as 0.8°. This way elements neighboring 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 (1600x1200 pixels). The heads of the subjects were 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 search was binocular. Data were analyzed off-line in the same way as in the first experiment.

Stimulus

The search display size subtended 17°x14°, 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 spacings of respectively 3.2°, 2.7°, 2.4°, 1.9°, 1.5°, 1.1°, 0.9°, 0.8° (center-to-center). 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° x 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; 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

5 subjects participated in all conditions (age 22 to 26). Two of the subjects (BV and EO) 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.

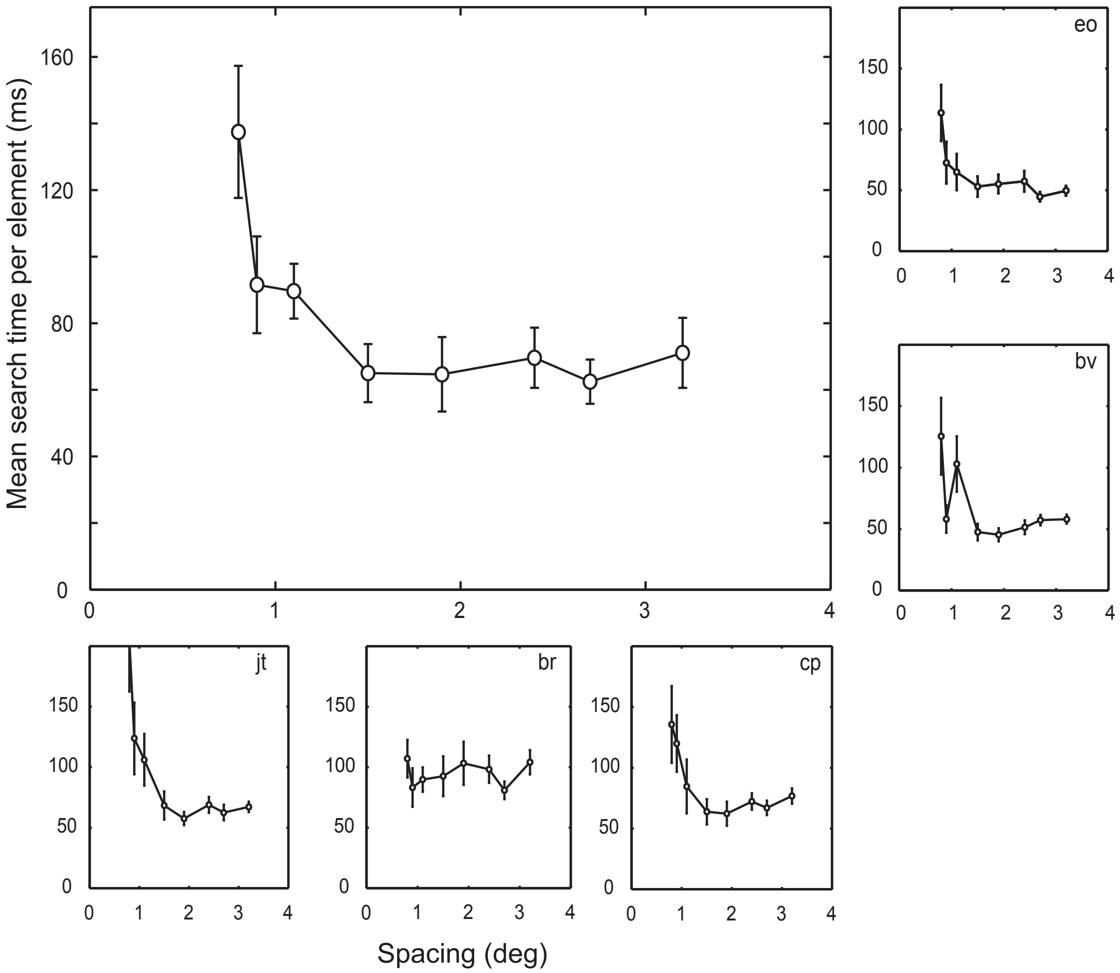

Figure 8. Mean search time per element vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean.

Results experiment 2

Search time per element

Mean search time per element was similar for a wide range of element spacings (figure 8). Even though there 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 elements 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 opposite to the effect of spacing found on search time per element in the first experiment. Search times per

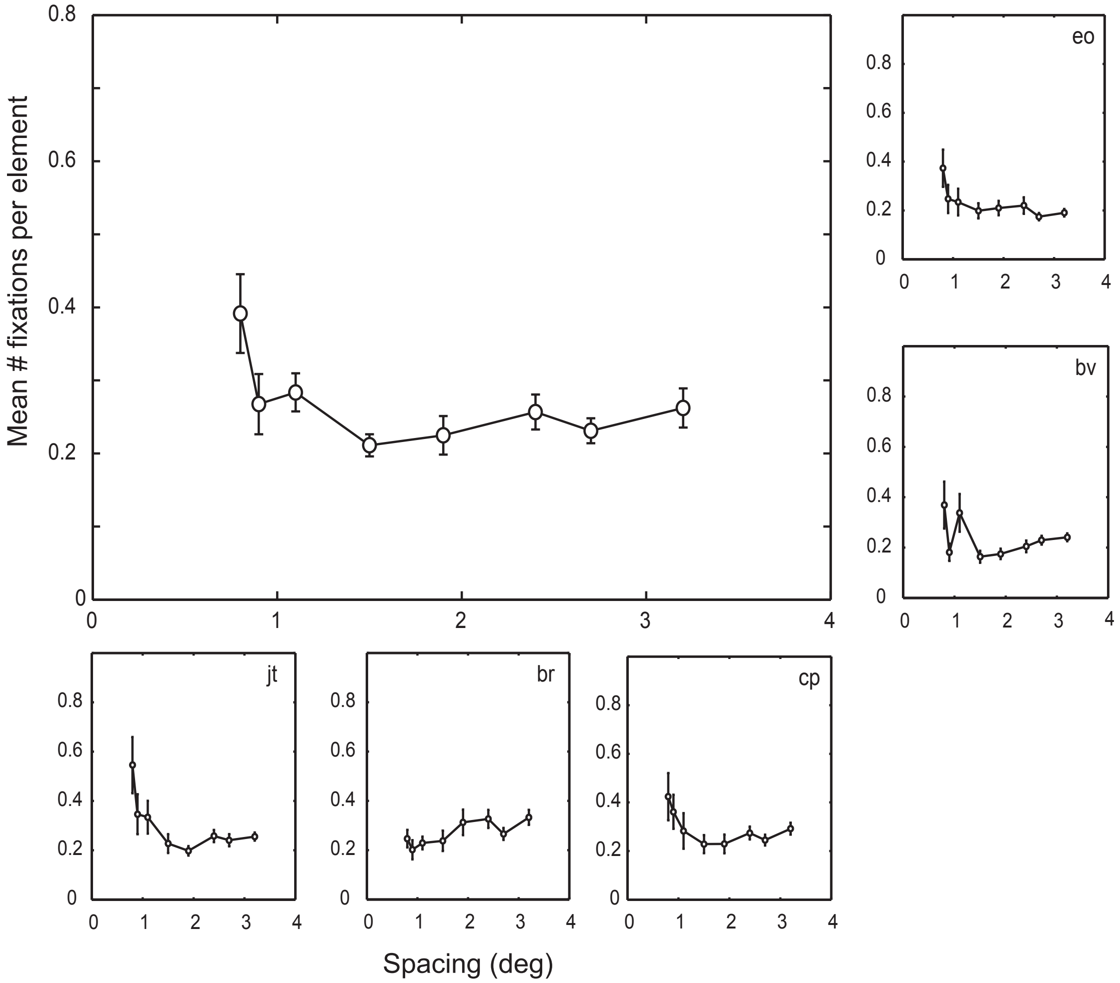

Figure 9. Mean number of fixations per element vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean.

element increased dramatically. At element spacing 1.5°, mean search time per element was 65 milliseconds. Mean search time per element at the smallest element spacings (0.8°) more than doubled to 137 milliseconds. In comparison, the largest difference in search time per element found from 1.5° to 3.2° was 8.7.

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 figure 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

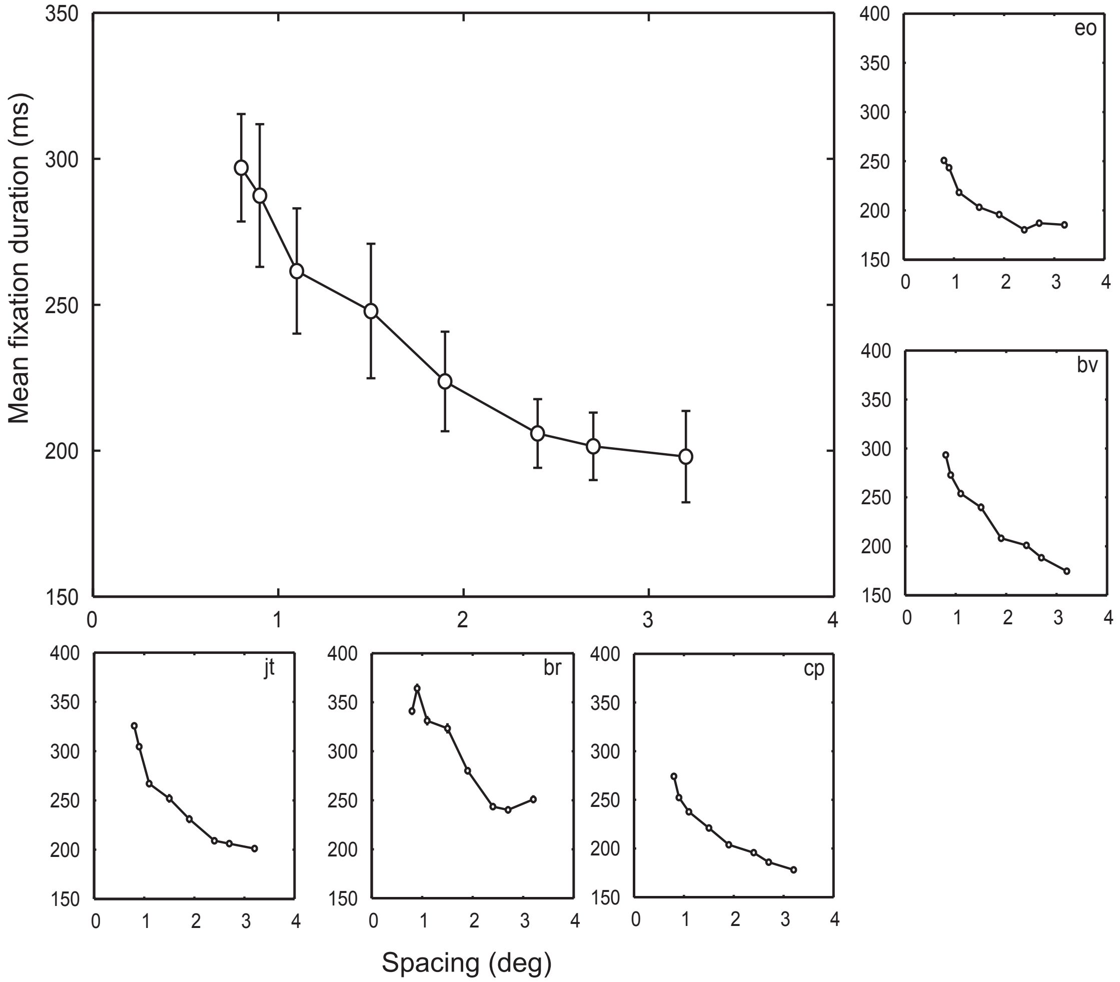

Figure 10. Mean fixation duration vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean.

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 search time per element to a great extent. This is in agreement with previous experiments (Motter & Belky, 1998a; Näsänen et al., 2001).

Fixation duration

Eye movement parameters were affected by the distance between elements [F(7,28) = 48.39, p < 0.001]. Fixation duration (figure 10) decreased with increasing element spacing over the whole range of element spacings measured in this experiment. 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.

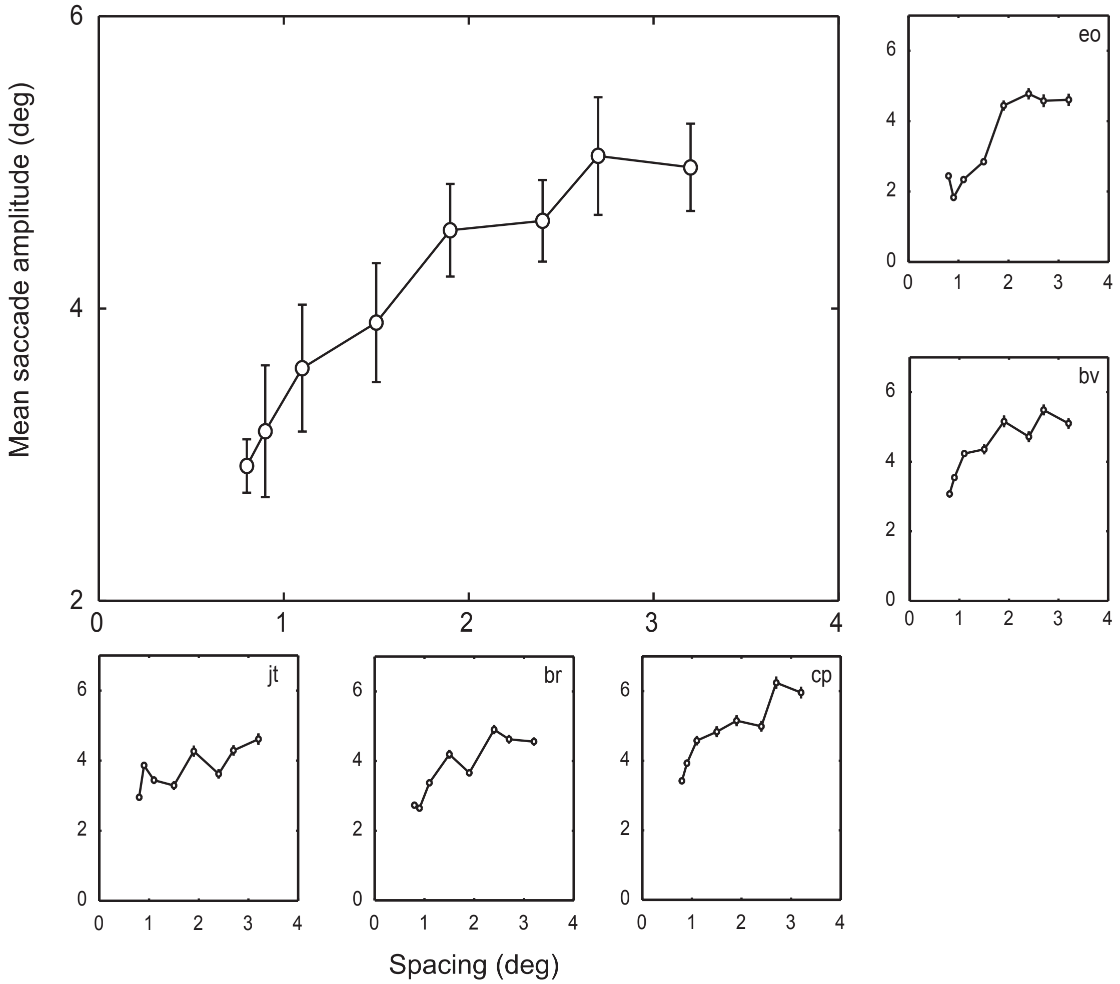

Figure 11. Mean saccade amplitude vs. element spacing. The large panel shows the mean across all subjects. Error bars represent standard errors of the mean.

Saccade amplitude

Saccade amplitude decreased with decreasing element spacing (figure 11) [F(7,28) = 15.51, $p < 0.001$]. Mean saccade amplitudes ranged from 2.9° at an element spacing of 0.8° to 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 spacing only has 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 3.1° 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 similarity in 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., Bertera & Rayner, 2000; Rayner & Fisher, 1987a,b). 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 & Rayner (2000) and Rayner & 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., Hooge & Erkelens, 1999; Motter & Belky, 1998b; Scialfa & Joffe, 1998). Another difference between the current search displays and the ones used by

Rayner & Fisher (1987a,b) and Bertera & 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 & 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 is 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 & 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; He, Cavanagh, & Intriligator, 1996; Toet & Levi, 1992; Wolford & Chambers, 1983). 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, Levi, & Legge, 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 & 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 (Kooi, Toet, Tripathy, & Levi, 1994; Nazir, 1992). 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 target eccentricity (Bouma, 1970; Kooi et al., 1994; Toet & Levi, 1992). For a search task, this means that elements at double element spacing from the point of location 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) extend 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 2 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 & Pelli, 1992). However, the amount of information processed does not only depend on the processing capacity, but also on the time available for processing. Indeed, Verghese & 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 ms 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 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 with 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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Chapter 3

Crowding degrades saccadic search performance

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Abstract

The identity of a target is more difficult to acquire when it is surrounded by distracters. The purpose of the present experiments was to investigate the implications of this crowding phenomenon for performance and eye movements in a real-life task as search with eye movements. The participants searched for a target in a one dimensional search strip. Above and below this search strip additional elements were added. In three conditions, the similarity of these mask elements to the search elements was varied. The spatial extent of crowding is known to increase with target – mask similarity (Kooi et al., 1994; Nazir, 1992). One condition did not contain masks. In a visibility experiment, we firstly validated this crowding manipulation. In the search experiment, we subsequently found that with increasing crowding search times were up to 76% longer. Eye movements were also affected. The number of fixations and fixation duration increased and saccade amplitude decreased with increasing crowding. We conclude that in order to understand eye movements in (everyday) tasks that require active exploration of the visual scene, crowding should be taken into account.

Introduction

The visual scene often consists of multiple objects. When exploring such a scene, the identification of an object might be surprisingly hard particularly in the visual periphery, because other objects interfere with the acquisition of visual information of the target object (Bex, Dakin & Simmers, 2003; Bouma, 1970; Hariharan, Levi & Klein 2005; He, Cavanagh & Intriligator, 1996; Toet & Levi, 1992). This is a phenomenon known as crowding or lateral masking. The relation between the perception of such a visual object and its environment has been extensively investigated. Remarkably, the consequences of crowding on the way a visual scene is explored by eye is less known. We investigated how crowding affects eye movements and performance and in an everyday task as searching.

Crowding has extensively been investigated in psychophysical experiments (i.e. experiments investigating the relation between physical stimuli and the psychological experience they evoke). In these tasks, it is not allowed to make eye movements. In a typical crowding task, a target amidst distracters at a predetermined location has to be identified (e.g., Bouma, 1970; Strasburger, Harvey & Rentschler, 1991) or discriminated (e.g., He, Cavanagh & Intriligator, 1996; Toet & Levi, 1992; Tripathy & Cavanagh, 2002). Whether distracters make it more difficult to resolve the target depends on several aspects of the target – distracter(s) configuration and the nature of the target and distracter(s). Firstly, the distance between target and distracters plays an important role. With decreasing distance between the distracters and the target, crowding increases (e.g., Bouma, 1970; Toet & Levi, 1992; Wolford & Chambers, 1983). Secondly, crowding increases with increasing retinal eccentricity of the target – distracter(s) configuration (e.g., Bouma, 1970; Strasburger et al., 1991; Toet & Levi, 1992). Typically, the threshold distance between the target and distracters at which distracters interfere with target perception is linearly related to the target eccentricity (see Chung, Levi & Legge, 2001, for an overview of the extents of crowding reported in the literature). In this context, it has been pointed out that crowding can be present at surprisingly large distances between target and distracters. Crowding has been found with target - distracter distances up to 0.5 times the target eccentricity (Bouma, 1970). Thirdly, crowding increases with increasing similarity between target and distracters. This extends across similarity in contrast polarity, depth (Kooi, Toet, Tripathy & Levi, 1994) and shape (Kooi et al., 1994; Nazir, 1992).

Much effort has been put in describing the dependence of crowding on target and distracter properties and to reveal the algorithm behind the crowding phenomenon. Less attention has been devoted to how crowding affects tasks that are related to real-life. Few researchers have investigated how crowding is related to search. One example is a research conducted by Carrasco, Evert, Chang & Katz (1995). In three visual search tasks, subjects were asked to respond whether the target was present or absent. It was found that it was harder (increasing reaction time, more errors) to find the target with increasing target eccentricity; adding more elements while keeping the display size constant enhanced this target eccentricity effect. In particular this latter result led Carrasco et al. (1995) to propose that crowding can play a role in the eccentricity effect (even though Wolfe, O'Neill & Bennett, 1998, debated the ubiquity of crowding in the eccentricity effect).

Another example is a research conducted by Vlaskamp, Over & Hooge (2005). They investigated the effect of spacing between search elements on the search performance and on eye movements. Increasing spacing affected the search time per element - the performance measure -, but only to a minor degree over a large range of elements spacings (element spacings ranged between 1.5° and 7.2°). Moreover, they found that the number of elements that was inspected per fixation was only slightly affected. Put in other words, the area that is inspected during a fixation scaled with the distance between elements [As was also found by for example, Motter & Belky (1998a) and Lindberg & Näsänen (2003)]. The explanation for the scaling of this area they offered was that the elements outside this inspection area could not be resolved because of crowding.

So, it has been proposed crowding may play an important role in search. However, crowding has been a variable that confounded with number of elements is the display and/or element eccentricity and/or element spacing. Element eccentricity affects crowding, but it affects the spatial resolution available for resolving the search elements as well (Anstis, 1974). Decreasing the spacing between search elements is another example of manipulating crowding. Vlaskamp et al. (2005) and Carrasco et al. (1995) decreased the spacing between search elements by adding elements to the display. Adding elements to the search display does not only affect crowding, but also the number of elements to be searched.

