



Saccade Target Selection and Object Recognition: Evidence for a Common Attentional Mechanism

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The spatial interaction of visual attention and saccadic eye movements was investigated in a dual-task paradigm that required a target-directed saccade in combination with a letter discrimination task. Subjects had to saccade to locations within horizontal letter strings left and right of a central fixation cross. The performance in discriminating between the symbols “E” and “3”, presented tachistoscopically before the saccade within the surrounding distractors was taken as a measure of visual attention. The data show that visual discrimination is best when discrimination stimulus and saccade target refer to the same object; discrimination at neighboring items is close to chance level. Also, it is not possible, in spite of prior knowledge of discrimination target position, to direct attention to the discrimination target while saccading to a spatially close saccade target. The data strongly argue for an obligatory and selective coupling of saccade programming and visual attention to one common target object. The results favor a model in which a single attentional mechanism selects objects for perceptual processing and recognition, and also provides the information necessary for motor action. Copyright © 1996 Elsevier Science Ltd.

Eye movements Saccade Visual attention Perception Object recognition Discrimination
 Obligatory coupling

INTRODUCTION

When we inspect a visual scene, periods of fixation are interrupted by fast ballistic movements of the eyes, the saccades. By means of these goal-directed eye movements, the fovea is brought to “interesting spots” of the scene. For instance, a common observation is that when a subject views the picture of a person, the nose and mouth are fixated more often and first in sequence compared to other objects of the picture, such as spots on the cheek. There is general agreement that the basic function of the saccades is foveation, necessary because adequate object recognition normally requires foveal representation of the to-be-recognized object.

Except for artificial laboratory situations, our visual environment normally provides a wealth of potential saccade targets. Therefore, as an important element of the goal-directedness of saccadic eye movements, a selection process is required that selectively delivers the spatial coordinates of the intended target object. The question we address here is how this saccadic landing point is

selected. Some authors have suggested that visual attention fulfils this function (e.g., Henderson, 1992; Schneider, 1995).

Unfortunately, there is no general agreement on how visual attention should be conceptualized in information processing terms. A minimal definition is that visual attention achieves the prioritized processing of certain pieces of visual information. How this is accomplished is the subject of a number of competing theories (e.g., Treisman, 1988; LaBerge & Brown, 1989; Wolfe & Cave, 1990; Van der Heijden, 1992—see Schneider, 1993 for an overview). At least, there is some consensus about experimental measures of prioritized processing. These are usually reaction time differences of speeded responses (e.g., Eriksen & Hoffman, 1972a; Posner, 1980) or accuracy differences in verbal report (e.g., Eriksen & Hoffman, 1972b; Müller & Rabbitt, 1989)—for a recent overview of data on both measures, see van der Heijden (1992). The standard result is that reactions upon attended objects or locations are faster, and that accuracy of reporting certain attributes of these objects is higher as compared to objects that are not attended.

Is visual attention—as reflected in these reaction time and accuracy differences—identical to the process which selects the saccade target? Alternatively, the process of saccade target selection may represent a mechanism separate from the visual attention mechanism. Since the late 1970s, several investigators have tried to tackle this

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important question (Posner, 1980; Klein, 1980; Remington, 1980; Shepherd *et al.*, 1986; Crawford & Müller, 1992; Reuter-Lorenz & Fendrich, 1992; Kowler *et al.*, 1995; Hoffman & Subramaniam, 1995). Shepherd *et al.* (1986) eliminated some of the methodological problems of the early investigations. They combined a simple detection task with a saccade task; reaction time served as the attentional measure. Their subjects had to saccade to one of two boxes left or right from the fixation point indicated by a central arrow. Shortly before or after the saccade, a second stimulus appeared in one of these boxes. Upon detection, the subject had to react as fast as possible with a key press. The manual reaction time was shorter when saccade target location and the location of the target for the manual reaction coincided, as compared to the condition where saccade target and manual reaction target appeared in opposite hemifields. Hoffman & Subramaniam (1995) used a dual task paradigm where subjects had to saccade to a specified location and to detect a target letter. The letter was briefly presented at one of four possible locations well before the eye movement. Detection performance was best when saccade target and letter target location were identical compared to conditions of differing locations. Kowler *et al.* (1995) also combined a letter identification with an eye movement task. Again, perceptual performance was best when the saccade was directed towards the to-be-identified letter.