This research is motivated by the fact that humans make many eye movements to explore the visual environment that often contains a lot of crowding. Especially the eye movements are interesting because they bring peripheral parts of the stimulus (where crowding is highest) to the fovea (where crowding is hardly present). We therefore addressed the question how crowding affects eye movement behavior and search performance in a search task. It should be noted that these are questions on the computational level. In the present research we do not go into the causes of crowding.

In contrast to Vlaskamp et al. (2005) and Carrasco et al. (1995) we manipulated crowding *independently* of the number of elements to be searched and the distance between these search elements. In the tasks presented here, the search area (a horizontal strip of target and distracters) contained the same search elements across conditions. Above and below the search area we added mask elements (Figure 1). These elements were not to be searched. Crowding can be varied in such a search task either by varying the distance between the search area and the mask elements (Toet & Levi, 1992), or by varying the physical similarity between target and masks (Kooi et al., 1994; Nazir, 1992). In the present experiments, we choose to manipulate crowding by means of the similarity between the target in the search strip and the masks in the strips above and below the search strip. To validate the crowding manipulation, we additionally conducted a visibility experiment in which the threshold eccentricity for target discrimination was determined for all conditions.

Experiments

The displays were highly similar in the search and visibility experiment. In a general section, we will first describe the displays to the extent that they were the same in the two experiments. Subsequently, aspects of the displays specific for each experiment will be described in two separate sections.

General methods

Stimuli

A display consisted of a one-dimensional search strip that contained 30 horizontally aligned elements. One element, the target, was a closed symbol. The other 29 elements were distracters. The distracters were almost similar to the target with the exception that each distracter had a gap randomly in one of the four edges. This gap measured 0.33°. The size of the elements (target and distracters) was 0.37° x 0.37° (18 x 18 pixels). The width of the element edges subtended 1/18 of the element side length. The total length of the search strip was 30.2°. The distance between elements was fixed, i.e. the distance between neighboring elements was the same across the search area. The elements were white on a black background (80 cd/m^2 and .05 cd/m^2).

Both experiments - the search experiment and the visibility experiment - consisted of four conditions. In three conditions, two strips of elements were added above and below the search strip (Figure 1). These two strips merely served to mask the search strip. Subjects were informed that these mask strips never contained the target, and that they were not to be searched. The two additional strips are referred to as mask strips; the elements in the mask strips are referred to as mask elements. The mask elements were equal in size to the search elements. Horizontally, they were positioned in between two search elements. The height of the stimulus with a search strip and the two mask strips subtended 1.08°. To measure to effect of surrounding masks on the search strip, we added a fourth (baseline-) condition in which there were no mask strips.

The size of the gap in the mask elements varied between the three mask

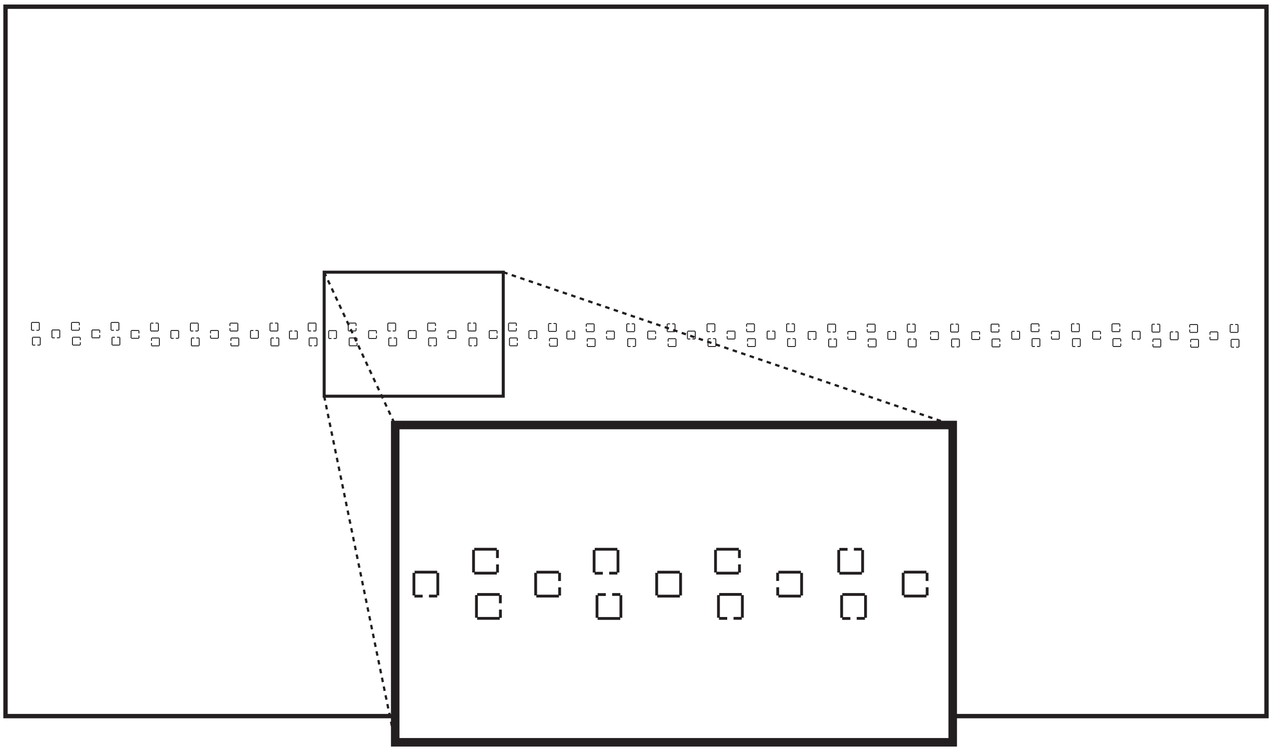

Figure 1. This is an example of the search display. The box in front of the search display contains a zoomed part of the search display. The display consisted of Cs and an O as the target. The horizontal middle strip was to be searched. Only this strip contained the target. The upper and lower rows served as mask strips. These strips were not to be searched. The size of the gap in the mask elements was varied in three out of four conditions. In the fourth condition, the mask elements were not present. In the search experiment, the elements were white on a black background.

conditions. The rationale behind this was that the degree of crowding of the target would increase with decreasing mask gap size. It is known that the extent of crowding of a target increases with target-distracter similarity (Kooi et al., 1994; Nazir, 1992). With decreasing gap size of the mask elements the masks are more similar to the target (gap size 0°). Therefore, the extent of crowding of the target was hypothesized to increase with decreasing gap size. The size of the gap in the mask elements was 0.04°, 0.17° or 0.33° - referred to as the gap 0.04, gap 0.17 and gap 0.33 condition.

Experiment 1 - Visibility experiment

Methods experiment 1

Subjects

Six male subjects (age 21 to 38) participated in the experiment. All the subjects had normal or corrected to normal vision. The subjects work at the psychonomics department or were students at the Universiteit Utrecht. The authors were two of the subjects. The other subjects were naïve with respect to the goal of the research.

Apparatus

Stimuli were generated by an Apple power G4 computer and presented on a LaCie Electronblue III 22” CRT monitor (1600x1200 pixels; pixel size: 0.25 mm x 0.25 mm). Stimuli were presented with Matlab for Mac OS 9 using the psychophysics toolbox (Brainard, 1997; Pelli, 1997). A chin rest held the heads of the subjects at 68 cm distance of the monitor.

Procedure

In the displays described in the general methods, the target was always positioned in the middle of the search strip. Its location was indicated by two thin vertically oriented bars (0.04° x 0.41°) above and below the target at 0.83° distance from the center of the target. The goal of the experiment was to measure the eccentricity at which this target could just be seen as the target. To this end we adopted the method of adjustment. Subjects fixated a small dot (sized 0.02° x 0.02°) that they could move back and forth horizontally through the search display by pressing the left and right arrow buttons on the keyboard. On half of the trials, the dot could be moved between the target and the leftmost element. The dot then appeared either centered on the target or centered on the leftmost element (each in 50% of the cases). On the other half of the trials, the dot could only be moved on the right side of the target. The dot appeared centered on the target or centered on the rightmost element (each in 50% of the cases). When the subjects could just recognize the target, they pressed the space bar to end the trial. The position of the fixation dot at the time the space bar was pressed was recorded.

The threshold eccentricity was measured for all four conditions (three mask conditions and one base-line condition) that were described in the general methods section. Per condition, eight trials were conducted (four possible start positions of the fixation dot times two repetitions), amounting to 32 trials in total. For each subject a new random sequence of the 32 trials was created. A new trial started immediately after the previous trial was ended.

Statistical Analysis

Differences in the results between the three conditions that contained mask elements were all tested for statistical significance with a one-way repeated measures ANOVA. In addition, we compared results of the baseline condition with the results of the gap 0.33 condition and tested with paired t-tests whether these results differed significantly. We choose to compare the results on the baseline condition only with the results on the gap 0.33 condition, because the baseline condition is expected to be most similar to the gap 0.33 condition.

Results experiment 1

For the conditions with mask strips, the eccentricity between the fixation dot and the target at which subjects indicated that they could just discriminate the target increased from 2.44° in the gap 0.04 condition to 2.55° in the gap 0.17 condition and to 3.27° in the gap 0.33 (Figure 2). In other words, the threshold eccentricity increased with more than 1/3 (34%) from the gap 0.04 to the gap 0.33 condition. A repeated measures ANOVA showed that there was a reliable difference on the threshold distance between the mask conditions [$F(2,5) = 11.045$, $p < 0.01$]. When mask strips did not enclose the search strip, the mean threshold eccentricity was much larger than in the conditions with mask strips. The mean eccentricity of 5.45° was compared by means of a paired t-test with the mask gap 0.33 condition, since the smallest difference was expected here. This eccentricity was reliably larger than in the condition with the largest gap [$t(5) = -7.8382$, $p < 0.001$].

Discussion experiment 1

This experiment was conducted to validate the crowding manipulation of the displays in the search experiments. Crowding was hypothesized to decrease with increasing gap size of the elements in the mask strip. This was confirmed by the results of this visibility experiment. Threshold eccentricity for target discrimination increased when the size of the gap in the mask elements increased. In addition, in the baseline condition (i.e. the condition without mask strips above and below the search strip) target threshold eccentricity was larger than in all the conditions that contained a mask strip.

In the second experiment, subjects will search for a target in displays that resemble the displays of the first experiment. Without the measurement of the threshold eccentricity in the current experiment, it could always have been argued that the displays do not differ in their degree of crowding. Any increase in the search time would then still have been explainable. It could have been argued that the search time increases because the masks are processed as if they were search elements. Increasing similarity of the mask to the target would then have led to an increase in the total processing time of the display. In the visibility experiment, it is unlikely that decreasing eccentricity with increasing target-mask similarity is due to processing of the masks. The subjects determined the presentation time of the display. This way they could compensate for any potential additional time required for mask processing.

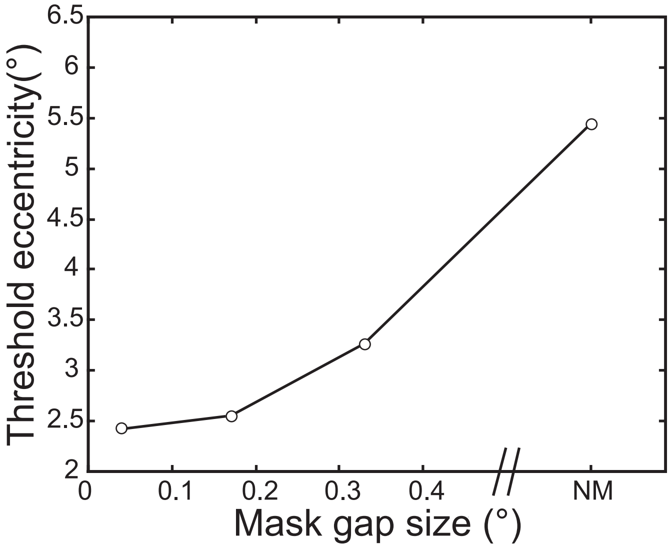

Figure 2. Threshold eccentricity vs. mask gap size (experiment 1). In three out of four conditions, the gap size of the mask elements was varied. The size of the gap is represented on the x-axis. The y-axis contains the threshold eccentricity for target discrimination. NM is the fourth condition, which did not contain mask elements.

Experiment 2 - Search experiment

Methods experiment 2

Apparatus

Stimuli were presented in a fashion identical to the visibility experiment. The room conditions were the same. A bite board prevented subjects from making head movements. In addition, eye movements were recorded with an SMI Eyelink I system. A camera of the eye tracking system recorded the movements of the left eye. It was attached to a stand and situated in front of this eye. The Eyelink eye tracker was controlled with the Eyelink Toolbox for Matlab (Cornelissen, Peters & Palmer, 2002).

Subjects

6 six subjects participated in the search experiment (age 23 to 32; four males and two females). The subjects either work at the psychonomics department or are students at the Universiteit Utrecht. They were naïve with respect to the goal of the experiment. All subjects had normal or corrected to normal (contact lenses) vision.

Stimuli

The stimuli are described in the general section. In contrast to the visibility experiment, the target position was randomly chosen from the search element positions.

Procedure

The experiment consisted of four sessions. In each session, 30 trials of each of the four conditions were presented in block consecutively. For each subject blocks were ordered according to a Latin square across sessions. A session started with a calibration of the eye tracker. When the calibration was successful the actual experimental session started. To maintain an accurate calibration throughout the session, each trial started with a so-called 'drift correction' an adjustment of the calibration based on the subjects fixation on a single dot in the display. The dot for the drift correction appeared on the left side of the screen at 14.9° of the centre of the display, vertically halfway the display. Subsequently, the subjects could initiate the drift correction themselves by pressing the space bar. Immediately after a successful drift correction, the drift correction display disappeared and the search display appeared. The position of the leftmost search element corresponded to the position of the drift correction. This way subjects always started searching on the left side of the search display. It should be noted, however, that subjects were not instructed to search the display from left to right; they could freely move their eyes. After finding the target, the subjects pressed space bar to end the trial while they fixated the target. The search time was defined as the time from onset of the search display until the start of the fixation on the target.

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 & Bruno, 1995). Minimum saccade amplitude was 0.1° and minimum fixation duration was 50 ms. When a small saccade was removed, fixations before and after this saccade were added together. When a fixation was removed, the amplitudes of the saccades before and after the removed fixation were added together.

Results experiment 2

The main question was whether search was harder when the mask elements were more similar to the target, i.e. when the size of the gap of the mask elements was smaller. The *mean search time* was found to decrease with increasing gap size of the mask elements (Figure 3A). It decreased from 3.16 seconds in the gap 0.04 condition to 2.09 seconds in the gap 0.33 condition. Thus, search times were 1.5 times as high in the gap 0.04 condition as in the gap 0.33 condition. The average search time in the gap 0.17 condition was 2.51

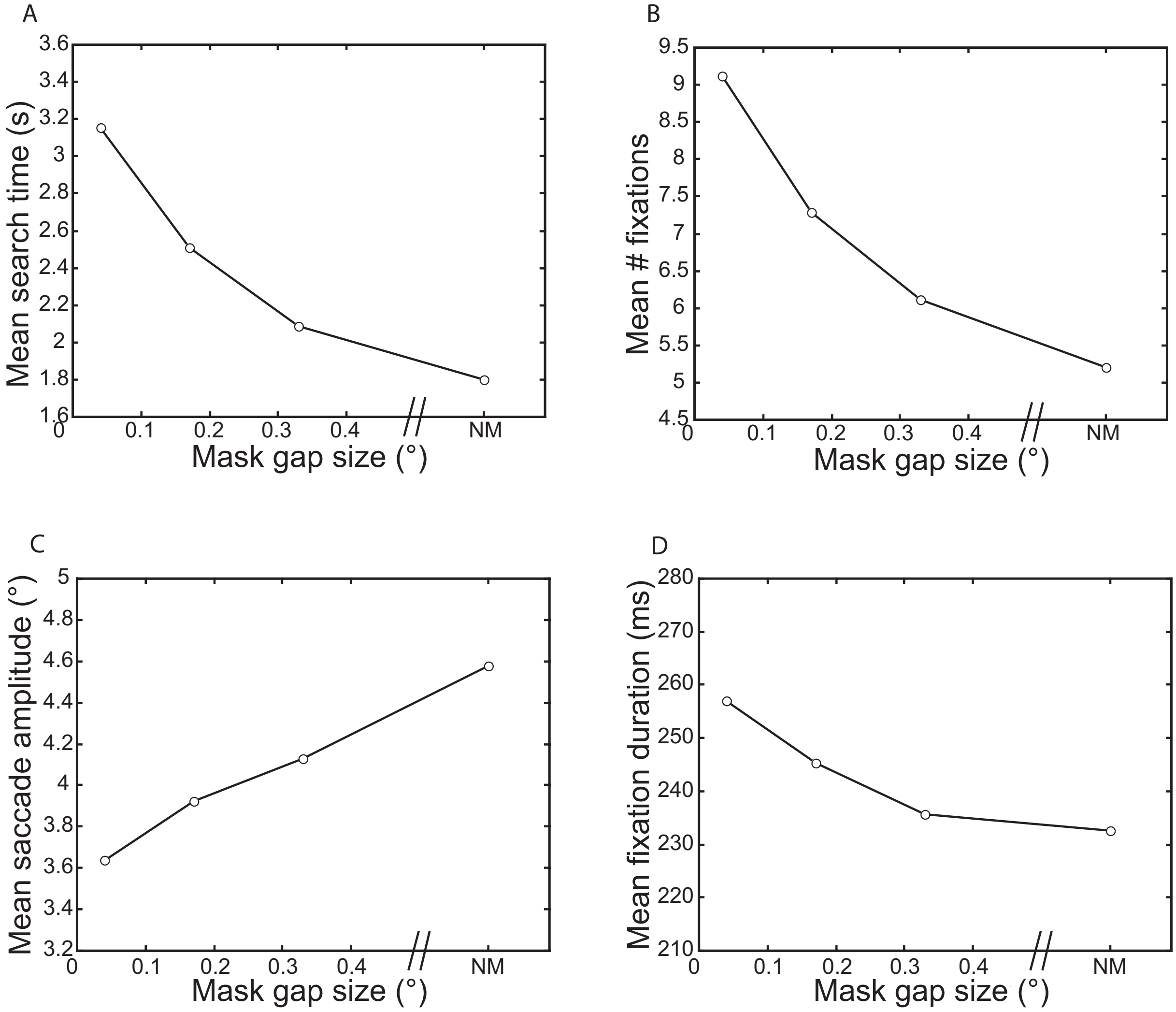

Figure 3. (A) Mean search time vs. mask gap size. The average search time across all subjects is depicted. NM is the baseline condition, which did not contain mask elements. (B) Mean number of fixations vs. mask gap size. (C) Mean saccade amplitude vs. mask gap size. (D) Mean fixation duration vs. mask gap size.

seconds. Search time was significantly affected by the size of the mask gap [F(2,10) = 45.252, $p < 0.001$]. In addition, the search times in the gap 0.33 condition and the baseline condition differed significantly as well [t(5) = 4.101, $p < 0.01$]. In the baseline condition the average search time was 1.79 seconds. In short, from the baseline condition to the gap 0.04 condition, search time increased with 76%.

Fewer fixations were required to find the target when the size of the gap was larger. The average *number of fixations* decreased from 9.12 in the gap 0.04 condition, to 7.30 in the gap 0.17 condition and 6.11 in the gap 0.33 condition (Figure 3B). The effect of mask gap size on the average number of fixations required to find the target was significant [F(2,10) = 86.89, $p < 0.001$]. Still fewer fixations were made in the baseline condition. In this condition the average number of fixations equaled 5.21. This was significantly smaller than the number of fixations in the gap 0.33 condition [$t(5) = 4.7$, $p < 0.01$].

The decrease in the number of saccades with increasing gap size of the mask elements was accompanied by a significant decrease in the mean *saccade amplitude* [$F(2,10) = 12.27$, $p < 0.01$]. The average saccade amplitude was 3.63° in the gap 0.04 condition and 3.92° and 4.13° in respectively the gap 0.17 and gap 0.33 condition (Figure 3C). Still larger saccades were made in the base-line condition (4.58°). Here, the average saccade amplitude was significantly larger than in the gap 0.33 mask condition [$t(5) = -4.14$, $p < 0.01$].

Fixation duration were also affected by mask gap size [$F(2,10) = 13.38$, $p < 0.01$] (Figure 3D). The average fixation duration decreased with increasing mask gap size. It amounted to 256 ms in the gap 0.04 condition, 245 ms in the gap 0.17 condition and 235 ms in the gap 0.33 condition. The average fixation duration in the gap 0.33 condition did not differ significantly from the fixation duration in the base-line condition [$t(5) = 1.27$, $p = 0.26$].

General discussion

The perception of an object becomes deteriorated in the presence of nearby distracters (Hariharan, Levi & Klein, 2005; He, Cavanagh & Intrilligator, 1996; Toet & Levi, 1992). While this crowding effect has been described into detail on the basis of psychophysical research, we focused on the consequences of crowding for eye movements and search performance. In a search task, we measured how crowding affects both the search time and the eye movements. We started with a validation of the crowding manipulation in a visibility experiment. Consecutively, the validated displays were applied in a search task. We will first discuss the effect of crowding on the eye movements. Subsequently, it will be discussed how crowding affected the search performance.

Increasing crowding decreased the average saccade amplitude. The saccade amplitude is related to the size of the area of the search display that is inspected during fixation (Jacobs, 1986; Rayner & Fisher, 1987b). This area has been termed in several ways, such as the perceptual span (Bertera & Rayner, 2000; McConkie & Rayner, 1975), the visual lobe (Widdel & Kaster, 1981) and the visual span (Jacobs, 1986; O’Regan, 1990). These terms slightly differ in their meaning, but they all refer to an area that is inspected during fixation. We will refer to this area as the visual span. The saccade amplitude decrease as a result of increasing crowding indicates that the visual span decreased.

The number of fixations required to find the target is related to the size of the visual span as well. With a larger span, a larger part of the display area is inspected during a single fixation. Consequently, fewer fixations are required to inspect the whole display (Geisler & Chou, 1995; Näsänen, Ojanpää & Kojo, 2001). In the present experiment, the number of fixations required to find the target increased with crowding. Thus, as the saccade amplitude, the number of fixations indicates a decrease of the visual span with increasing crowding. In addition, the visibility experiment also pointed out that target-mask similarity decreased the eccentricity at which a target was discriminated. The previous corroborates with the literature, the threshold eccentricity is considered a measure of the visual span size (recognition threshold, O'Regan, Lévy-Schoen, Jacobs, 1983; detection threshold, Jacobs, 1986; various thresholds, O'Regan, 1990).

Not only spatial aspects of search were affected by increased crowding. Fixation duration also increased with crowding. Why does fixation duration increase with decreasing visual span size (due to increasing crowding) in the present experiment? This relation has been found earlier. For example, when target - distracter similarity was varied (Jacobs, 1986) or by varying the contrast between search elements and the background (Näsänen et al, 2001). One might therefore suspect the reason for the increase in fixation duration in the present experiment to be similar as well. We feel that these longer fixations may reveal information about stimulus processing. In the earlier researches (Jacobs, 1986; Näsänen et al, 2001), fixation duration might have depended on the analysis of the foveated element, on the analysis of the elements in the parafovea or on both. However, the present research does differentiate between these possibilities. From psychophysical research it is known that crowding is hardly present in the fovea (Hariharan, Levi & Klein, 2005). Towards the visual periphery crowding is increasingly present. The current research therefore suggests that the fixation duration does not solely rely on the analysis of the foveally inspected element. Instead, fixation duration might be related to the inspection of parafoveal elements. The increase in fixation duration might be an attempt to process as many elements in the parafovea as possible. This attempt could be part of a coordinated saccade amplitude and fixation duration strategy to deal with the crowding: With increasing crowding, saccade amplitude was decreased to adjust to the decreased size of the visual span. Fixation duration was increased to increase the processing time for elements in the parafovea.

The eye movements reveal that crowding has a deteriorating effect on search. During a fixation, a smaller area was inspected with increasing crowding. Therefore, the number of fixations required to find the target increased. Since the duration of a fixation also increased, search time inevitably became longer.

Target-mask similarity vs. target-distracter similarity

An alternative explanation for the current results is that mask elements are processed as if they are part of the search area. According to this explanation, the number of elements of the search area inspected per time unit is expected to decrease with decreasing gap size. For, search times are known to increase with target-distracter similarity (e.g., Hooge & Erkelens, 1999; Vlaskamp et al., 2005). An obvious way to find evidence for this alternative explanation is to check for the position of the fixations (are mask elements fixated or not?). The masks and the search elements were separated (center to center) 0.5° horizontally and 0.35° vertically. The spatial resolution of the Eyelink eyetracker is too low to determine to which extend the mask elements were fixated. According to the Eyelink I specifications, the average gaze position error of the Eyelink ranges between 0.5° and 1.0°. In addition to this, Van der Geest & Frens (2002) state that the Eyelink should be treated with care when the accuracy of fixation position is required to be smaller than 1°.

To be able to rule out the alternative explanation we conducted a control experiment. Two subjects participated in a search task that consisted of two conditions. The first condition was identical to the gap 0.04° condition of the search experiment. The target only appeared in the central strip and the subjects were instructed to search for the target in the central strip. In the second control condition, the target could appear in all three strips (i.e., also in the mask strips). The subjects were also informed that the target could appear in all three rows. If the alternative explanation (the mask elements are processed to the same extend as the search strip elements) holds, search times are expected to be identical in both control conditions. The results sharply contrast with this expectation. Search times increased with a factor 5.1 (subject BV: 1.8 seconds vs. 9.3 seconds; $p < 0.001$) and a factor 6.9 (subject TB: 2.8 seconds vs. 19.2; $p<0.001$) when the target was present in all three rows, suggesting that the mask elements are not processed to the same extend as the elements of the search strip in the search experiment.

In addition, it can be concluded from this control experiment that the *target – mask* manipulation is unlike the *target – distracter* similarity manipulation applied in many other search studies in the literature (Hooge & Erkelens, 1996, 1999; Jacobs, 1986; Rayner & Fisher, 1987b). In those studies, the target and distracters were both part of the search area. This is not to say that crowding does not play a role there. On the contrary, the present results indicate that target-distracter similarity may affect search because it affects the level of crowding. Target – distracter similarity also affects the search performance, the number of fixations, fixation duration and saccade amplitude in a similar way as crowing does (Jacobs, 1986; Hooge & Erkelens, 1996, 1999; Rayner & Fisher, 1987b).

Saccadic search and the subconscious processing of crowded information

A crowded element is not accessible for conscious perception. Nevertheless, He et a. (1996) found that when the orientation of a target Gabor patch cannot be discriminated due to flanking patches, the orientation of a subsequently presented test patch at the location of the target patch is still affected by the targets orientation. In addition, Parkes, Lund, Angelucci, Solomon & Morgan (2001) found that a crowded target is taken into account when calculating a statistic of all items in a display (average orientation of all patches in a display). This argues that crowded information is processed at least up to the level of feature extraction (see also Cavanagh, 2001; Hariharan, Levi & Klein, 2004; Tripathy & Cavanagh, 2002) and possibly even beyond (Rajimehr, Vaziri-Pashkam, Afraz & Esteky, 2004). This leaves open the possibility that target information that is inaccessible consciously can still be turned into use when performing a search task. One could hypothesize that search performance and eye movements might be rather unaffected when the level of crowding is the sole manipulation of the search display. However, in the present experiments, crowding heavily affected search performance and eye movements. These data therefore show that elements that are crowded are not sufficiently processed for localization either.

Crowding in natural situations

In everyday life, objects hardly appear completely isolated from other objects. For example, when reading a text, each letter is surrounded by other letters and lines of text are usually surrounded by other lines of text. Or, when looking for scissors in a kitchen drawer, there might be knifes, a corkscrew, a tin opener and so on in there as well. It is therefore likely that crowding is omnipresent. To understand the eye movement strategy (adjustment of fixation duration and saccade amplitude) and performance in daily visual tasks, the present study shows that crowding should be taken into account as an important factor.

The results of the present study can also be turned to use. On the one hand, it can be argued that one should attempt to avoid the occurrence of crowding as much as possible. For example, when arranging screen text on a computer, the distance between lines should be sufficiently large (Kruk & Mutter, 1984). On the other hand, the deteriorating effect of crowding should be considered when performing a search task. To find a target as fast as possible, one should first search those areas that contain the fewest number of objects that are similar to the target object.

Conclusion

Psychophysical research has described crowding in relation to the physical stimulus in detail (e.g., Bouma, 1970; Toet & Levi, 1992). In the present computational study, we moved from this description of crowding to the *consequences* of crowding in a more daily setting. In a search task, we investigated how eye movements are adjusted to varying levels of crowding. This crowding manipulation was validated with a visibility experiment preceding the eye movement experiment. With increasing crowding, fixation duration increased, the number of fixations increased and the saccade amplitude decreased. In addition, we measured search performance. Increasing crowding decreased search performance. These results show that the presence of irrelevant objects outside a search area strongly affect saccadic search performance.

Chapter 4

Task-irrelevant distracters detain the eye in saccadic search

Submitted as
Vlaskamp, B.N.S, & Hooge, I.T.C. (submitted). Task-irrelevant distracters detain the eye in saccadic search.

Abstract

During search in high density displays, fixations durations are much longer than in low density displays (Bertera & Rayner, 2000; Vlaskamp, Over & Hooge, 2005). Is visual search in dense displays more difficult or do eye movement related processes play a role? Subjects searched for the presence of a target in a horizontal search strip consisting of 4 search elements. They searched from left to right. The second and third element (from the left) were presented with or without surrounding task-irrelevant elements. We analyzed fixation times at the second element in the strip as a function of the presence or absence of a surrounding at the second element (fixation element) and at the third element (saccade target). Adding a surrounding to the fixation element increased fixation duration up to 95 ms and adding a surrounding to the saccade target slightly decreased fixation duration. A second - psychophysical - experiment demonstrated that the surrounding of the fixation element increased the visual analysis time by 55 ms. We conclude that fixation duration increases in dense displays because 1) visual analysis times are longer when neighbors are close 2) neighboring elements might delay the fixation disengagement due to foveal stimulation [as in the remote distracter paradigm (Walker et al., 1997) or the gap-overlap paradigm (e.g., Fischer & Ramsperger, 1984)].

Introduction

Looking for scissors in the kitchen drawer, an icon on the computer desktop and a car on a parking place are all examples of search tasks. In situations like these, one often wants to find a target as fast as possible. Sometimes, it might even be critical such as in the case of snipers looking for the enemy and security personnel at an airport looking for weapons. Likely, in many of these search tasks multiple fixations are made to find the target. Besides the number of fixations, the durations of the fixations contribute to the total search time. It is therefore important to know what factors affect the duration of fixation in search.

Several well-established factors that affect the fixation duration are related to the visual analysis of the scene. Fixation duration has been found to depend on the nature of the target, the nature of the distracters and the background of the search display. Fixation duration increases with increasing similarity between target and distracters (Hooge & Erkelens, 1996, 1998, 1999; Jacobs, 1986; Rayner & Fisher, 1987a,b; Vlaskamp, Over & Hooge, 2005), decreasing luminance contrast between search elements and the background (Näsänen, Ojanpää & Kojo, 2001; Ojanpää & Näsänen, 2003) and increasing crowding (Vlaskamp & Hooge, 2006). Fixation duration also depends on the amount of visual information inspected during a single fixation. Fixation duration increases with the number of search elements inspected per fixation (Mackworth, 1976; Moffitt, 1980; Nattkemper & Prinz, 1986; Ojanpää, Näsänen & Kojo, 2002; Salthouse & Ellis, 1980; Scialfa & Joffe, 1998).

However, these factors cannot explain a remarkable finding by Vlaskamp, Over & Hooge (2005). In their search experiment, subjects searched for a target in displays that varied along a wide range of inter-element distances (0.8° to 7.1°). Along the whole range of distances, fixation duration increased with decreasing spacing between elements. Fixation duration only increased slightly with spacings larger than 1.5°. However, with spacings smaller than 1.5° this increase was very steep. There, fixation duration increased from 244 ms at inter-element spacings of 1.5° to 293 ms at spacings of 0.8°. The data do not provide any indication that this increase resulted from an increased number of search elements inspected per fixation. On the contrary, the number of elements inspected per fixation decreased. As a consequence, the inspection time per element inflated. Does this mean that the visual analysis time increased? Possibly, other time consuming processes play a role too. Below, we will discuss two of these possible processes.

Foveal visual stimulation

In several single saccade tasks, it has been found that saccade latency (i.e., the time before a saccade starts) increases with foveal visual stimulation. For example, in a gap – overlap paradigm Fischer & Ramsperger (1984) asked subjects to make a saccade from a fixation marker to a saccade target at the moment the saccade target appeared. The saccade target appeared always at the same position at 4° left or right of the fixation marker (in a second experiment the target position was randomized among these two positions. This essentially led to the same results). The latency typically took up to 150 ms. However, when the fixation marker disappeared 200 ms before the onset of the saccade target, saccade latencies were found to be as short as 100 ms (express saccades). Weber & Fischer (1994) additionally showed that express saccades hardly occur when non-target stimuli are presented at the fovea.

In another paradigm, Walker, Deubel, Schneider & Findlay (1997) found as well that saccade latencies became longer with foveal stimulation. They asked subjects to make a saccade as quickly as possible to a saccade target as soon as it appeared. Across conditions, targets appeared within 8° eccentricity in a wide range of directions. The subjects knew the direction in which the saccade target would appear. Simultaneously with the occurrence of the saccade target a distracter was presented. Subjects were told not to attend this distracter. Walker et al. (1997) found that the distracter increased saccade latency when it appeared anywhere in the visual field except for a sector within 20° of the target axis (remote distracter effect). Most importantly, this latency increment became more profound when the distracter was closer to the fovea. Both the gap-overlap paradigm and the remote distracter effect indicate that foveal stimulation prolongs the time before a saccade is released.

Possibly, foveal stimulation also affects the fixation duration in multiple fixation search. However, this cannot be claimed on the basis of the remote distracter paradigm and the gap-overlap paradigm, since these two paradigms differ too much from multiple fixation search. For example: 1) In contrast to the single saccade tasks, saccades in multiple fixation search are self-paced. 2) Whereas in multiple fixation search foveal information is inspected, subjects are asked to ignore the foveal information in the remote distracter and gap – overlap paradigms. 3) The gap-overlap and the remote distracter paradigm involve only a single saccade.

Selection of a peripheral saccade target

Another factor that might affect the fixation duration is the time required to select the target for the next saccade. When there are many possible saccade targets nearby the fixation location, the time required to select a saccade target might increase because there are so many elements to choose from (however, Hooge & Erkelens, 1999, did not find that the difficulty of the saccade target selection affected fixation duration). Alternatively, the visibility of the saccade target might be affected by crowding. Crowding occurs when the perceptibility of an item is degraded due to the presence of other items nearby. Crowding is particularly present in the visual periphery (Bouma, 1970; Toet & Levi, 1992). The features that build up an item are not lost when crowding occurs. Instead, they appear ‘jumbled’ with the features of neighboring items (Pelli, Palomares & Majaj, 2004). This might affect the time required for the determination of the position of the saccade target.

In order to gain more insight into processes that affect fixation duration, we have examined in two experiments how fixation duration is affected by visual information surrounding the search elements. In most search tasks, search elements are surrounded by other search elements (e.g., Bertera & Rayner, 2000; Gilchrist & Harvey, 2000; Hooge & Erkelens, 1999; Jacobs, 1986; Motter & Belky, 1998a; Näsänen, Ojanpää & Kojo, 2001; Vlaskamp, et al., 2005). In these tasks, elements neighboring a fixated element might affect fixation duration because they are inspected as well. We inserted task-irrelevant elements at a predefined location close to the search elements [a recent experiment by Vlaskamp & Hooge (2006) has shown that these task-irrelevant elements are not processed as search elements]. In this experiment, fixation duration increased drastically due to the task-irrelevant elements, and only when they were close to the foveated search element and not when they were close to the element that served as the target for the next saccade. A possible cause of the fixation duration increase was explored in a second - psychophysical – experiment. In this experiment, we examined to what extent the fixation duration increment could be attributed to an increased analysis time of the foveated search element.

Experiment 1 – Search

Methods

Subjects

Five subjects participated in the experiment (age: 19 to 21; 2 male, 3 female). All of the subjects had normal vision. They were all students at the Universiteit Utrecht. They participated in the experiment as part of their curriculum study psychology.

Apparatus

Stimuli were generated by an Apple G4 computer and presented on a LaCie Electronblue III 22” monitor (crt monitor; 1600x1200 pixels; 85 hz). The heads of the subjects were stabilized by means of a chin rest at 50 cm distance from the monitor. Eye movements of the left eye were recorded with a head mounted SMI Eyelink I eye tracker (for details see Van der Geest & Frens, 2002). Gaze positions were corrected for head movements. Stimuli were presented with Matlab for Mac OS running the Psychophysics Toolbox (Brainard,

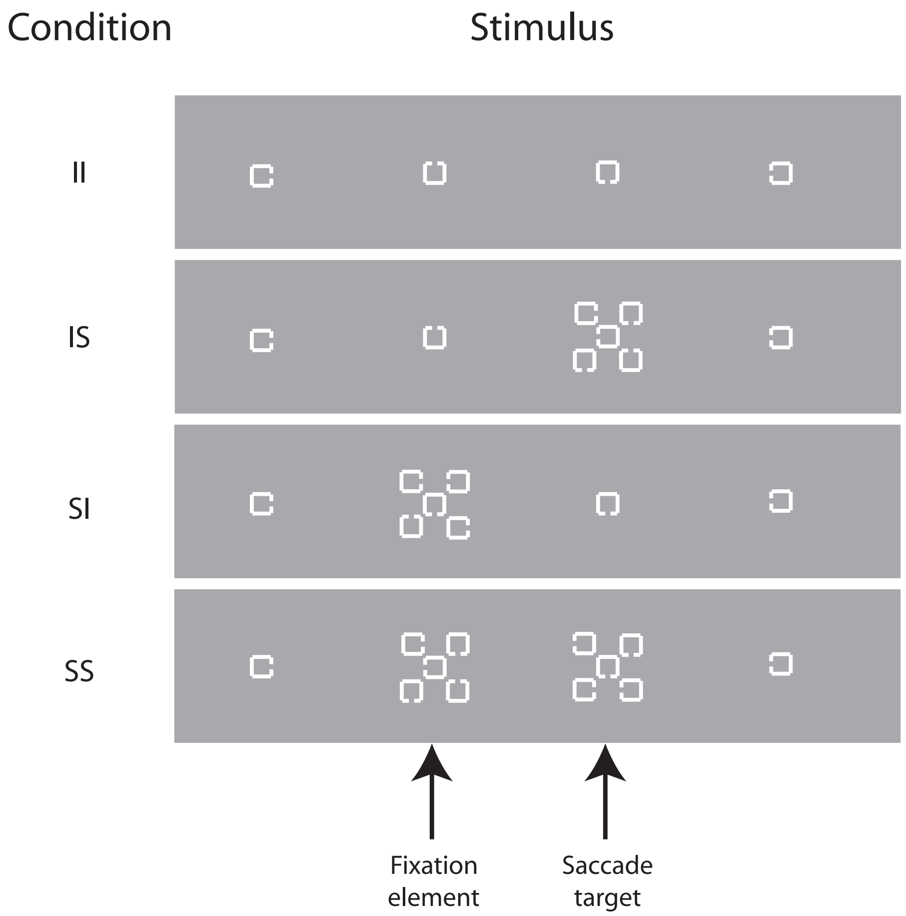

Figure 1. Examples of the four conditions in the saccadic search task (experiment 1). From the top to the bottom, the pictures represent the conditions II, IS, SI, SS (see methods Experiment 1). Subjects always started the search on the leftmost element. This forced them to search from left to right. Durations of fixations on the second element from the left (the fixation element) are reported. After these fixations, subjects headed to the third element. This element is therefore referred to as the saccade target.

1997; Pelli, 1997). Eye movement recording was controlled by the Eyelink Toolbox for Matlab (Cornelissen, Peters, & Palmer, 2002). The eye movement data were analyzed off-line.

Stimuli

A display consisted of 4 horizontally aligned search elements (Figure 1 contains some examples of search displays). The search elements were squares (size: 0.50°x0.50°; edge width was 1/18 x edge length) that contained a gap (size 0.06°) in one of the 4 edges. The edge containing the gap was randomly chosen for each element. The target was similar to the other elements but did not contain any gap. On half of the trials, one of the four elements was the target. The element luminance was 80 cd/m^2 and the background luminance was 24 cd/m^2. The elements were separated by 5.64° from each other (center to center). They were situated at 8.45° and 2.82° left from the center of the screen and at 8.45° and 2.82° on the right from the center of the screen. This large spacing between elements in combination with the small gap of the distracters and the medium contrast level between search elements and background made it unlikely that an element neighboring a fixated element could be discerned as a target or distracter.

Sometimes, the two central search elements were surrounded by 4 additional elements. These elements were similar to the distracters in the search strip. They also contained a gap of 0.06°. These elements were not to be searched. They never contained the target and the subjects were told so (Vlaskamp & Hooge, 2006, found that these task-irrelevant elements are not inspected as if they were search elements). These task-irrelevant surrounding elements were positioned at all corners of the search elements. The separation between the corner of a search element and the nearest corner of a surrounding element was 0.08° (center to center distance was 0.72°). The first and fourth element were never surrounded by other elements.

Subjects always started searching on the leftmost element and in those cases that they did not encounter a target (50% target absent trials) they ended on the rightmost element. The fixations on the second element were analyzed (for reasons given below). We will therefore refer to this element as the fixation element. The analysis was conducted on the fixations that were followed by a saccade to the third search element from the left. This element is therefore referred to as the saccade target.

The fixations of interest were on the fixation element. Fixations on this element provide insight into the dependence of fixation duration on the fixated element, since we manipulated the surrounding of the fixation element. These fixations also provide insight into the dependence of fixation duration on the saccade target, since we manipulated the surrounding of the saccade target too. Because the search ended when the target was found, trials in which the target was the first element from the left or the fixation element were not analyzed.

The combinations of isolated and surrounded fixation elements and saccade targets amounted to the following four conditions (see Figure 1 for an example of each condition): the elements on the fixation element and saccade target were presented in isolation (condition II); the fixation element was isolated and the saccade target was surrounded (IS); the fixation element was surrounded and the saccade target was isolated (SI); the fixation element and the saccade target were both surrounded (SS).

Procedure

Subjects performed the search task in a darkened room. Prior to the search task, the eye tracker was calibrated with the standard 9-dots Eyelink calibration. After successful calibration, the session started. Each trial was preceded by a standard Eyelink self-paced one-dot drift correction on the center of the screen. In order to make sure that subjects started their search on the left most element, the drift correction was followed by a display that only contained a fixation cross (consisting of two lines size 0.08° x 0.59°) at the same position as the left most element in the search displays (at 8.45° on the left from the center of the screen). Subjects fixated this cross and pressed the space bar to initiate the trial. When the space bar was pressed, the gaze position was measured. If the gaze position coincided with the position of the cross, the search display appeared. Otherwise, the trial restarted with the drift correction. Half of the trials in each condition contained a target. Upon finding the target, subjects fixated it and pressed the space bar to end the trial. If they did not find a target, they fixated the right most search element while they pressed space bar. Because subjects always started searching on the left most element and were asked to end on the right most element if they did not encounter the target, they searched from left to right. However, it should be noted that they were not explicitly required to do so.