These results suggest that the mechanisms for prioritized visual processing and saccade programming are spatially coupled. An important question refers to the spatial selectivity of this coupling. Since Shepherd *et al.* (1986) manipulated saccade target and manual reaction target between hemifields, their data were not conclusive about whether the performance advantage concerned only the specific target locations or the hemifield as a whole. Kowler and colleagues' (1995) two subjects had to report one out of eight letters presented in a circular array. The superior performance to the letter where the eye was directed shows that attentional selectivity can be at least specific to an octant of the visual field.

The assumption of a common attentional mechanism implies that the programming of a saccade and the attentional focusing on the target cannot be dissociated. Alternatively, it might be possible that two selection mechanisms exist that are usually, but not necessarily coupled. For scene inspection, it should indeed make sense to allocate visual attention to locations where the saccade will be directed, since these locations normally contain objects of interest worth receiving some prioritized processing. On the other hand, for specific tasks it might well be possible to direct visual attention to one location, while preparing a saccade to another. The results of Shepherd *et al.* (1986), Hoffman & Subramaniam (1995) and Kowler *et al.* (1995) have provided the first evidence that a decoupling of visual attention and saccade target selection is not possible.

Here we investigate the questions put forward above. First, to what extent is the coupling between visual

attention and saccades specific to the target location? Second, is the coupling obligatory or optional? We present a new dual-task paradigm where a target-directed saccade was combined with a discrimination task as the attentional measure. A central cue indicated a saccade target (ST) consisting of one of the items of two horizontal strings of letters that were present to the left and to the right of the central fixation point. After the cue appeared but well before the eye movement, a discrimination target (DT) was presented for a short time interval within the item string on the side where the saccade was directed to. In Experiment 1, the positions of ST and DT were varied independently within the string. If visual attention and saccade can be controlled independently, discrimination performance should not depend on the location of the ST. On the other hand, if both selection processes are coupled, then discrimination should be best when ST and DT refer to the same location as compared to conditions with non-coincident locations. Experiment 2 was designed to investigate whether the coupling between attention and saccade programming is obligatory. Here, the DT location was *always* the central item of the string. If coupling of attention and saccade control were optional, the subjects should have been able to program the saccade to the indicated location, while simultaneously directing visual attention to the central location in order to achieve optimal performance.

Our experimental paradigm was introduced in Deubel & Schneider (1992) and further elaborated in Schneider & Deubel (1995). In these studies saccades were directed by peripheral cues, however, providing results similar to those presented here for central, symbolic cues.

GENERAL METHODS

Subjects

Five subjects aged 20–32 yr participated in the experiments. All had normal vision and were experienced in a variety of experiments related to oculomotor research, but were naïve with respect to the aim of the study. Each subject performed four sessions of each of the experiments; a session consisted of 216 single trials.

Experimental set-up

The subject was seated in a dimly illuminated room. The visual stimuli were presented on a fast 21" color monitor (CONRAC 7550 C21) providing a frame frequency of 100 Hz at a spatial resolution of 1024 × 768 pixels. Active screen size was 40 × 30 cm; the viewing distance was 80 cm. The video signals were generated by a freely programmable graphics board (Kontron KONTRAST 8000), controlled by a PC via the TIGA (Texas Instruments Graphics Adapter) interface. The stimuli appeared on a grey background which was adjusted to a mean luminance of 2.2 cd/m². The luminance of the stimuli was 25 cd/m². The relatively high background brightness is essential for avoiding the effects of phosphor persistence. In a physical measurement of luminance decay by means of a linear PIN diode,