Subjects performed four sessions of 120 trials. The trials of the conditions were randomly distributed across the sessions. The number of trials per condition amounted to 120. The total amount of trials was 480. Prior to the actual experiment, subjects performed 20 practice trials: 5 trials of each condition.

Data analysis

Saccade detection

The Eyelink data were processed to extract fixations and saccades. 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 & Bruno, 1995). Fixations were defined as the periods of time in between the detected saccades. 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.

Discarded fixations

As noted in the methods section, fixations on the fixation element were analyzed. However, not all fixations on this element were included in the final analysis. Some of the trials were not analyzed at all. Since we were interested in fixations on the fixation element, those trials that contained a target on either the first element or the fixation element were excluded from further analysis. Only the trials without a target and the trials with a target on the saccade target and element on the right side of the search display were taken into account. The number of trials that were removed as a result of the position of the target differed slightly per condition, because the assignment of the target position to one of the four search element positions was fully random. The number of trials included per condition ranged between 85 and 94.

Fixations had to meet several criteria to be included in the final analysis. Fixation durations are subjected to several sources of variance. For example, fixation durations prior to corrective saccades tend to be shorter than other fixations. Another example is that the duration of a fixation preceding a saccade towards a previously fixated object tends to be longer than the average fixation duration (Hooge, Over, Wezel & Frens, 2005). In order to exclude other sources of variance as much as possible, fixations had to meet the following criteria. Firstly, the fixation on the fixation element had to be preceded by a fixation on the first element (the element on which subjects started searching) and had to be followed by a fixation on the saccade target. Secondly, the fixation element was to be inspected within a single fixation. Fixations that were part of a number of consecutive fixations on the fixation element were to be excluded to be sure that the discrimination of the search element was not distributed across several fixations. Thirdly, a fixation counted as a fixation on a search element if the distance between the fixation position and the center of a search element was less than 1° [the limit is related to the Eyelink accuracy. See for example Van der Geest & Frens (2002) for details on the spatial accuracy of the Eyelink]. After applying the criteria for selecting the fixations for further analysis, 72% of the trials was preserved in the II-condition, 75% of the trials in the IS-condition, 66% in the SI-condition and 71% in the SS-condition.

Results

The main measure is the fixation duration on the fixation element. It was the aim to inspect the dependence of fixation duration on the presence of task-irrelevant elements in the fovea. In addition, it was asked how fixation duration depends on the presence of task-irrelevant elements surrounding the saccade target. Figure 2 shows the fixation duration on the fixation element for all four conditions. A 2 (fixation element surrounding) X 2 (saccade element surrounding) repeated measures ANOVA revealed that the fixation duration on the fixation element increased when this element was surrounded [$F(1,4)=120.04$, $p< 0.001$]. When the saccade target was surrounded too, fixation duration increased 95 ms from 241 ms (IS) to 336 ms (SS) (This is an increase of 39%). When the saccade target was isolated, the fixation duration increased from 263 ms (II) to 337 ms (SIS)(this equals an increase of 28%).

The peripheral saccade target affected fixation duration to a lesser extent, but there still was a main effect of the surrounding of the saccade target [$F(1,4)=15.33$, $p = 0.017$]. This effect was opposite to the expectations. It decreased when the saccade target was

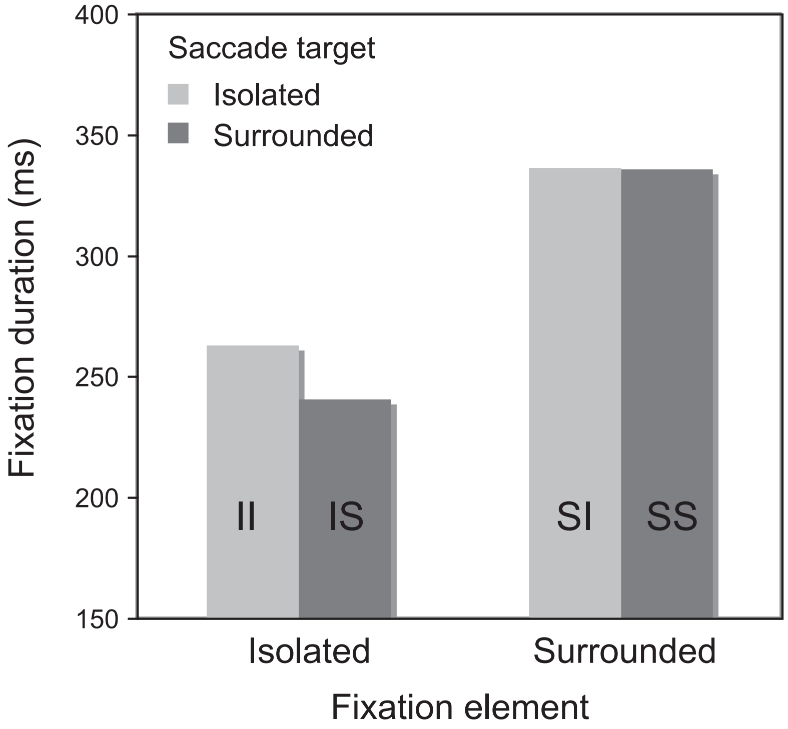

Figure 2. Fixation duration as a function of the presence of a surrounding at the fixation element. Light gray bars indicate that the fixation is followed by a saccade to an isolated saccade target; dark gray bars indicate that the saccade target is surrounded.

surrounded by other elements (from 263 ms to 241 ms). In other words, less time is required to make a saccade to a peripheral saccade target when it is amidst other elements. From Figure 2, it might appear that this effect mainly resulted from the condition in which the fixation element was isolated. Yet, there was no interaction between the surrounding at the fixation element and the surrounding at the saccade target [F(1,4)= 7.01, p = 0.056].

The fixation duration effect of the surroundings is not related to differences in landing position across conditions. The mean horizontal landing positions were between -2.79° (II) and -2.93° (SI) and vertical between -0.07° (II) and -0.13° (SS). The mean standard deviation of the landing positions varied between 0.35° (SS) and 0.42° (IS) horizontally and 0.24° (II) and 0.25° (SS) vertically. Separate 2 X2 (fixation element surrounding x saccade target surrounding) Bonferroni corrected repeated measures ANOVA's pointed out that none of these measures reached significance (all p-values larger than 0.088).

Subjects performed the task very well. The number of response errors that subjects made was equally low in all conditions (II: 7.5%; SI, 6.7%; IS, 7.7%; SS 7.7%). This was confirmed by an eye movement analysis. In less than 3% of the trials, subjects did not fixate the target or the last element (target absent trials) at the moment they pressed a key.

Discussion experiment 1

Fixation duration increased as a consequence of the presence of surrounding elements close to inspected search elements. Fixation duration increments were as large as 95 ms. When the saccade target was situated amidst task-irrelevant elements the fixation duration decreased. In the following, we will only briefly address the results concerning the presence of a surrounding at the saccade target. The remainder of the paper will deal with the effect of a surrounding at the fixation element, because we were interested in the factors that contributed to the long fixation durations with other elements close by (see introduction). Moreover, the surrounding of the fixation element affects fixation duration to a much larger extent.

In the introduction, we raised the possibility that a surrounding at the saccade target increases fixation duration. We found the opposite. The decrease in fixation duration due to the presence of elements surrounding the saccade target is quite surprising compared to results from single saccade tasks. In those tasks, displays containing a single saccade target mostly do not evoke different saccade latencies than displays containing additional items nearby the saccade target. This holds for latencies accompanying the remote distracter effect in the case that a distracter is added close to the axis running from the fixation point to the saccade target (Walker et al., 1997) and this also holds for latencies found with the global effect (Findlay, 1982; Deubel, 1984; Findlay & Gilchrist, 1997) even though the global effect occurs less frequently with increasing latency (Ottes, Gisbergen & Eggermont, 1984; Jacobs, 1987; Coëffé & O'Regan, 1987). Finally, it is conceivable that the saccadic system acts on the saccade target and its surrounding elements as if it were a large single target. Latencies to single saccade targets have been found to be independent of saccade target size (Kowler & Blaser, 1994) or even to increase with target size (Dick, Ostendorf, Kraft & Ploner, 2004; Ploner, Ostendorf & Dick, 2004).

Yet, the fixation duration decrease with a surrounded saccade target corresponds to findings from multiple fixation search (Rayner & Fisher, 1987b; Bertera & Rayner, 2000; Cornelissen, Bruin, & Kooijman, 2005). These studies simulated tunnel vision. It was found that subjects fixated for a shorter duration when the artificial tunnel was increased in size. Together with these studies, the present experiment shows that high peripheral stimulation relative to foveal stimulation facilitates the generation of a saccade. However, it is difficult to generalize these findings to multiple fixation search in dense displays. There, the effect of the peripheral stimulation might be cancelled by the foveal stimulation, because foveal stimulation is high too.

The surrounding at the fixated element affected fixation duration to the largest extent. In the introduction, we discussed two processes that potentially affect fixation duration. Foveal visual stimulation might delay the start of the saccade in a similar way as in the gap-overlap experiments (Fischer & Ramsperger, 1984; Weber & Fischer, 1994) and the remote distracter experiments (Walker et al., 1997; Ludwig, Gilchrist & McSorley, 2005). Alternatively, the fixation duration increased because the time to analyze the foveated element increased. In the next experiment, it was tested psychophysically whether more time is required to discriminate an element when it is surrounded by other elements.

Experiment 2 – Psychophysics

Methods

Subjects

Six subjects participated in this experiment (5 male, 1 female). At the time of the experiment, they were either working at the Psychonomics department of the Universiteit Utrecht or they were students at the Universiteit Utrecht. The age of the subjects ranged from 22 to 30. One of the authors (BV) participated in the experiment. All had normal or corrected to normal vision.

Apparatus

The apparatus concerning the stimulus presentation was identical to the first experiment. The eye tracker was not used in this experiment.

Stimuli

Subjects were presented with one element at the center of the screen either with or without a surrounding. This element and the surrounding were identical to the search elements and their surroundings in the first experiment. Subsequently, a mask was presented. The mask consisted of 64 elements. Each element in the mask was either similar to the target (closed square) or similar to a distracter (square with a gap in one of the four edges). The elements were placed on a regular 8x8 lattice with an inter-element distance of 0.26° horizontally and vertically. Next, the elements were given a random jitter of 0.26° in both the vertical and horizontal direction. The luminance of the mask and its background were identical to the luminance of the elements and the background in the target display.

Procedure

The course of a trial is schematically presented in Figure 3. Each presentation started with a fixation cross (0.28° x 0.28°, line width 0.03°) presented at the center of the display. This fixation cross was present for a random period between 1000 ms and 1500 ms. Then, the target display appeared. This target display contained either a distracter or a target with or without a surrounding at the location of the fixation cross. The target was present in 50%

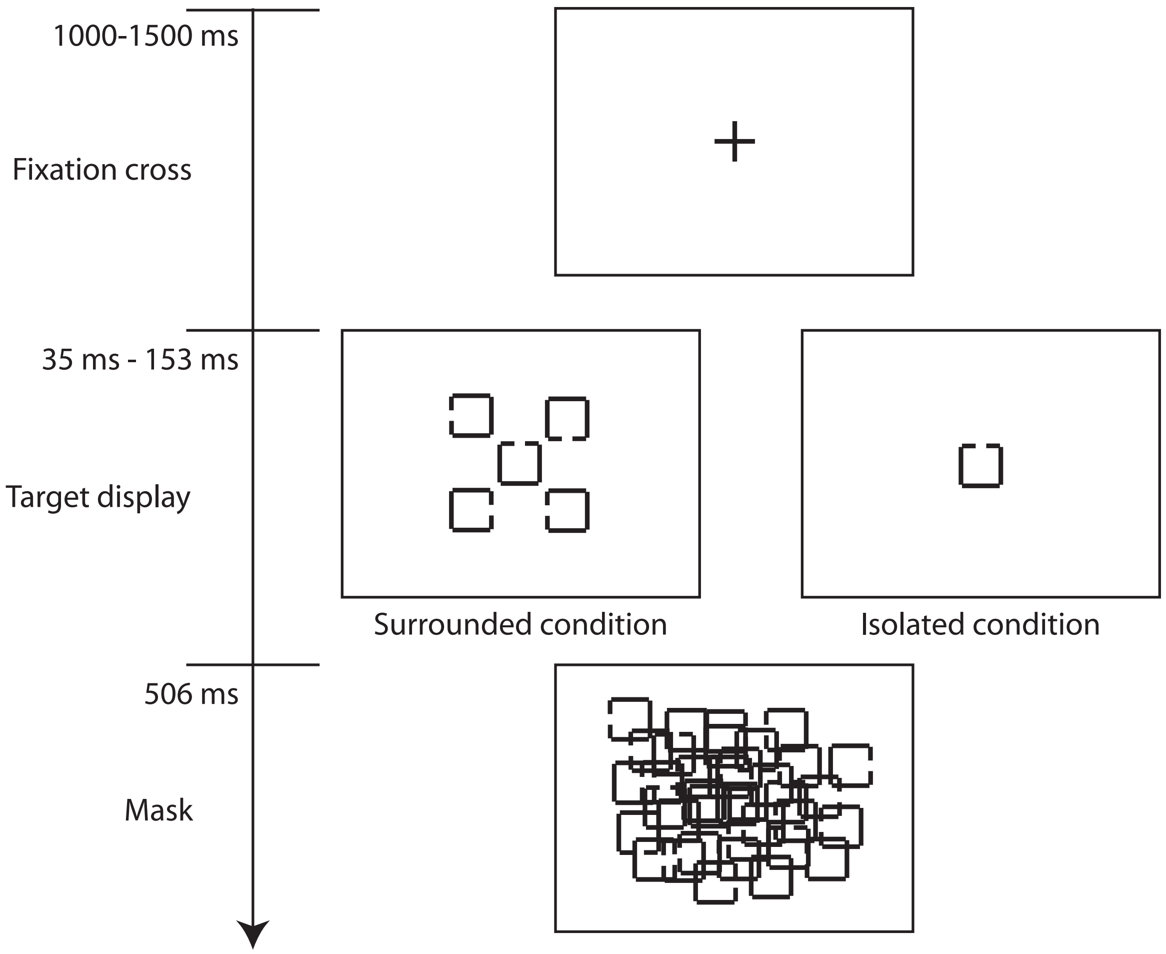

Figure 3. A schematic representation of the displays presented in the psychophysical experiment (experiment 2). The experiment started with a fixation cross. After a random interval between 1000 and 1500 ms, this display was replaced by the display that contained the element that was to be discriminated with or without a surrounding. This display was followed by a mask.

of the trials. The presentation duration of the target display was varied according to the method of constant stimuli. Presentation durations were 35 ms, 59 ms, 82 ms, 106 ms, 129 ms and 153 ms. Finally, the target display was followed by the mask, which was presented for 506 ms. By means of the arrows on the keyboard subjects indicated whether they had seen a target or a distracter.

The experiment consisted of four blocks. Two blocks contained only isolated elements; the other two blocks contained the surrounded elements. In each block 156 trials were presented (26 trials per presentation duration). Prior to the experiment, 72 practice trials were presented per condition (isolated target vs. surrounded target). Each condition was presented in a single block. The practice trials were easier than the actual trials. Target displays were presented for 153 ms, 176 ms and 200 ms. Each of these presentation durations appeared 26 times per condition. Three of the subjects started with the isolated

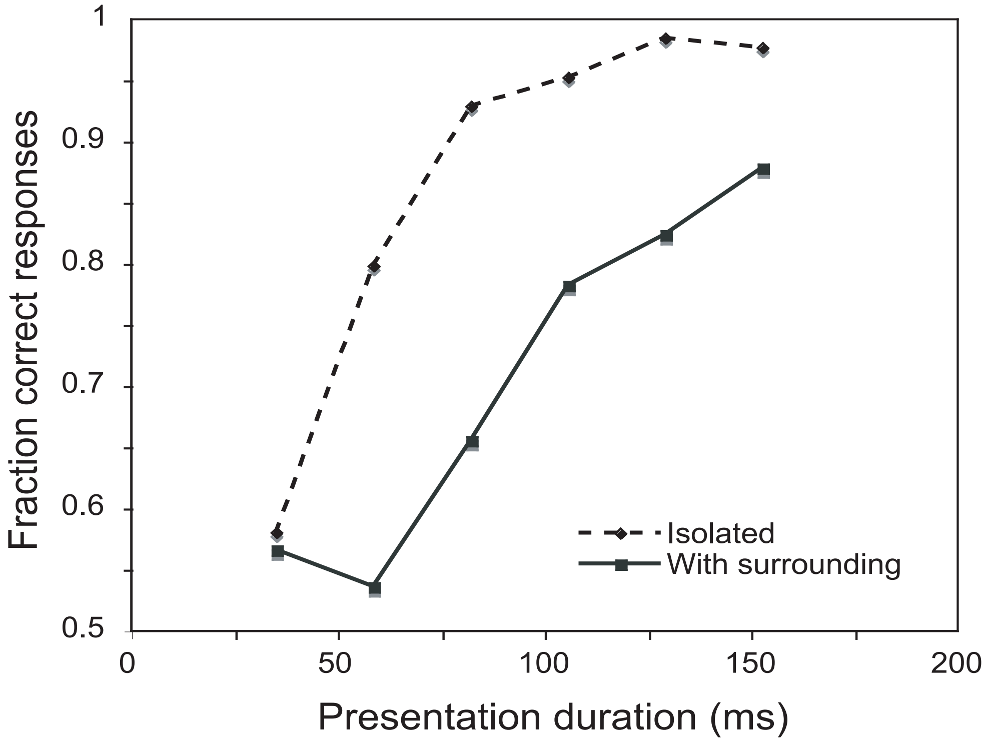

Figure 4. Fraction correct responses as a function of presentation duration. The fractions are averaged across subjects. The solid line represents the condition with a surrounding; the dashed line represents the condition without a surrounding.

element condition (in the practice sessions as well as in the experimental sessions). The other three started with the surrounded element condition.

Results

The fraction correct responses as a function of presentation duration was fitted with a cumulative Gaussian function (least squares method) for the two conditions and for each subject separately. For each fitted function, the presentation duration that coincided with a fraction correct responses of 0.75 was calculated. These values were taken to test whether the analysis times of the isolated and the surrounded condition differed. The average r-square across subjects and the r-square standard deviation were 0.95 and 0.033 for the isolated condition and 0.78 and 0.19 for the surrounded condition.

The presentation duration at a fraction of 0.75 correct responses was on average 55.2 ms in the isolated condition and 109.8 ms in the surrounded condition. They differed reliably according to a two way repeated measures ANOVA [$F(1,5) = 29.16$, $p < 0.01$]. In Figure 4, the mean fraction correct responses across subjects is plotted as a function of presentation duration. Clearly, the discrimination was more difficult when a surrounding was present.

General discussion

In the search experiment, fixation duration was affected both when the saccade target was surrounded and when the fixation element was surrounded. Surprisingly, fixation duration decreased with a surrounded saccade target. Most importantly, fixation duration increased with a surrounded fixation element. The second experiment showed that the time required to discriminate an element increases when it is surrounded. This latter result indicates that the fixation duration increase in the search experiment might at least partially be consumed for discriminating the target. Still, the foveal stimulation caused by the surrounding might affect fixation duration too by delaying fixation disengagement. Below we will firstly discuss the relation between fixation duration in a search task and foveal stimulation. Secondly, the time required to discriminate an element with surrounding elements will be discussed.

Fixation duration and foveal stimulation

In a saccadic search task, Vergilino-Perez and Findlay (2003) found that fixation duration depended on the amount of search elements that were close to the fovea. Subjects searched for 1 of 2 possible targets in an array of 12 elements. They started their search with a saccade from the starting point to a search array. During this first saccade the search array was shifted in the same or opposite direction of the saccade direction. In comparison to a static control condition (where the search array was not shifted), it was found that the fixation duration increased when the array was shifted opposite to the saccade direction; the fixation duration decreased when the array was shifted in the saccade direction. In these two conditions the number of elements close to the fovea respectively increased and decreased. Vergilino-Perez and Findlay (2003) reasoned that it was the foveal stimulation that increased fixation duration. They suggested that the increase in fixation duration was related to an obstruction of fixation disengagement as has been found in the remote-distracter effect (Walker et al., 1997) and the gap-effect (Fisher & Ramsperger, 1984).

Cornelissen et al. (2005) hinted as well at the possibility that foveal stimulation plays a role in search with eye movements. In their view the balance between foveal stimulation and peripheral stimulation affects fixation disengagement. Peripheral stimulation would trigger saccades. In their study, subjects searched for a target while either the display area around the location of the gaze was invisible (artificial scotoma) or the area in the visual periphery was invisible (artificial tunnel vision). Fixation duration was found to increase with decreasing tunnel size (5°, 10°, 15°, full field). With decreasing tunnel size, the amount of foveal stimulation increases relative to the amount of peripheral stimulation. This might delay fixation disengagement. With increasing scotoma size (0°, 5°, 10°, 15°), fixation duration was found to increase. Here, the amount of peripheral stimulation decreases (even in the condition with the smallest scotoma, the scotoma fully covered the fovea) thereby increasing the time required for fixation disengagement.

We agree with Vergilino-Perez and Findlay (2003) and Cornelissen et al. (2005) that foveal stimulation might delay fixation disengagement. In the present saccadic search experiment, fixation duration increased on average with 84.5 ms. In the psychophysical experiment we found that the time required for discriminating the target only increased with 55 ms when it was surrounded. The difference between the two conditions in the time required for discriminating the target and the fixation duration might be related to a delayed fixation disengagement due to foveal stimulation.

The idea of an obstruction of fixation disengagement due to foveal stimulation relative to peripheral stimulation is supported by neurophysiological evidence from monkey studies (see also Walker et al., 1997). The superior colliculus contains a motor map that is directly involved in generating saccadic eye movements (see for overviews, Munoz & Fecteau, 2002; Munoz & Everling, 2004). Two different populations of neurons are present in the superior colliculus. Fixation cell activation keeps the eye relatively stable in space. Saccade neurons are involved in generating a saccade. Fixation cells and saccades cell inhibit each other: saccade cell activation is accompanied by a de-activation of fixation cells and vice versa. Visual stimulation at the fovea increases fixation cell activity whereas peripheral stimulation increases saccade cell activity. The amount of foveal stimulation relative to the amount of peripheral visual stimulation thus might affect the time required for fixation disengagement. Recently, the superior colliculus has been shown to be involved in yielding saccadic eye movements in humans (Neggers, Raemakers, Lampmann, Postma & Ramsey, 2005).

It is conceivable that in the present search displays the surrounding of a foveated search element stimulates the superior colliculus such that fixation disengagement is delayed. It is another question what happens in ‘full-field’ search displays. If these search displays have a high density of search elements, the foveal stimulation is high, but the peripheral stimulation is high as well. It is hard to predict how this affects the balance between fixation cell activity and saccade cell activity in the superior colliculus. It is unknown how the stimulation from such ‘full field’ search display enters the superior colliculus.

Why does a surrounding affect the visual analysis time?

In the present experiments an obstruction of fixation disengagement does not make up the whole story for the fixation duration increase with a surrounding. The largest share of the fixation duration increase can be attributed to an increase of foveal inspection time. Why does the time required to discriminate an element increase when it is surrounded by other elements? An obvious possibility is that crowding plays a role here. Crowding has been described as the phenomenon that a target amidst other items is harder to identify (e.g., Bouma, 1970) or discriminate (e.g., Toet & Levi, 1992). It has been found that crowding in the fovea only occurs with very small spacings between target and flankers (in contrast to crowding in the visual periphery). Some argue that crowding in the fovea is different from peripheral crowding and that it comes down to simple contrast masking (Levi, Hariharan & Klein, 2002; Hariharan, Levi & Klein, 2005). Since the surrounding elements in the present research were not placed alongside the edges of the search elements, foveal crowding would not be expected to play a major role in the present experiments. Recently, however, Fine (2004) found that the perception of a foveally presented letter was hampered by two flanking letters up to 2 letter spacings away. Like in the present experiment, she found crowding in the fovea with short presentation durations (across conditions ≤64.6 ms for 78% correct responses). In most crowding experiments, presentation durations are longer [e.g., Hariharan et al. (2005) and Levi et al. (2002) used 195 ms; Toet & Levi (1992) used 150 ms; Bouma (1970) used 200 ms]. The present experiment replicates the findings of Fine (2004) with different stimuli and a different task. Fine (2004) used trigrams of letters in her experiment whereas we used figurative elements. The task in Fine's study was to recognize the target letter (all 26 Latin letters were included). In our study a 2AFC method was applied (most crowding studies use an AFC-task). Taken together, the findings of Fine (2004) and the present findings demonstrate that short presentation durations make foveal crowding manifest.

Conclusion

In search, fixation duration increases with increasing element density (e.g., Bertera & Rayner, 2000; Vlaskamp et al., 2005). Previously, it was suggested that this fixation duration increase is related to an increased number of inspected elements per fixation (Moffitt, 1980; Ojanpää, Näsänen & Kojo, 2002). On the basis of the present experiments, we add that surrounding elements prolong the visual analysis time of the foveated item. Moreover, fixation duration is possibly affected by a delay in fixation disengagement (as has been suggested by Cornelissen et al., 2005; Vergilino-Perez & Findlay, 2003). Both of these processes should be taken into account when interpreting fixation behavior in search, but they might also play a role in reading and in scene perception.

Chapter 5

The benefits of making a saccade to a crowded stimulus

Submitted as
Vlaskamp, B.N.S., Deubel, H., & Hooge, I.T.C.(submitted). The benefits of making a saccade to a crowded stimulus.

Abstract

Flanking items deteriorate the discrimination of a target item. This crowding phenomenon is strongest in the visual periphery. Saccades ‘break’ the crowding by directing the fovea to the target item. During saccade preparation, attention is allocated to the saccade target (Deubel & Schneider, 1996). In the present experiment, we found that this leads to a second advantage of making a saccade towards a crowded item: the perceptibility is increased already when a saccade to the item is prepared. Observers discriminated a target amidst 2 distracters. Target and distracters were orthogonally placed with respect to the axis running from the fixation point to the target and appeared with 5 distinct target – distracter spacings. They were presented for 110 ms and were preceded by premasks. A central cue indicated the position at which the target appeared. During target presentation observers either moved their attention covertly while maintaining fixation or prepared a saccade towards the target. We found that the percentage of correct responses was significantly higher during saccade preparation.

Introduction

Items are more difficult to identify or to discriminate when they are situated amidst other items than when they appear in isolation. This phenomenon has been termed crowding or lateral masking. Crowding is particularly present in the visual periphery (e.g., Bouma, 1970; Toet & Levi, 1992); items in the fovea suffer from crowding to a much smaller extent (e.g., Fine, 2004), if at all (Hariharan, Levi & Klein, 2005). Therefore, when a part of the visual scene appears crowded, eye movements help to inspect that part (Vlaskamp & Hooge, 2006; Wertheim, Hooge, Krikke & Johnson, in press). Eye movements displace the fovea to the location of interest and thereby 'break' the crowding.

The topic of crowding has been studied extensively. Most of this research on crowding has mainly been conducted under 'static' conditions: In a typical task, observers are required to maintain fixation while target and distracters are presented somewhere in the visual field. This type of research has resulted in several well-established factors that affect the level of crowding. For example, crowding has been found to increase with target eccentricity (e.g., Bouma, 1970; Toet & Levi, 1992), with decreasing spacing between target and distracters (e.g., Bouma, 1970; Fine, 2004; Toet & Levi, 1992) and with target-distracter similarity (Kooi, Toet, Tripathy & Levi, 1994; Nazir, 1992; Vlaskamp & Hooge, 2006).

Do these experiments reflect how people perceive crowded items in real life? Whereas observers are required to maintain fixation in these tasks, people normally make eye movements. Making a saccade towards a crowded item might bring a double advantage. Firstly, the saccade aids in breaking the crowding because the item is foveated when the saccade has ended. The second advantage might occur just prior to the start of the saccade: preparing a saccade couples attention tightly to the saccade target as if the focus of attention precedes the saccade (Deubel & Schneider, 1996; Doré-Mazars & Collins, 2005; Doré-Mazars, Pouget & Beauvillain, 2004; Gersch, Kowler & Dosher, 2004; Godijn & Theeuwes, 2003; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher & Blaser, 1995; Peterson, Kramer & Irwin, 2004). For example, in the experiments of Deubel & Schneider (1996), five horizontally aligned masks were presented on either side of a fixation point. For a short period of time these masks were replaced by one target and four distracters. The observers' task was to discriminate the target. However, simultaneously with the target presentation the observers also prepared a saccade to a specified element (the saccade target). When the saccade target and the discrimination target coincided, the proportion of correctly discriminated targets was higher than when they did not. Deubel & Schneider concluded that the allocation of attention is tightly and obligatory coupled to the target of the saccade prior to the start of the saccade. Since there were 5 elements horizontally aligned on a side (1.09° spacing), Deubel & Schneider additionally concluded that attention preceding a saccade is spatially selective.

Attention has been found to affect a target's perceptibility when the target is crowded during maintained fixation (Van der Lubbe & Keuss, 2001; however, see Nazir, 1992). Van der Lubbe & Keuss (2001) conducted crowding experiments in which they investigated the effect of focusing attention on the target. In their first experiment, they presented a target in the parafovea horizontally aligned with two distracters. Three more horizontally aligned distracters were presented in the opposite hemifield. Preceding the presentation of the target and distracters, Van der Lubbe & Keuss (2001) cued the target position. Depending on the condition, the target was solely cued, together with one or both distracters on the same side, or together with all distracters. Observers gave faster discrimination responses and made fewer errors with a decreasing number of cued elements. Two more experiments confirmed these findings and showed an interaction effect: the deteriorating effect of decreasing the distance between the elements was attenuated by focusing attention.

Does the displacement of attention prior to making a saccade result in a processing benefit in a crowded stimulus compared to a covert displacement of attention while fixation is maintained? In order to explore this issue, we have designed a crowding experiment in which observers either maintained fixation or made a saccade to the target. The target appeared shortly on the left or right side of the fixation point. The fixation point was a symbolic cue indicating the target position that gave observers ample time to move their attention to the target position while maintaining fixation. The saccade conditions beared similarities with the experiment by Deubel & Schneider (1996). As in their experiment, observers made a saccade towards a saccade target. Just prior to the saccade, discrimination target and distracters were visible. However, dissimilar to the experiment by Deubel & Schneider the results on these saccade trials were compared to the observers' performance while they kept fixating the central fixation point. Also, the discrimination performance was measured for several target – distracter spacings. We expected that smaller spacings should evoke more crowding (e.g., Bouma, 1970).

Methods

Participants

8 observers participated in the experiment. All observers –7 female, 1 male- had normal or corrected to normal vision. Observers were students or co-workers at the Ludwig-Maximilians-Universität in Munich.

Apparatus

Observers were seated in a dark room. The heads of the observers were stabilized by means of a chin and forehead rest. The stimuli were presented on a 21 inch Conrac 7550 C21 monitor (screen size 40 x 30 cm), at a viewing distance of 80 cm. Stimuli were presented at

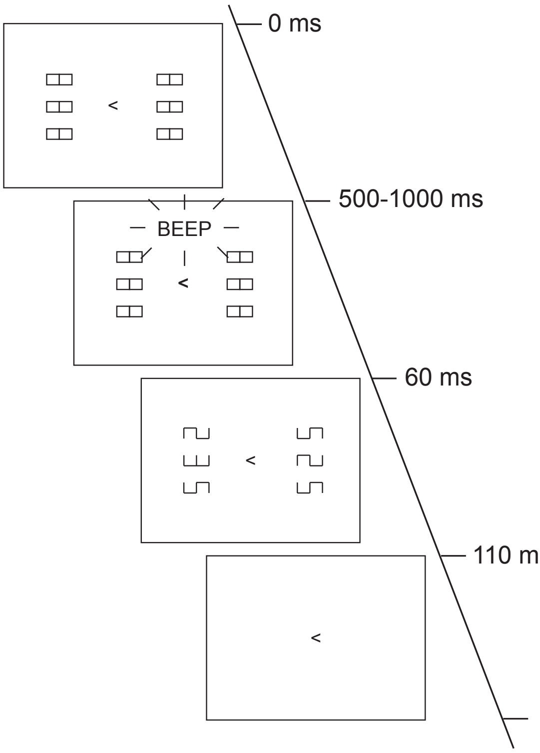

Figure 1. Display presentation sequence. The display presentation order is depicted from top to bottom. The first display contained masks left and right of a fixation symbol that cued the position at which the target was to occur (100% valid cueing). After a random time interval between 500 and 1000 ms a beep was presented signaling that the target was about to be presented; this also served as the go-signal in the saccade condition. Another 60 ms later, the masks were replaced by one target and 5 distracters. This display was presented for 110 ms. At the end of a trial only the fixation symbol remained.

a rate of 100 hz by means of a Kontron KONTRAST 8000 video card which was controlled through a TIGA (Texas Instruments Graphics Adapter) interface on a PC. Eye movements were recorded with a SRI Generation 5.5 Dual-Purkinje image eye tracker (Crane & Steele, 1985). They were sampled at a frequency of 500 hz. A 486 PC with an MS-DOS operating system controlled the stimulus presentation and the eye movement data acquisition.

Stimulus and procedure

In a trial, three frames were presented consecutively (Figure 1). In the first frame three masks were presented on both the left and right side of a fixation symbol (that also served as a cue) at an eccentricity of 6°. The masks were 90° rotated 8's, sized 0.17°x 0.11°. On each side, the masks were vertically aligned. The middle mask was centered on the horizontal axis of the monitor. The distance between the central mask and the upper mask was identical to the distance between the central mask and the lower mask. This frame was presented for a random period between 500 ms and 1000 ms. After this period an auditory cue (4000 hz, 50 ms duration) was presented to signal that the target frame was about to appear. This also served as the go-signal for the saccade. It then took another 60 ms before the second (target) frame appeared.

In the second frame, the masks on both sides of the cue were replaced by the target and by distracters. The target was similar to an M or a W. The distracters were similar to S's that were at random either 90° rotated clockwise or 90° counter clockwise (see Figure 1 for examples of these stimuli). The size of the target and the distracters was equal to the size of the masks (0.17°x 0.11°). Only the central element of the three elements on each side could be replaced by the target. The target and distracters were visible for 110 ms. For each condition, the target appeared equally often on the left as on the right side of the central cue. The cue was an arrow that indicated the target position with 100% validity. The third and final frame only contained the central cue. Observers indicated whether they saw a W or an M by pressing a button on a button box.

There were two experimental manipulations. The first was a saccade/fixation manipulation. This consisted of the instruction either to keep fixating the central cue or to make an eye movement to the target position indicated by the cue. The stimulus presentation was identical in both conditions, and the beep was also present in both conditions. The second experimental manipulation concerned the spacing between target and distracters. In both saccade and fixation conditions observers were confronted with 5 different spacings between the three elements on either side (center-to-center distance between target and distracters on one side was 0.417°, 0.473°, 0.529°, 0.584°, 0.639°).

Procedure

The experiment consisted of two sessions run on separate days. In both sessions three experimental blocks of 140 trials were performed. Prior to the first session, observers received a written instruction on paper. When they indicated that they understood the task, we tested whether their acuity was high enough for performing the task. For this purpose, they were shown the target in displays without the flanking distracters. All observers were able to perfectly discriminate the target. In order to acquaint them to the task, observers subsequently engaged in two practice sessions of each 60 trials in which they discriminated the target while maintaining fixation.

The conditions alternated across blocks. Observers always started with the fixation condition. Within each block each of the five target-distracter separations appeared 28 times: 14 times on either side of the cue. This amounted to a total of 84 trials per eccentricity (3 blocks x 28 presentations). Prior to each block (saccade and fixation condition), the eye tracker was calibrated.

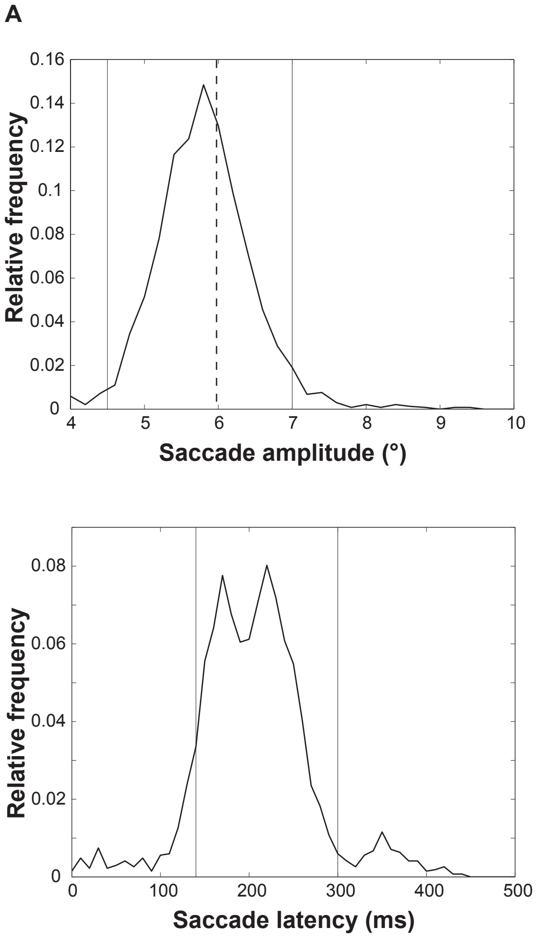

Figure 2. Relative frequency distributions of saccade parameters. The vertical lines mark the criteria that have been applied for including trials in the discrimination performance analysis: (A) saccade amplitude and (B) saccade latencies.

Data analysis

The eye movement data and manual responses were analyzed off-line. Before analyzing a trial any further, the eye movement data had to meet several criteria. In the fixation conditions, obviously only trials in which observers did not make any eye movements were included. The critical period started 50 ms before the beep until 400 ms after stimulus presentation. Less than 4% of the trials were rejected because observers erroneously made an eye movement away from fixation. For the saccade condition, only trials in which a saccade was made from the central cue to the target with an amplitude of 4.5° to 7° were accepted (a saccade amplitude of 6° was required to accurately land on the target; the tolerance for undershoots was a larger since saccades tend to undershoot the saccade target. 8% of the trials did not meet this criterion). Figure 2A shows the combined saccade amplitude distribution for all observers. Temporal limitations were also imposed upon the saccades. Saccades were required to land 15 ms after the target disappeared or later. The maximum saccade latency was 300 ms (the distribution of the saccade latencies of all observers is shown in figure 2B). This is a broad time window for our goal: we wanted to present the target and distracters during saccade preparation. Attention is allocated to the saccade target most tightly when it is presented within the last 50 ms prior to saccade execution (Doré-Mazars et al., 2004). Together, these criteria resulted in the removal of 41 % of the saccade trials for further analysis. This was mainly because observers landed on the saccade target before it disappeared (19% of the trials); two more reasons for trial removal for further analysis were that observers did not make an eye movement at all (8.9%) and that they made their saccade 300 ms after stimulus onset (8.5%).

Results

In Figure 3, the fraction of correct responses across observers is plotted as a function of the spacing between target and distracters. The continuous line represents the fixation conditions; the dashed line represents the saccade condition. The figure shows the well-known fact that the effect of crowding increases when the distance between target and distracters is decreased. Here, the proportion correct responses increased from 0.54 at a spacing of 0.417 degrees to 0.68 at a spacing of 0.639 degrees for the fixation condition and from 0.54 to 0.79 for the saccade condition. The effect is reliable [$F(4,28) = 14.342$ $p < 0.001$]. The manipulation of interest is the saccade/fixation manipulation, however. Across spacings, the proportion correct responses was higher when observers prepared a saccade to the target. The differences in the proportion correct responses between the two conditions produced a significant main effect [$F(1,7) = 15.194$, $p < 0.01$]. Finally, there was no interaction between the spacing and saccade/fixation manipulations [$F(4,28) = 2.2213$, $p > 0.05$].

Discussion

We compared discrimination of a crowded target while observers maintained fixation with discrimination just prior to making a saccade. Previously, it has been shown that programming an eye movement allocates attention to the saccade target (e.g., Deubel & Schneider, 1996; Kowler et al., 1995). We have found evidence that the preparation of a saccade not only couples attention to the saccade target, but it allocates even more attentional resources to the target than when attention is allocated covertly. Below, the relation between crowding and attention will be discussed. Subsequently, it will be discussed why discrimination performance is better prior to starting a saccade.

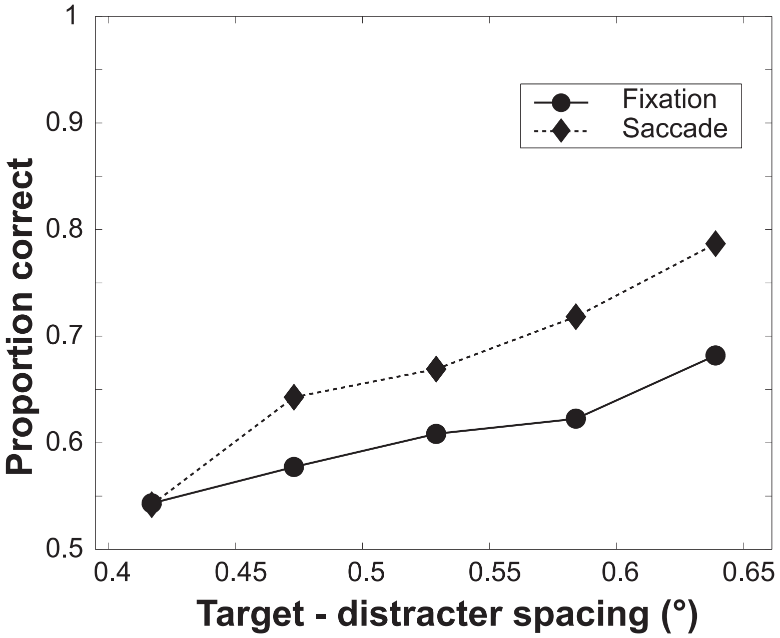

Figure 3. Proportion correctly discriminated targets as a function of the spacing between target and distracters. The solid line with circles denotes the fixation condition; the dotted line with diamonds denotes the saccade condition.

Crowding and attention

In the present experiment, it was found that the spacing between the elements led to a crowding effect. In the saccade condition, the proportion correct responses was higher than in the fixation condition. Statistically, the latter effect is independent of the effect of spacing. One might therefore argue that the saccade/fixation manipulation only affects attention and not crowding per se. Yet, it cannot be excluded that attention plays a role in the crowding effect. According to some models, crowding is a consequence of spatial properties of attention. Wolford & Chambers (1983) have suggested that crowding occurs because flankers draw attention away from the target. Since less attentional resources are available at the target position, target identification is harder. Recently, a different model has been proposed that also includes a crucial role for attention in crowding (Intriligator & Cavanagh, 2001). In this model, attention selects a part of the visual scene for further analysis. Features of distinct items within such an attentional window are combined to a single object. According to Intriligator & Cavanagh (2001), crowding results if the size of this selection window is too coarse for selecting a single item. The selection window can scale to encompass a large item, but Intriligator & Cavanagh (2001) suspect that the smallest attainable window is an absolute one. However, in order to incorporate the present findings, making a saccade should decrease the size of the selection window beyond the smallest size reached during fixation.

However, it is debated whether crowding is the consequence of spatial properties of attention (e.g., Pelli, Palomares & Majaj, 2004). Instead, manipulations of attention have low-level effects that might reduce the crowding. Attention has been found to increase the perceived stimulus contrast (Carrasco, Ling & Read, 2004). Carrasco et al. argue that the ‘effective contrast’ increases, i.e. there is a greater sensitivity at the neuronal level. “It is as if attention boosted the actual stimulus contrast” (p. 312). This low-level effect of attention is a candidate for reducing the crowding. Kooi et al. (1994) showed that crowding is strongest when target and distracters are similar to each other. This also holds for the contrast of target and surrounding items. Particularly a higher contrast of the target relative to the contrast of surrounding items weakens crowding. Therefore, if attention selectively increases the ‘effective contrast’ of the target while leaving surrounding items less affected (or maybe even unaffected) this might well reduce the crowding.

Another possibility is that the impact of information outside the focus of attention is diminished. Several authors have shown that the processing of elements is suppressed if they are close to the focus of attention (Bahcall & Kowler, 1999; Cutzu & Tsotsos, 2003; Theeuwes, Kramer & Kingstone, 2004). For example, Bahcall & Kowler (1999) developed a task in which observers had to identify two letters. If these two letters were at small separations (as small as 0.5°), the proportion of correctly identified letters was smaller than with larger separations. Focusing the target attentionally might therefore decrease the perceptibility of surrounding elements. Consequently, these surrounding elements might interfere less with the processing of the target.

The cost of fixating

We found that in the fixation condition the proportion correctly discriminated targets was smaller than in the saccade condition. How is this possible? The relationship between the preparation of a saccade and the displacement of attention has been studied extensively. From this, it is known that prior to making a saccade, attention is allocated to the saccade target position (e.g., Deubel & Schneider, 1996; Kowler et al., 1995). Doré-Mazars et al. (2004) recently added that the amount of attentional resources available at the saccade target location accumulates just prior to the saccade start. They found that detection performance at the saccade target position was highest in the last 50 ms before the start of the saccade. Thus, the programming of a saccade and the displacement of attention are tightly related to each other. We propose that the connection between saccade programming and the displacement of attention is such that when sufficient attentional resources are allocated to a particular location a saccade is made; if there are not enough attentional resources allocated, there will be no saccade. Consequently, in order to maintain fixation, less attention can be allocated to a peripheral location than when a saccade is made.

Conclusion

In the visual periphery, surrounding items decrease a target's perceptibility. A way to reveal such a crowded target is by making a saccade towards it. This breaks the crowding because the saccade directs the fovea at the target. The present experiment has shown that a second advantage occurs just prior to the saccade start. Attention is allocated to the crowded saccade target and thereby increases the target's perceptibility. This increase is small relative to the decrease in crowding once the target is fixated, but it allows a more elaborate preprocessing of the target.

Acknowledgements

We thank Werner X. Schneider for the helpful discussions. The study was supported by the Deutsche Forschungsgemeinschaft (Grant DE 336/2 to H.D.) and a grant from the Netherlands Organization for Scientific Research (NWO).

Chapter 6

Strategies in saccadic search

In preparation as

Vlaskamp, B.N.S., & Hooge, I.T.C. (in prep). Strategies in saccadic search.

Abstract

We studied eye movements to reveal search strategies. We distinguish short-term and long-term strategies. Short-term strategies concern the immediate setting of fixation duration and saccade amplitude. Long-term strategies cover the period from the beginning of a search until the task is completed. This strategy is used to control the scan path. In our search displays, target detectability was manipulated by varying the element luminance (target and distracters alike). Displays contained either elements with the same luminance (uniform displays) or three strips of elements, each with a different luminance (mixed displays). These strips were either oriented horizontally or vertically. This descriptive study revealed that: (1) Fixation duration decreases with increasing element luminance, but saccade amplitude is not affected (both in uniform and mixed displays). From this we conclude that varying element luminance does not affect target conspicuity and that visual analysis times increase with decreasing luminance. (2) Observers have a strong tendency to first search areas with high element luminance. This finding is in line with the ‘coarse to fine strategy’. In this strategy observers first inspect easy parts of the display (where target detection is faster) and subsequently continue with the more difficult parts. (3) The observers had a strong tendency to search horizontally. They even showed this behavior for vertical strips in the mixed search displays. (4) Search in vertical luminance strips was more efficient than in the horizontal luminance strips conditions. We discuss this finding in relation to the phenomenon of crowding.

Introduction

Searching for objects is a very important task of the brain. From an evolutionary point of view it has great survival value. Finding food, partners etcetera is important as well as avoiding encounters with potential hazards like predators. Foveal animals such as cats, monkeys and humans usually search by directing their fovea toward the target, which they accomplish by making saccadic eye movements. In between saccadic eye movements, the eye is relatively stable. It is during such a fixation that the visual system takes in information. Because foveal animals search with saccades, this report will mainly deal with the role of eye movements and visual perception during saccadic search.

What are the prerequisites for an efficient search? To answer this question a first requirement is a good definition of efficient search. We use the following definition: search is efficient when as many targets as possible are found within a short as possible time interval.

In order to search efficiently, temporal and spatial aspects of search are important. A spatially efficient searcher uses the minimally required number of fixations to find the target. To accomplish this, it should be avoided that a location is inspected more than once. Moreover, fixation areas should not overlap. A temporally efficient searcher limits his fixation duration strictly to the time required to judge whether or not the fixated area contains the target. The fixation should not be too long, but not too short either. In the latter case, another fixation and eye movement to that location may be required (Hooge & Erkelens, 1996).

The present study is meant to derive a description of search behavior. We discern two kinds of strategies. Firstly, there is the eye movement strategy (a short term strategy that stretches over a period of 1 second or less). This strategy concerns the setting of the eye movement parameters. With eye movement parameters we refer to the saccade amplitude and the fixation duration. In order to search efficiently, it is a prerequisite that both saccade amplitude and fixation duration are adjusted to the demands of the search task during that particular fixation. There is a vast amount of evidence showing that the visual stimulus affects these eye movement parameters. For example, with increasing target-distracter similarity fixation duration increases, saccade amplitude decreases and the number of fixations required to find the target increases (Jacobs, 1986; Rayner & Fisher, 1987a,b; Hooge & Erkelens, 1996,1998, 1999; Vlaskamp, Over & Hooge, 2005). Recently, increasing crowding has also been found to increase fixation duration and to decrease saccade amplitude (Vlaskamp & Hooge, 2006).

A second class of strategies is the search strategy. These strategies have a longer time scale. They may stretch up from the start until the end of the search (designated by the detection of the target or by the judgment of its absence). An example is the reading strategy (see Hooge, Stapelkamp, Over, Vlaskamp & Frens, 2004). For this reading strategy, the display is searched from left to right (and/or right to left) and from top to bottom (and/or bottom to top). For subjects, the use of this strategy has a clear advantage in that the location of inspected search elements does not have to be retained in memory (Hooge et al., 2004). So, this search strategy assures that all search elements are inspected. The reading strategy is especially effective in displays with regularly dispersed search elements. Another example of such a search strategy is the coarse-to-fine strategy. As search progresses in time, fixation durations increase and saccade amplitudes decrease (Antes, 1974; Over, Hooge, Vlaskamp & Erkelens, 2006). The explanation is that observers set their eye movement parameters to first search at a coarse scale with short fixations and large saccades for the more conspicuous targets. Later, in order to find less conspicuous targets, observers search at increasingly finer scales with long fixations and small saccades. This strategy is particularly suitable for situations in which each location has the same probability to contain the target, and where target conspicuity varies across the stimulus, for example due to a varying background. This strategy even shows up in stimuli with fully known target conspicuity indicating that searchers apply this search strategy automatically.

At first sight, natural displays are ideal stimuli to investigate strategies. However, the information content of natural stimuli such as pictures is hard to determine. This makes analyses and interpretation of the eye movement data and especially the underlying strategy very difficult if not impossible. More abstract stimulus displays have the advantage that the information content is under the experimenters control, but subjects may use suboptimal strategies that are normally used when they act with the world outside the experimental laboratory. Good examples of the previous are found in the work of Over et al. (2006), Findlay & Gilchrist (1998) and Araujo, Kowler & Pavel (2001).

We choose to investigate search and eye movement strategies in complex abstract search displays. We try to achieve that our stimuli contain aspects of both abstract stimuli and natural images in order to evoke more natural eye movement behavior. In natural images, detectability of a target may vary across the scene due to variations of the background. In analogy to Näsänen, Ojanpää & Kojo (2001), we manipulated the luminance of the search elements. Search in high luminance elements is easier (as reflected by shorter search times) than search in low luminance elements. The present experiment consisted of two conditions. In the first condition, displays contained three sectors of low, middle and high luminance search elements respectively. In the second condition, the displays contained only one level of element luminance. With these displays, it is possible to investigate the search strategy as well as the eye movement strategy by comparing both the eye movement parameters and fixation locations.

Four questions that we will address are:

(1) How are eye movement parameters affected by the element luminance?

(2) Does the eye movement strategy differ between mixed and uniform search displays? In the mixed displays, we may find saccade amplitudes and fixation durations that differ from those in the uniform displays, because fixations at difficult non-targets affect fixation durations at easier non-targets (Hooge, Vlaskamp & Over, 2006). Not much is known about the temporal aspects of eye movement parameter adjustment in relation to the physical stimulus in search.

(3) Do the separate (luminance defined) search areas in mixed displays facilitate systematic search as compared to uniform displays? In the mixed displays, the search area is divided in three smaller areas. If one searches the areas consecutively, re-inspections of single elements may be prevented because within a single area fewer element locations need to be stored in memory. Moreover, after having inspected all elements in a single area, the whole area may be 'tagged' as inspected. This is not possible in the uniform displays and therefore tagging is assumed to be less efficient in uniform displays.

4) Do humans take the detectability of the target into account when choosing the optimal search strategy? When searching for a target, it would be efficient to adopt the strategy that leads to the fastest detection of the target. As mentioned above, the search time decreases with increasing target detectability. In the mixed displays, it would therefore be an efficient strategy to search the high luminance area first and the middle luminance area second. The low luminance area should only be inspected if the target is still not found in the high and middle luminance strips.

Methods

Subjects

5 subjects participated in the experiment (4 male; 1 female). All subjects were naive with respect to the goal of the experiment. The age of the subjects ranged from 24 to 30 years. All subjects had normal or corrected to normal vision.

Apparatus

Stimuli were generated by an Apple G4 computer and were presented on a LaCie Electronblue III 22" monitor (crt monitor; 1600x1200 pixels; 75 hz). The heads of the subjects were stabilized by means of a chin rest at 64 cm distance from the monitor. Eye movements of the left eye were recorded at 500 hz with a head mounted Eyelink II eye tracker. Gaze positions were corrected for head movements. Stimuli were presented with Matlab for Macintosh running the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Eye movement recording was controlled by the Eyelink Toolbox for Matlab (Cornelissen, Peters

& Palmer, 2002). The eye movement data were analyzed off-line.

Stimuli

Subjects were presented with search displays that contained 81 search elements (9 x 9). The search elements were placed on a hexagonal grid; the distance between neighboring elements was 3.31°. The total size of the display subtended 35°x 27°. The search elements were squares that were defined by their edges (element size: 0.44° x 0.44°); the edge width was 1/20 of the element side length. On of the four edges contained a gap (0.25°). The edge that contained the gap was randomly chosen for each element. The target was a closed square. The background of the search display was black (0.04 cd/m^2). The luminance (of the elements) was either 1.11 cd/m^2 (low luminance condition), 2.86 cd/m^2 (middle luminance condition) or 78.4 cd/m^2 (high luminance condition). We do not refer to the contrast of the elements with the background. (Michelson) Contrast is a relative measure and since the background luminance was very low, the contrasts were high for all three luminance elements (>0.93). We feel that referring to the luminance would do more justice to the different analysis times that are required for the three element luminances (as will be clear from the results).

The search displays were manipulated in two ways. Firstly, the elements had one of the three above-mentioned luminances. Secondly, a display contained elements either with one luminance only (uniform displays) or all three luminances (mixed displays). In the mixed displays, there were three distinct areas within which the elements had the same luminance. Each area contained of 1/3 of the total number of elements in the search display. These areas had a rectangular shape (9 x 3 search elements). These rectangular areas were horizontally oriented (horizontal strip display) or vertically (vertical strip display). Across these mixed display conditions, the 6 possible combinations of distributing the luminance across the areas all occurred equally often (for the horizontally oriented areas as well as for the vertically oriented areas). Importantly, the target was present in 50% of the trials. Moreover, in the mixed conditions, the target occurred equally often in all strips.

Procedure

The experiment was divided into 4 sessions. A single session contained 72 trials. The conditions were presented in a random order. Prior to the start of a block the EyeLink was calibrated with the standard EyeLink 9-dots calibration. The calibration was validated. Each trial started with a self-paced one-dot drift correction. The drift correction was conducted on a solid high luminance background (78.4 cd/m^2) in order to minimize dark adaptation. After successful drift correction, a search display was immediately presented. Subjects searched until they found the target or until they decided no target was present. They indicated by means of the arrow buttons on the keyboard whether a target was present in the display

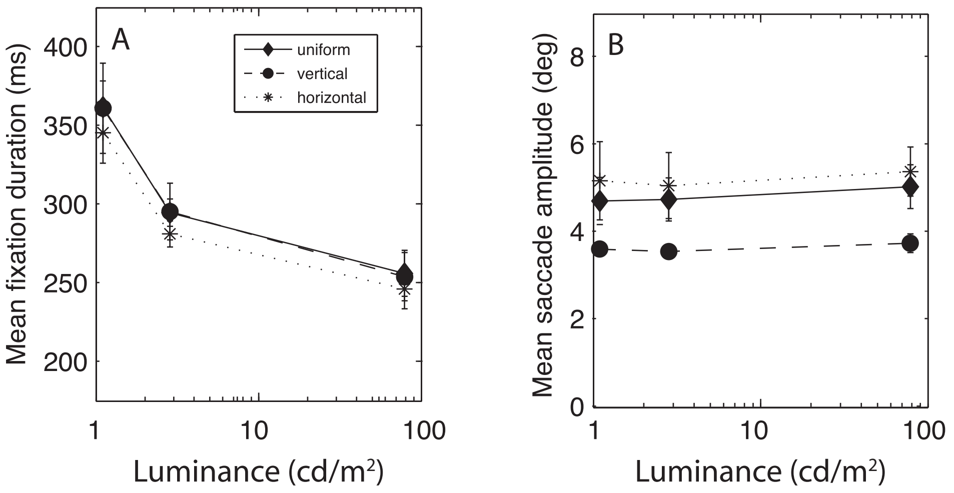

Figure 1. The mean fixation duration (A) and mean saccade amplitude (B) are given as a function of the element luminance. In both panes, the data from the three types of displays are given: The solid line represents the duration of fixations in the uniform displays, dashed in the vertical strip displays and dotted the horizontal strip displays. The data are averaged across subjects. The error bars in the figure represent the standard error of the mean.

or not. The key press ended the trial and the search display was replaced by the drift correction display for the next trial.

Eye movement analysis

The Eyelink data were processed to extract fixations and saccades. Saccades were detected with a velocity threshold of 50°/s. Our Matlab program determined the transition between saccade and fixation by searching back and forth until the velocity was two standard deviations higher than the velocity during fixation (as in Van der Steen & Bruno, 1995). Fixations were defined as the periods of time in between the detected saccades. Saccades with amplitudes smaller than 1.5° were removed from the analysis. If a small saccade was removed, fixations before and after this saccade were added together. A saccade amplitude threshold of 1.5° was chosen, because many small saccades up to 1.5° occurred. These saccades had amplitudes that were much smaller than the distance between elements (3.31°). These small saccades are interesting in their own right, but they are irrelevant to our questions. They particularly occurred in the low luminance condition.

Results

The subjects' task was to report whether a target was present or not. Subjects were well capable of discerning a target from a distracter. There were only 7 false alarms in total. On the other hand, not all targets were found. The percentage of detected targets was

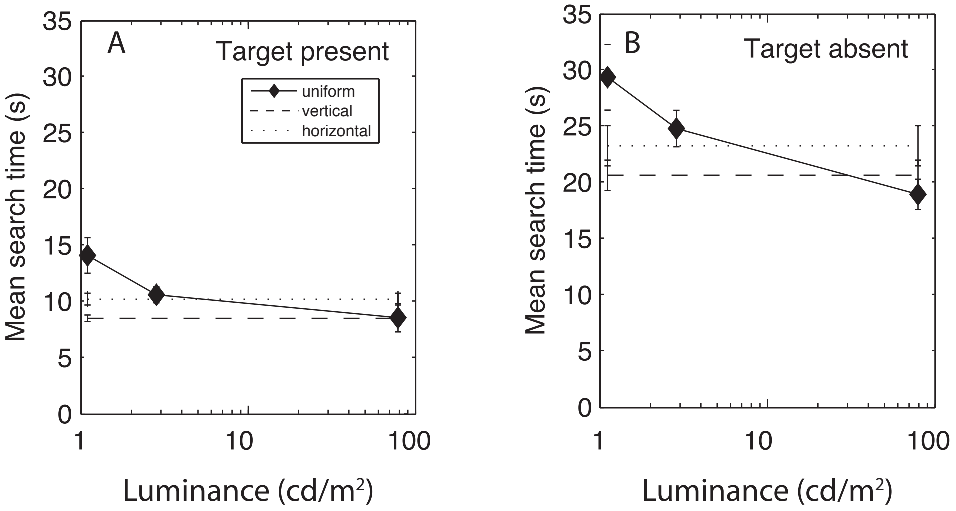

Figure 2. The mean search time in the target present (A) and target absent (B) trials as a function of the element luminance. In both panes, the solid line represents the search time in the uniform displays. Since a vertical or horizontal strip displays contained elements of all three luminances, the search times were not subdivided according to element luminance. Search times belonging to these displays are represented by straight lines: The dashed lines stand for the search time in the displays with the vertical strips and the dotted lines for those in the displays with the horizontal strips. The error bars represent the stand error of the mean; the standard error of the mean of the displays with the vertical strips and horizontal strips are given by the error bars on the left and right side of the lines.

84% (low luminance), 93% (middle luminance) and 90% (high luminance) [F(4,8)=2.117, p=0.1828].

Fixation duration and saccade amplitude

Figure 1A shows the fixation duration as a function of element luminance. The first fixation is not included in this analysis; these fixations started before the display appeared (Hooge & Erkelens, 1996) and may belong to a different distribution (Van Loon, Hooge & Van den Berg, 2002). The fixation durations are averaged across subjects. As expected, fixation duration clearly decreased with increasing element luminance. On average, the fixation duration decreased from 355 ms in the low luminance condition to 251 ms in the high luminance condition [F(2,8) = 22.193, p = 0.0005]. The type of display did not affect fixation duration [F(2,8) = 1.975, p = 0.2009] nor did display type interact with element luminance [F(4,16) = 0.287, p = 0.8823]. The fixation duration increase may point to a higher number of elements analyzed per fixation. To check for this we analyzed saccade amplitude, which is a good indicator for this (Jacobs, 1986). Figure 1B shows the mean saccade amplitude. For the mixed displays, we excluded the saccades that brought fixation from one strip to another. Mean saccade amplitude was not affected by the element luminance [F(2,8) = 0.528, p = 0.6091]. We can now conclude that the luminance only affected fixation duration.

The fact that saccade amplitude did not depend on the element luminance indicates that the visual span remained the same across element luminances. The dependency of fixation duration on the element luminance may therefore solely be related to the time required for the analysis of an element. This is a remarkable finding to which we will come back in the discussion.

Display type (horizontal, vertical and uniform) did affect the saccade amplitude [F(2,8) = 4.896, p = 0.049]. The amplitudes in the vertical strips were the smallest, the saccades in the horizontal strips and in uniform displays were almost similar in size. The mean amplitude (3.61°) in the vertical strips was only slightly larger than the distance between elements in the display (3.31°). There was no interaction between the display type and the element luminance on the saccade amplitude [F(4,16) = 0.296, p = 0.8766].

Search time

Based on the fixation durations we expect the search time to decrease with increasing element luminance. The search time data from the uniform displays are given by the solid lines in Figures 2A and 2B; the dashed and dotted lines represent the vertical and horizontal strips. Figure 2A contains search times for the target present trials and Figure 2B contains search times for the target present trials. In target present trials we find longer search times for low luminance elements than for high luminance elements [F(2,8) = 5.970, p = 0.0259]. We see the same for search times of target absent trials [F(2,8) = 16.749, p = 0.0014]. In the mixed displays, subjects turned the distribution of luminance across the display to their advantage: Search times collapsed across the mixed displays were shorter than those averaged across the uniform displays [target present: t(4)=3.606, p = 0.0226; target absent: t(4)=6.883, p = 0.0023].

Careful inspection of the search times reveals an interesting finding: Search times for displays consisting of horizontal strips are longer than those for displays consisting of vertical strips [target present: t(4)=2.9615, p = 0.0415; target absent: t(4) = 3.3739, p = 0.0279]. Since fixation durations did not differ for these two display types, we expect the number of fixations to be higher for the horizontal strips.

Number of fixations

In Figure 3, the number of fixations are given separately for the target present (A) and target absent (B) trials. In both graphs, the number of fixations from the uniform displays are represented by the solid line. The dashed and dotted lines stand for the vertical and horizontal strip displays respectively. In the uniform displays, the target present trials yielded no differences across luminances in uniform displays [F(2,8) = 0.807, p = 0.4796], whereas the target absent trials did [F(2,8)=37.10, p = 0.001]. In line with our prediction from the search time section, we found that subjects made more saccades in the horizontal strips

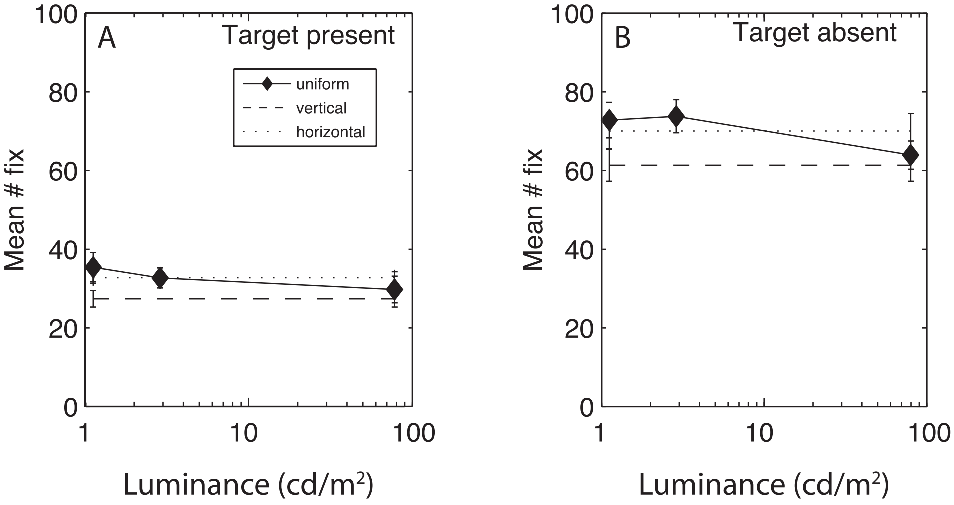

Figure 3. The mean number of fixations in the target present (A) and the target absent (B) trials as a function of the element luminance. In the two panes, the solid line represents the search time in the uniform displays. Since the vertical and horizontal strip displays contained elements of all three luminances, the number of fixations were not subdivided according to element luminance. In both panes, the number of fixations belonging to these displays are represented by straight lines: the dashed lines stand for the search time in the displays with the vertical strips and the dotted lines for those in the displays with the horizontal strips. The error bars represent the stand error of the mean; the standard error of the mean of the displays with the vertical strips and horizontal strips are given by the error bars on the left and right side of the lines.

than in the vertical strips in the target present trials [t(4) = 3.0185, p = 0.0392]. In the target absent trials, there were also fewer fixations in the vertical strips than in the horizontal strips, even though this difference did not reach statistical significance [t(4)= 2.6075, p = 0.0596].

The spatial distribution of fixations in time

Did the subjects adopt the coarse-to-fine strategy? If subjects use this strategy, they would first search the area where the target is easiest to detect. Of course, in the present experiment this strategy can only play a role in the mixed displays. With this strategy subjects would search the high luminance strip first (the uniform displays demonstrated that search times are shortest with high luminance elements). For each fixation we determined its ordinal number and the element fixated (low luminance, middle luminance or high luminance). Here, we have plotted the number of fixations of each type as a function of ordinal fixation number averaged across subjects (Figure 4). We only analyzed the target absent trials because in these trials our subjects had to inspect all elements in order to be able to decide whether the display contained the target or not. Each line represents fixations in one of

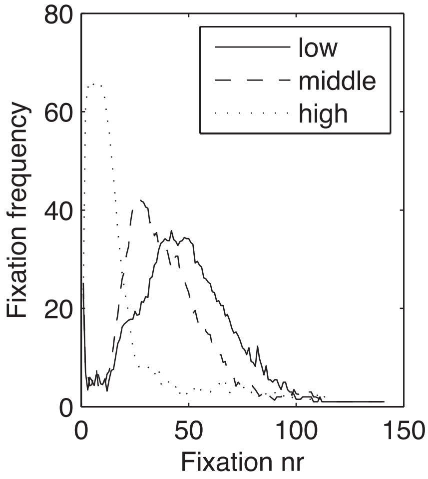

Figure 4. The fixation frequency as a function of the ordinal fixation number in a trial for each of the three luminance strips in the mixed displays. The peak of the dotted line in the left part of the figure indicates that on the first fixations subjects searched in the area with the high luminance elements.

the three luminance strips. Clearly, subjects had a strong preference to inspect the high luminance strips first. Within the first 20 fixations, subjects almost only inspected the high luminance strip. The number of target absent trials in the mixed displays amounted to 72; the first peak tops at 66 fixations. During these first fixations, subjects hardly looked at the low and middle luminance elements. The first fixation forms an exception to this. Due to the drift correction procedure, subjects fixated the middle of the screen at display onset. After the first 25 fixations, the high luminance strip is hardly inspected anymore. Starting at fixation number 15, the frequency of fixations at low and middle luminance grows.

Discussion

Eye movement strategies

With decreasing element luminance we found that the fixation duration increased while the saccade amplitude remained unaffected. At first sight, this is a peculiar finding. It has often been reported that an increase of the fixation duration that comes with a change in the search display is accompanied by a decrease of the saccade amplitude (Jacobs, 1986; Rayner & Fisher, 1987; Cornelissen, Bruin & Kooijman, 2005; Vlaskamp & Hooge, 2006; Vlaskamp et al., 2005). So, why is saccade amplitude not affected by element luminance? In search, one usually finds that the saccade amplitude varies with the conspicuity of the target (Jacobs, 1986). According to Engel (1971, p. 563), conspicuity is ‘an object factor in relation to its background, for example, a red ball surrounded by similar red balls, is inconspicuous, whereas in other types of surroundings it may be conspicuous'. Thus, the conspicuity of a target is increased if its contrast with other search elements is increased with respect to one or multiple dimensions (e.g., object orientation, color contrast etc.). Accordingly, varying the element luminance for target and distracters alike may not alter target conspicuity. As target conspicuity was the same across element luminances, the saccade amplitude remained the same. The fixation duration increase with decreasing element luminance can be explained as being due to the sensory processing time required for resolving the fixated elements.

If target conspicuity does not vary with element luminance, we expect that the number of elements inspected per fixation also remains the same. Insight into the number of elements inspected per fixation can be provided by the number of fixations required to find the target (or to judge that no target is present): If refixations are discarded, the number of fixations is directly related to the number of elements fixated. After subtracting refixations from the total number of fixations per trial, we find that the number of fixations does not vary with element luminance [number of fixations: 27.00, 26.65, 24.15 for low, middle, high luminance in the target present trials, $F(2,8)=0.432$, $p = 0.6634$, and 51.18, 50.94, 49.00 in the target absent trials, $F(2,8)=1.531$, $p = 0.2736$]. This shows that the number of elements inspected per fixation (as an alternative estimator for target conspicuity) is invariant to the element luminance. Interestingly, we reported in the results section that the number of fixations increased with decreasing element luminance. Since refixations were included there, this increase can only be due to the refixations. This indicates that low luminance elements may have been fixated too shortly for full analysis (see Hooge & Erkelens,1996; 1998), even though fixation durations were long already (355 ms on average).

The idea that saccade amplitude is invariant to search element luminance because target conspicuity is not varied, appears to be at odds with the relation between saccade amplitude and element-background contrast found by Näsanen et al. (2001). They studied eye movements during search as a function of the contrast between search element luminance and background luminance. Since target and distracters always had similar luminance, we would expect saccade amplitudes to remain the same across element contrasts too, because target conspicuity was not varied. Yet, Näsänen and colleagues found that saccade amplitudes decreased with decreasing element contrast. This was especially evident for the lowest contrasts (0.0186-0.0379, Michelson contrast). Possibly, target conspicuity varies non-linearly with element contrast in this low contrast range. However, the result of Näsänen et al. may be hard to generalize. The size of the saccade amplitude increase was small (0.7° over a contrast range from 0.0186 to 0.412; the element size was 0.9° where the inter-element distance was not supplied) and different for each subject. Also, there were data of 3 subjects included but one observer did not show any difference between the highest and lowest contrast conditions. In another but similar study, Ojanpää & Näsänen (2003) also varied the luminance contrast. In addition, they manipulated the size of the search elements and found that saccade amplitude was not affected by luminance contrast for two of the three element sizes.

Fixation duration in mixed luminance displays

For our experiments, fixation duration depended on the luminance of the search elements. This relationship was independent of whether the element was presented in a mixed or uniform display. This means that the time required for analyzing an element is not affected by the analysis time required for previously fixated elements. However, Hooge et al (in press) did find that fixation durations are affected by previous fixations. Which seems to contradict the results of the current experiments. The duration of a fixation on an element was lengthened when it was preceded by a fixation on an element that required a longer visual analysis time. The duration of fixations on elements that required a longer analysis time than the preceding element were not influenced by the preceding element. However, because the fixation duration effect is a short term effect, only lasting for a few fixations, an effect of fixation history on fixation duration may not show up: in the present study subjects mostly made series of saccades to elements with the same luminance (see next section). Yet, the fixation duration effect of Hooge et al. (in press) may also not be manifest for another reason. Subjects started searching in the high luminance strip and went on with elements in lower luminance strips. From Hooge et al. (in press), it is known that fixation durations are adjusted to the fixation task immediately but only when a longer fixation duration is required than on the previous fixation. This is exactly the situation that occurs when subjects move their gaze from the high luminance area to a lower luminance area. Yet another reason may be that the required fixation duration is anticipated on previous fixations. In the study of Hooge et al. (in press) subjects may not have had a preview of the search element they were about to fixate. Accordingly, subjects may have had to little time to correctly adjust the fixation duration to the demands of the fixation task. Subjects in the current experiments might have estimated the time required to analyze an element before fixating it, because the element luminance may be acquired in the visual periphery. This creates on opportunity to anticipate the required fixation duration.

Search strategies

Coarse-to-fine

The coarse-to-fine strategy predicts that searchers first examine search areas that require little time per area to inspect. Subjects followed this strategy rather strictly. They started their search in the luminance strip with the highest target detectability (high luminance) only to continue in the other luminance strips after the high luminance strip was completely inspected. This strategy serves to find a target as fast as possible. Another finding may be also be related to the coarse-to-fine strategy: subjects made only few saccades between luminance strips. In both the horizontal and the vertical strips only 10% of the saccades were between strip saccades (if search were purely random, approximately 67% of the saccades would have been between strip saccades). Thus, the coarse-to-fine strategy is used rather coercively and leads to stereotyped search paths.

Subjects appear to have a bias to search areas with high target detectability first. This may not always be advantageous. Imagine what happens if two or more observers search for a target at the same time. As these searchers are able to search more search area per time unit, one would normally expect that targets are found faster then when there is only one searcher. However, this is under the assumption that these searchers search different parts of the search area. The present study shows that if target detectability varies as a function of position across the visual scene, observers search the same areas at the same time due to the coarse-to-fine strategy, which essentially eliminates the advantage of searching with multiple searchers. A way to anticipate that observers search coarse-to-fine could be, for example, to appoint different search areas to the searchers by instruction. Alternatively, biases due to coarse-to-fine search may be prevented by informing the searchers about the locations that are inspected by others (Zelinsky, Dickinson, Chen, Neider & Brennan, 2005).

The reading strategy

In other saccadic search studies in our lab, subjects often applied a ‘reading strategy’ (Hooge et al., 2004). In the reading strategy, the display is searched from left to right (and/or right to left) and from top to bottom (and/or bottom to top). In this experiment, we found evidence for this particular search strategy as well. Figure 5 shows separate frequency distributions of saccade directions in the uniform displays, the horizontal strip displays and the vertical strip displays. The bin-centers of distribution are the 6 directions where neighboring elements are located relative to the fixated element. In the uniform displays, saccades head in a horizontal direction most often and least often along the other directions which is clear evidence for the reading strategy. The distribution of saccade directions of saccades in the horizontal strip displays is almost identical to that of the uniform displays and therefore suggests that the same strategy has been applied. Search in the vertical strip displays differs from the other two kinds of displays. Here, there are more saccades in the other directions than in the horizontal strips. This may be because the coarse-to-fine strategy is such strictly applied that it overrides the reading strategy. However, the reading strategy is coercive too. Saccades in horizontal direction still outnumber saccades in other directions (though only slightly) and therefore indicate that subjects still searched

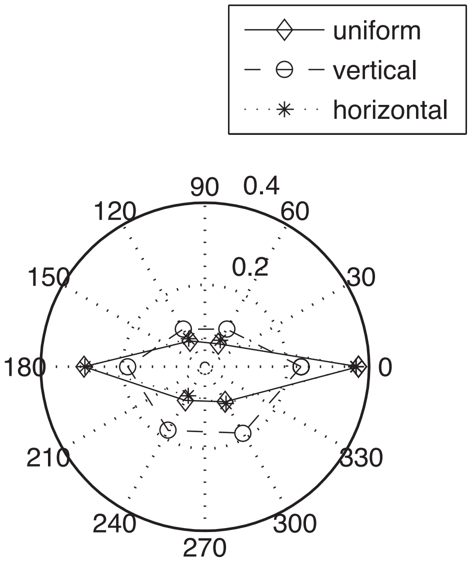

Figure 5. The relative frequency distribution of saccade directions in the three display types (uniform, vertical strips, horizontal strips). The data are binned around 6 directions. These are the directions at which neighboring elements are located, when an element is fixated.

row by row, even though the rows within a single element luminance only contained a few elements. Taking this section and the previous section together, the scan paths in the present search displays can be described by referring to just two strategies: the coarse-to-fine strategy and the reading strategy.

The advantage of making saccades in vertical direction

In the mixed displays, a surprising difference between search in the horizontal and vertical strip displays emerged on the search time. Subjects required less time to find the target in the vertical strip displays than in the horizontal strip displays. Since the fixation durations fixations lasted equally long in both displays types, the longer search times must be due to a higher number of. Why did subjects require fewer fixations in the vertical strip displays? It may be due to a lower number of fixations on previously inspected locations (refixations) and/or due to a larger number of elements inspected per fixation. Evidence in favor of this latter explanation comes from a comparison of the number of fixations in both display types after refixations have been removed: Fewer fixations were required in the vertical strip displays, in the target absent trials as well as in the target present trials (though significance was not reached in the target present trials). [target present: 22.54 fixations in the vertical strips and 26.35 in the horizontal strips, $F(1,2) = 6.520$, $p = 0.0631$; target absent: 46.24 fixations in the vertical strips and 51.85 in the horizontal strips

F(1,2)=10.415, p = 0.0321]. The shorter search times in the vertical strip displays were not due to differences in refixation frequencies [the number of refixations relative to the number of fixations in target present: 0.152 in the vertical strips, 0.149 in the horizontal strips, F(1,2) = 0.072, p = 0.8015; target absent: 0.222 in the vertical strips, 0.237 in the horizontal strips, F(1,2)=2.283, p = 0.2053].

Subjects inspected more elements per fixation in the vertical strips. Possibly crowding played a role here. Crowding refers to a reduced perceptibility of an item due to the presence of surrounding items (Bouma, 1970; Toet & Levi, 1992; Vlaskamp & Hooge, 2006). The degree of crowding has been shown to depend on the difference in element luminance between the target item and surrounding items. If the luminances of a target item and surrounding crowders differ, the degree of crowding is smaller than when they have the same luminance (Kooi, Toet, Tripathy & Levi, 1994). But why would searchers particularly benefit from this in the vertical displays? Information is mainly acquired in the direction the eye moves (Pollatsek, Raney, Lagasse & Rayner, 1993). As has been mentioned above, in the present displays, people have a strong tendency to make saccade along the horizontal direction. In the vertical strips, only three elements are horizontally aligned. When moving the eyes in a horizontal direction (which also is the direction from which most information is acquired), elements from a neighboring strip are situated on the peripheral side of the inspected elements (or no element at all). These elements evoke less crowding than when elements with the same luminance would have been there (importantly, elements on the peripheral side lead to stronger crowding then elements on the foveal side, Bouma, 1970). In the horizontal strips, subjects also searched in the horizontal direction. Yet, in this case elements from the same luminance are on the peripheral side of the inspected elements.

Conclusion

The present study was an explorative study meant to derive a description of search behavior. In this study, complex abstract search displays were deployed to come to a more complete description of search and eye movement strategies than would have been possible with simpler stimuli or with more ‘natural’ stimuli (such as pictures). This study revealed that search from the beginning until the end can be described by just two strategies: the coarse-to-fine strategy (Over et al., submitted) and the reading strategy (in which searchers mainly direct their eyes horizontally through the display). Maybe, the latter strategy particularly applies when search displays with regularly dispersed search elements are involved. Eye movement strategies (concerned with -short term- eye movement parameters settings) appear to be well describable by those strategies found in uniform displays. (e.g., Moffitt, 1980; Jacobs, 1986; Vlaskamp et al., 2005). This is because at each fixation a strategy appears to be chosen that is suited for the (immediate) demands of the fixation location. Moreover, searchers link with their eye movements locations in the search display that can be searched with the same eye movement strategy that was applied for the previously inspected location. Finally, we remark that the target conspicuity plays a determining role in the eye movement strategy that is chosen. We found that even though fixation duration dropped sharply with element luminance, saccade amplitude was not affected at all. Our explanation is that element luminance does not affect target conspicuity whereas target target detection is faster with higher luminances.

Nederlandse Samenvatting

Visuele waarneming is belangrijk voor mensen. Ze voorziet in informatie op basis waarvan mensen kunnen interacteren met de buitenwereld. Zo kunnen ze gedetailleerde visuele informatie uit de buitenwereld waarnemen. Maar, de visuele spatiële resolutie neemt af in de periferie. Toch kunnen mensen snel interessante plekken in het visuele veld bekijken met hoge resolutie door het centrum van het netvlies (de fovea) erop te richten met behulp van een oogbeweging. Oogbewegingen kunnen dus van belang zijn voor hetgeen mensen waarnemen. Er is ook een omgekeerde relatie tussen oogbewegingen en visuele perceptie: de verwerkte visuele informatie vormt een factor bij de beslissing wanneer en waarheen een oogbeweging te maken. Bij de visuele exploratie van de omgeving maken de ogen veelal snelle bewegingen die ook wel saccades genoemd worden [saccades bereiken pieksnelheden boven de 500°/s (Collewijn, Erkelens & Steinman, 1988)]. Saccades worden afgewisseld met periodes waarin een object of locatie wordt gefixeerd. Tijdens deze fixaties vindt opname van visuele informatie plaats.

De relatie tussen oogbewegingen en visuele perceptie is het onderwerp van dit proefschrift. Jacobs (1986) leverde een belangrijke bijdrage aan de studie hiernaar. Hij hypothetiseerde dat saccades direct afhangen van de spatiële limieten van de waarneming. Tijdens een fixatie kan slechts een beperkt gedeelte van het visuele veld met een gegeven nauwkeurigheid geïnspecteerd worden. Dit deel van het visuele veld wordt ook wel de 'visual span' genoemd (Jacobs, 1986) en ligt rondom het fixatiepunt. De grootte van de visual span wordt in het uiterste geval door de spatiële resolute van het netvlies beperkt. De 'direct control hypothesis' van Jacobs (1986) geeft een duidelijke voorspelling over de amplitude (= grootte) van een saccadische oogbeweging. Ze stelt dat de amplitude van een saccade direct gerelateerd is aan de grootte van de visual span. Over de fixatieduur doet deze hypothese geen expliciete voorspelling. De grootte van de visual span blijkt te variëren met visuele stimulus. Jacobs (1986) vond bijvoorbeeld in een zoektaak dat de visual span kleiner werd naarmate doel en distractoren meer op elkaar leken.

Door de jaren heen heeft onderzoek aangetoond dat de visual span een waardevol concept is om oogbewegingen te begrijpen. Zo is gebleken dat de amplitude van saccades inderdaad gerelateerd is aan de visual span grootte, hoewel deze relatie niet zeer strikt is. Jacobs (1986) zelf, bijvoorbeeld, vond in een zoekproef dat ongeveer 80% van de variantie in de saccade-amplitude verklaard kon worden door de grootte van de visual span. Ook andere onderzoekers vonden met verschillende technieken dat de saccade-amplitude varieert met de grootte van de visual span (bijv. Bertera & Rayner, 2000; Cornelissen, Bruin & Kooijman, 2005; Näsänen, Ojanpää & Kojo, 2001; Rayner & Fisher, 1987a, 1987b). De fixatieduur bleek minder eenduidig gerelateerd te zijn aan de visual span grootte. Er is gevonden dat met een grotere visual span de fixatieduur korter werd (bijv. Jacobs, 1986; Näsänen et al., 2001), maar er is ook gevonden dat de fixatieduur juist langer werd (bijv. Bertera & Rayner, 2000; Cornelissen et al., 2005).

Wat bepaalt de grootte van de visual span? Zoals gezegd wordt de grootte van de visual span in het uiterste geval gelimiteerd door de beschikbare spatiële resolutie in de visuele periferie. Jacobs (1986) en ook anderen (bijv. O'Regan, 1990) hebben een rol voor 'crowding' gesuggereerd. Crowding refereert naar een vermindering in de waarneembaarheid van een object doordat er andere objecten omheen staan (bijv. Bouma, 1970; Toet & Levi, 1992). Dit engelse woord is lastig te vertalen. Misschien is 'drukte' een woord waarvan de betekenis in de buurt komt. Ik kies er echter voor om crowding te gebruiken. Een goed voorbeeld van crowding wordt gegeven door Cavanagh (2001): een letter in een tekst op korte afstand van het gefixeerde woord is moeilijk te lezen. Dit heeft niet zozeer te maken met een gebrek aan spatiële resolutie. Stond de letter er geïsoleerd dan had het misschien wel herkend kunnen worden. Het zijn de letters die er omheen staan die de waarneming verstoren.

Crowding lijkt de grootte van de visual span te kunnen beperken. Afhankelijk van de omstandigheden kan crowding de waarneming van objecten over grote gebieden binnen het visuele veld verstoren. Dit wordt weergegeven in Bouma's wet (Bouma, 1970). Bouma vond dat de waarneembaarheid van een doelobject kan verminderen als een tweede object minder dan een half keer de eccentriciteit van het doelobject af staat (!). Dit betekent dat de waarneming over grote gebieden binnen het visuele veld verstoord kan zijn door crowding. Daarnaast betekent het ook dat het effect van crowding zich uitbreidt met toenemende retinale eccentriciteit van het doelobject en de distractoren. Met zulke gevolgen zou crowding de 'bottleneck' kunnen vormen op de eccentriciteit waarop objecten met een gegeven nauwkeurigheid kunnen worden waargenomen en zou daarmee dus invloed kunnen hebben op de grootte van de visual span.

Het is de vraag of een beperking van de visual span door crowding ook oogbewegingen beïnvloedt. Dit kan niet bepaald worden op basis van bestaande studies. De meeste studies met betrekking tot crowding hebben vooral tot doel gehad crowding te beschrijven en te begrijpen wat de processen zijn die tot crowding leiden (Bouma, 1970; Toet & Levi, 1992; He et al., 1996). Typisch is dat de rol van oogbewegingen niet wordt onderzocht door ervoor te zorgen dat de proefpersonen tijdens het experiment blijven kijken naar een zogenaamd fixatiepunt. Bij mijn weten is er weinig onderzoek gedaan naar de gevolgen van crowding voor (oogbewegings)gedrag (een voorbeeld is een recent onderzoek van Wertheim et al., in druk). Een reden hiervoor zou kunnen zijn dat het lastig is om de effecten van crowding te bestuderen wanneer er oogbewegingen gemaakt worden. Het is namelijk belangrijk de effecten van spatiële resolutie onder controle te hebben om te kunnen bepalen of de waarneembaarheid van objecten verstoord wordt door crowding. Deze controle vervalt wanneer proefpersonen oogbewegingen maken. Hoewel onderzoek moeilijk is, juist omdat er dan vele variabelen gecontrolleerd moeten worden, kiezen we er in deze dissertatie voor de proefpersoon vrij oogbewegingen te laten maken.

Studies die specifiek over de gevolgen van crowding voor oogbewegingen gaan zijn nodig omdat het onduidelijk is in hoeverre crowding de verwerking van visuele informatie blokkeert. Er zijn aanwijzingen dat visuele informatie die niet bewust wordt waargenomen doordat er crowding plaatsvindt, toch haar sporen nalaat in de hersenen (He, Cavanagh & Intriligator, 1996) en soms zelfs nog gebruikt kan worden (Ariely, 2001; Parkes, Lund, Angelucci, Solomon & Morgan, 2001). Het is echter niet bekend of en in hoeverre informatie die door crowding niet bewust wordt waargenomen de oogbewegingen beïnvloedt.

Wij hebben gekeken of en hoe oogbewegingen en crowding samenhangen. Om deze relatie te onderzoeken hebben we met name gebruik gemaakt van zoektaken. Een zoektaak is uitermate geschikt, omdat de afstemming tussen oogbewegingen en de waarneembaarheid van doelen een belangrijke rol speelt om een doel snel te kunnen vinden.

In hoofdstuk 2 wordt een indicatie geleverd voor het belang van crowding bij de verkenning van de visuele omgeving. De centrale vraag in dit onderzoek was of bij het zoeken naar een doel de afstand tussen elementen de zoekprestatie beïnvloedt. Uit de literatuur kan niet worden opgemaakt welk effect de afstand tussen elementen heeft op de oogbewegingstrategie (dat is de strategie die gehanteerd wordt voor de instelling van de fixatieduur en saccade amplitude). Een voorspelling is dat wanneer de afstand tussen elementen kleiner wordt er meer elementen per fixatie geanalyseerd kunnen worden en er derhalve minder fixaties nodig zijn om het doel te vinden. Wij hebben onderzocht of afstand tussen elementen van invloed is op de oogbewegingsstrategie en op de zoekprestatie (gemeten als de zoektijd per element). In het eerste experiment hebben we zowel de afstand tussen elementen gevarieerd (de afstand tussen elementen varieerde tussen 3.4° en 7.1°) als de gelijkheid tussen doel en distractoren. Met het verkleinen van de afstand tussen elementen werd ook de zoektijd per element korter. Dit effect was echter verrassend klein in vergelijking tot wat er gebeurde met de zoektijd per element als de distractoren meer op het doel leken. In het tweede experiment hebben we gekeken of de afstand tussen de zoekelementen ook weinig invloed heeft op de zoektijd per element bij nog kleinere afstanden tussen elementen. De afstanden tussen elementen varieerden tussen 0.8° en 3.2°. Voor afstanden tussen de 3.2° en de 1.5° vonden we geen verband tussen de zoektijd per element en de afstand tussen elementen. Alleen bij de afstanden tussen elementen die kleiner waren dan 1.5° vonden we dat de zoektijd per element veranderde.

Proefpersonen hadden meer tijd per element nodig naarmate de afstand tussen elementen kleiner werd. Onze verklaring voor de opmerkelijke vinding dat de zoektijd per element slechts in geringe mate afhankelijk is van de afstand tussen elementen, is dat het aantal elementen dat per fixatie geïnspecteerd wordt min of meer constant blijft doordat crowding de visual span grootte beperkt. Dit is als volgt te begrijpen: een verkleining van de afstand tussen elementen verhevigt de crowding. Maar, dit wordt weer teniet gedaan doordat bij een gegeven fixatie elementen dichterbij het fixatiepunt liggen.

In het derde hoofdstuk wordt het idee dat crowding implicaties heeft voor de prestaties en de oogbewegingen in een zoektaak verder onderzocht. De proefpersonen zochten naar een doel in een één-dimensionele horizontale ‘zoekstrip’ (elke trial bevatte een doel). Boven en onder deze zoekstrip waren extra elementen geplaatst. Deze ‘maskers’ maakten geen onderdeel uit van de set zoekelementen en derhalve kon geen van deze elementen het doel zijn. Er waren drie condities waarin maskers aanwezig waren. Per conditie verschilde de gelijkheid tussen maskers en het doel. Het is bekend dat crowding sterker wordt naarmate doel en maskers meer op elkaar lijken (Kooi et al., 1994; Nazir, 1992). In de vierde conditie waren er geen maskers rond de zoekstrip. Nadat in een apart zichtbaarheidsexperiment de crowdingmanipulatie gevalideerd was, hebben we het zoekexperiment uitgevoerd. Daarin vonden we dat met een toename van crowding de zoektijden tot 76% langer werden. Ook veranderden de oogbewegingen door de crowdingmanipulatie: het aantal fixaties en de fixatieduur namen toe met crowding terwijl de saccade amplitude afnam. De verlenging van de fixatieduur kan wijzen op een strategie waarbij met toenemende crowding een langere visuele analyse de inperking van de visual span grootte tegengaat. Wij concluderen op basis van deze gegevens dat om oogbewegingen te begrijpen bij een actieve verkenning van de visuele omgeving oogbewegingsonderzoekers rekening moeten houden met crowding.

In het vierde hoofdstuk wordt specifiek het effect van een zeer hoge elementdichtheid op de fixatieduur bestudeerd. In hoofdstuk twee vonden we namelijk bij de zeer hoge dichtheden (element afstanden < 1.5°) dat de fixatietijd sterk toenam bij verkleining van de afstand tussen elementen. Dit effect is ook gerapporteerd door Bertera & Rayner (2000). De vraag die we stelden was of de fixatieduur onder deze omstandigheden langer wordt doordat zoeken moeilijker (langere visuele analysetijd per element) is bij hogere dichtheden, of dat processen die gerelateerd zijn aan het genereren van oogbewegingen een rol spelen. In het eerste experiment dat beschreven is in dit hoofdstuk zochten de proefpersonen een doel temidden van vier elementen die een horizontaal ten opzichte van elkaar geplaatst waren op ruime onderlinge afstand (5.64°). In 50% van de trials was een doel aanwezig. De proefpersonen zochten van links naar rechts. Het tweede en derde element (van links) werden soms geflankeerd door vier elementen die niet relevant waren voor de zoektaak: geen van deze vier elementen kon het doel zijn en de proefpersonen wisten dat ook. Van de fixaties op het tweede element in de zoekstrip werden de tijden geanalyseerd. Dit element noemen we daarom het fixatie-element. Omdat proefpersonen vanaf dit fixatie-element een oogbeweging maakten naar het derde element, noemen we het derde element het saccadedoel. De fixatietijden van het fixatie-element werden gerelateerd aan of er irrelevante elementen aanwezig waren rondom het fixatie-element en/of rondom het saccadedoel. De plaatsing van de irrelevante elementen rondom het fixatie-element leidde tot een verlenging van de fixatietijd tot 95 ms. Verrassend was dat irrelevante elementen rondom het saccade doel de fixatietijd juist iets verkortten. In een tweede experiment werd de langere fixatietijd als gevolg van de taak-irrelevante elementen rondom het fixatie elementen onder de loep genomen. Dit experiment liet zien dat de tijd die nodig was voor de visuele analyse van een gefixeerd element verlengd werd met 55 ms. Wij concluderen dat de fixatieduur langer wordt als de dichtheid van de elementen in een zoekscherm hoger wordt omdat de visuele analysetijd van een element toeneemt naarmate aanpalende elementen dichterbij liggen. Daarnaast denken we ook dat door de elementen rondom een gefixeerd element de start van een saccade uitgesteld wordt door ‘foveale stimulatie’, zoals dat bekend is uit de literatuur over het ‘remote distracter’ effect (Walker et al., 1997) en het ‘gap-overlap’ paradigma (bijv. Fischer & Ramsperger, 1984).

De hoofdstukken 2 t/m 4 geven met name inzicht in hoe crowding het zoeken en de oogbewegingen beïnvloedt. In hoofdstuk 5 hebben we onderzocht of juist het maken van oogbewegingen een door crowding verslechterde waarneembaarheid van een doel beïnvloedt. Uiteraard ‘breken’ saccades de crowding door de fovea op een doel te richten. Wij onderzochten het effect van het voorbereiden van een saccade op de waarneembaarheid van een doel. Dit onderzoek was gebaseerd op de bevinding dat aandacht sterk aan het saccadedoel gekoppeld wordt tijdens de voorbereiding van een saccade (Deubel & Schneider, 1996). De taak die de proefpersonen uitvoerden bestond uit het discrimineren van een doel temidden van twee distractoren. Het doel en de distractoren stonden onder elkaar links of rechts van het fixatiepunt in het midden van het scherm en ze werden gepresenteerd gedurende 110 ms met 5 verschillende onderlinge afstanden. De presentatie van het doel en de distractoren werd voorafgegaan door maskers. Een ‘cue’ in het centrum van het scherm (op de fixatiepositie) gaf de positie aan waar het doel verscheen. Proefpersonen bleven de centrale cue tijdens de gehele trial fixeren of ze maakten een oogbeweging naar het doel (het doel was verdwenen voordat de saccade eindigde). We vonden dat het percentage correcte responsen significant hoger was als het doel gepresenteerd werd tijdens de preparatie van een saccade naar dat doel dan wanneer de proefpersoon moest blijven fixeren. Wij concluderen dat er een verwerkingsvoordeel is van het prepareren van een saccade naar een doelobject waarvan de waarneming door crowding verstoord is ten opzichte van de situatie dat er geen saccade naar gemaakt wordt. Dit kan verklaard worden door modellen die stellen dat crowding het gevolg is van een beperkte spatiële resolutie van aandacht (een resolutie die beperkter is dan het oplossend vermogen van de retina). Een voorbeeld van een dergelijk model is te vinden in Intriligator & Cavanagh (2001). Ook modellen die stellen dat aandacht een verwerkingsvoordeel oplevert onafhankelijk van crowding kunnen de resultaten verklaren. Het voorbereiden van een saccade zou dan ook tot een verwerkingsvoordeel leiden bij de waarneming van objecten die om een andere reden verminderd waarneembaar zijn (bijv. door een laag luminantiecontrast).

Het laatste hoofdstuk bestaat uit een exploratieve studie naar oogbewegingstrategieën. We onderscheidden twee soorten strategieën: (1) strategieën die binnen een tijdsbestek van één of enkele fixaties en saccades kunnen veranderen en samenhangen met de vereisten van de zoektaak tijdens die fixatie(s) (bijvoorbeeld de tijd die nodig is voor de analyse van de visuele informatie die verkregen is tijdens de fixatie); (2) strategieën die zich over een langere termijn uitstrekken (maximaal van begin van een zoektrial tot het einde) en het scanpad bepalen. Een voorbeeld van een dergelijke strategie is de ‘leesstrategie’ waarbij mensen van links naar rechts (of van rechts naar links) en van boven naar onder (of van onder naar boven) zoeken (Hooge et al., 2004). We hebben deze zoekstrategieën onderzocht in displays waarin we de detecteerdbaarheid van het doel manipuleerden door de luminantie van de zoekelementen (dus doel én distractoren) te variëren. De zoekschermen bestonden uit elementen met dezelfde luminantie (uniforme zoekschermen) of uit drie rechthoekige gebieden met elementen met een verschillende luminantie (gemengde zoekschermen). Deze gebieden waren horizontaal of verticaal georiënteerd. De vier belangrijkste vindingen waren: (1) De fixatieduur is korter naarmate de luminantie van de elementen hoger is, maar de saccade amplitude blijft hetzelfde (dit geldt zowel voor de uniforme als de gemengde zoekschermen). Op basis hiervan concluderen wij dat de element luminantie de opvallendheid van het doel niet beïnvloedt en dat de visuele analysetijd toeneemt met afnemende luminantie. (2) In de condities met de gemengde zoekschermen was er een sterke neiging eerst de hoge luminantie gebieden te doorzoeken. Dit komt overeen met een ‘coarse-to-fine’ strategie (bijv. Over et al., 2006). Het volgen van deze strategie leidt ertoe dat eerst de gemakkelijke delen (delen waar een doel sneller gevonden wordt) van een zoekscherm worden doorzocht en vervolgens de moeilijkere delen worden doorzocht. (3) Er werden vooral oogbewegingen gemaakt in een horizontale richting. Dit was zelfs zo bij gemengde zoekschermen met de verticaal georiënteerde gebieden (waar slechts korte sequenties van oogbewegingen met dezelfde instellingen gemaakt konden worden). (4) De proefpersonen vonden in de zoekschermen met verticaal georiënteerde gebieden de doelen sneller dan in de zoekschermen met de horizontaal georiënteerde gebieden. Een verklaring hiervoor is dat de proefpersonen minder last van crowding hadden in de zoekschermen met de verticale gebieden: in de richting waarin de ogen bewogen in de zoekschermen met de verticale gebieden hadden de elementen verschillende luminanties, dit in tegenstelling tot de zoekschermen met horizontale gebieden. Als er een verschil in luminantie is tussen objecten is er minder crowding (Kooi et al., 1994).

Conclusie

In de literatuur is een aantal maal op een mogelijke rol voor crowding in de aansturing van oogbewegingen gewezen (bijv. Jacobs, 1986; O'Regan, 1990). Crowding is vooral onderzocht met psychofysische methoden. Dit heeft beschrijvingen en modellen van crowding opgeleverd (bijv. Bouma, 1970; He et al., 1996; Toet & Levi, 1992). Drie 'crowdingregels' zijn in de loop van de tijd uitgekristalliseerd: crowding wordt sterker naarmate objecten dichter bij elkaar staan (bijv. Bouma, 1970; Toet & Levi, 1992), naarmate ze verder in de visuele periferie staan (Bouma, 1970; Toet & Levi, 1992) en naarmate ze meer op elkaar lijken (Kooi et al., 1994; Nazir, 1992). Het is echter nog de vraag of en hoe crowding het oogbewegingsgedrag beïnvloedt. Om hier inzicht in te krijgen kan niet alleen op de psychofysische metingen worden vertrouwd. De studies naar crowding zijn onder zeer gecontroleerde omstandigheden uitgevoerd (zonder dat oogbewegingen gemaakt mochten worden!) waarbij de drempels van waarneming opgezocht werden. In het dagelijks leven worden de drempelgebieden juist vaak vermeden. Wie steekt er nu een weg over met een kans van 99% om de overkant te halen? De oogbewegingsstudies in dit proefschrift onderzochten of de kennis over crowding uit de psychofysische studies een voorspellende waarde heeft voor oogbewegingen.

Om het oogbewegingsgedrag te bestuderen hebben we gebruik gemaakt van zoektaken. Zoeken is een dagelijkse activiteit voor mensen en zoektaken zijn daarom een goed model voor taken in de buitenwereld. Uit deze studies kwam naar voren dat crowding een beperkende factor vormt bij het visueel verkennnen van de buitenwereld en dat oogbewegingen gemaakt worden om over deze beperking heen te komen (dit is recent ook bevestigd door Wertheim et al., in press). We hebben de relatie tussen oogbewegingen en crowding in detail bestudeerd. Uit onze studies kunnen we afleiden dat de sterkte van crowding een specifiek effect heeft op de instelling van oogbewegingen: met een toename in de sterkte van crowding worden kleinere saccades gemaakt en wordt er langer gefixeerd. Dit sluit aan op de 'direct control' hypothese van Jacobs (1986). Volgens deze hypothese wordt bij het maken van oogbewegingen rekening gehouden met de omvang van het gebied waarbinnen tijdens een fixatie objecten met een bepaalde nauwkeurigheid kunnen worden waargenomen. Dit gebied (de visual span genoemd) wordt kleiner als de crowding toeneemt. In overeenstemming met deze hypothese vinden wij dat de saccade amplitude schaalt met de grootte van dit gebied. Daarnaast vinden we een verlenging van de fixatieduur, wat kan wijzen op een oogbewegingsstrategie waarbij de visuele analysetijd verlengd wordt om de inperking van de visual span grootte door crowding tegen te gaan. Crowding speelt dus een rol bij de beslissing wanneer en waarheen een oogbeweging te maken omdat het een bottleneck vormt op de eccentriciteit waarop doelen waargenomen kunnen worden. Op basis van de crowdingsregels kunnen daarom voorspellingen gemaakt worden over de fixatieduur en de saccade amplitude. De reikwijdte van de regels die opgaan voor crowding kan nu uitgebreid worden naar het oogbewegingsgedrag.

De crowdingregels komen voort uit psychofysische proeven waarin geen oogbewegingen worden gemaakt en toch blijken ze oogbewegingen goed te voorspellen. Betekent dit dat de nauwkeurigheid van de perifere waarneming gelijk is tijdens continue fixatie en fixatie tussen twee oogbewegingen in? Dit proefschrift toont aan dat er een verschil is. De prestatie bij het discrimineren van een object blijkt 10% hoger te liggen wanneer er een saccade gemaakt wordt al voordat het object gefixeerd wordt. Dit suggereert dat de grootte van de visual span zoals gemeten tijdens continue fixatie (Geisler & Chou, 1995; Jacobs, 1986; Vlaskamp & Hooge, 2006) een onderschatting is van de visual span grootte tijdens het zoeken met oogbewegingen.

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Curriculum Vitae

Björn Vlaskamp werd geboren op 24 oktober 1975 te Olst, Nederland. In 1994 behaalde hij zijn gymnasium diploma aan het Geert Groote College te Deventer. In datzelfde jaar verhuisde hij naar Utrecht om de studie Psychologie te volgen aan de Faculteit Sociale Wetenschappen van de Universiteit Utrecht. In 2001 studeerde hij af in de theoretische psychologie. Vanaf januari 2002 was hij werkzaam aan de capaciteitsgroep Psychonomie, Faculteit Sociale Wetenschappen van de Universiteit Utrecht, als promovendus onder begeleiding van co-promotor Dr. Ignace Hooge en promotor Prof. Dr. Frans Verstraten. Voor zijn promotie-onderzoek heeft hij drie maanden onderzoek gedaan in het laboratorium van Prof. Dr. Heiner Deubel (Department Psychologie, Ludwig-Maximilians-Universität) in München. Zijn promotie zal plaatsvinden op 4 april 2006. Daarna zal hij als post-doc gaan werken in het laboratorium van Prof. Dr. Marty Banks aan de University of California, Berkeley.

Björn Vlaskamp was born in Olst, the Netherlands, on October 24, 1975. In 1994 he obtained his advanced high school diploma (gymnasium) from Geert Groote College, Deventer. In that same year, he moved to Utrecht to study psychology at the Faculty of Social Sciences at Utrecht University, where he completed his theoretical psychology degree in 2001. In January, 2002, he began work as a PhD candidate with the Psychonomics Department, part of the Faculty of Social Sciences at Utrecht University, under the supervision of Dr. Ignace Hooge and Prof. Dr. Frans Verstraten. For his doctoral research he spent three months in Munich working in a laboratory under Prof. Dr. Heiner Deubel in the Department of Psychology at the Ludwig-Maximilians-Universität. His doctoral defense will take place on the 4th of April, 2006, after which he shall begin work as a post-doc under Prof. Dr. Marty Banks at the University of California, Berkeley.

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