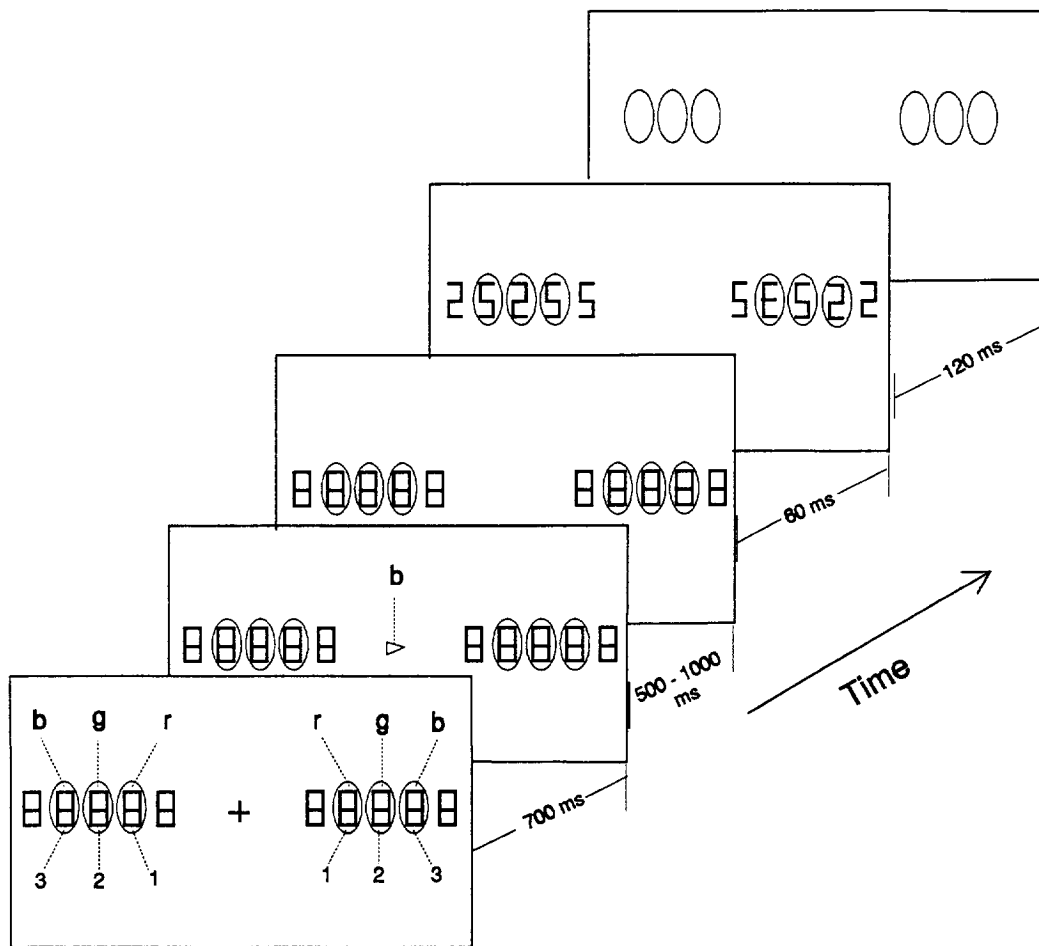


FIGURE 1. Stimulus sequence with symbolic cuing (Experiment 1). First, the subject fixates a central cross for 700 msec, viewing letter strings to the left and to the right of fixation. The three central items in each string (numbered consecutively 1–3) appear on colored ellipses of red, green, and blue (indicated by r, g, and b in the figure). After a waiting time of 700 msec, a central cue consisting of a colored triangle appears indicating saccade target position. Thus, when the cue is blue pointing to the right as in the figure, the saccade has to be directed to the item at position 3 in the right string. The subject is instructed to prepare to saccade to the item thus indicated, but to release the saccade only after offset of the central cue occurring 500–1000 msec later. After another delay of 60 msec, the discrimination target and the masks are presented for 120 msec. Both disappear before the onset of the saccade. Thus, when the eye movement finally occurs, only the colored ellipses remain visible. Finally, the subject has to indicate the identity of the discrimination target.

we verified that the target luminance decayed to subthreshold values within less than 20 msec (Wolf & Deubel, 1993). In order to further exclude the possibility that persistence effects allow for target discrimination after the saccade, we performed a pilot study in which dark stimuli were used on a bright background. The results were identical.

Eye movements were recorded with a SRI Generation 5.5 Dual-Purkinje-image eyetracker (Crane & Steele, 1985) and sampled at 400 Hz. The device projects a focused infrared light source into the eye, and tracks both the first Purkinje image (the reflection from the front surface of the cornea) and the fourth Purkinje image (the reflection from the back surface of the lens). As the eye rotates, the first Purkinje image moves in the same direction as the eye, while the fourth image, from the concave surface of the back of the lens, moves in the direction opposite the eye (relative to the optical axis). Thus, coincident movement of both images indicates

head motion, while the difference between the two image motions indicates eye rotation. Special purpose servo-mechanics allow a frequency response better than 250 Hz and a noise level equivalent to about 20 arc sec rms (Crane & Steele, 1985). Unlike earlier eye trackers, the fifth generation device can follow saccadic movements of 15 deg or more without losing the eye.

Head movements were restricted by a biteboard and a forehead rest. The experiment was completely controlled by a 486 Personal Computer. The PC also served for the automatic off-line analysis of the eye movement data in which saccadic latencies and saccade start and end positions were determined.

Calibration and data analysis

Each session started with a calibration procedure in which the subject had to sequentially fixate 10 positions arranged on a circular array of 6 deg radius. The tracker behaved linearly within 8 deg around the central fixation.

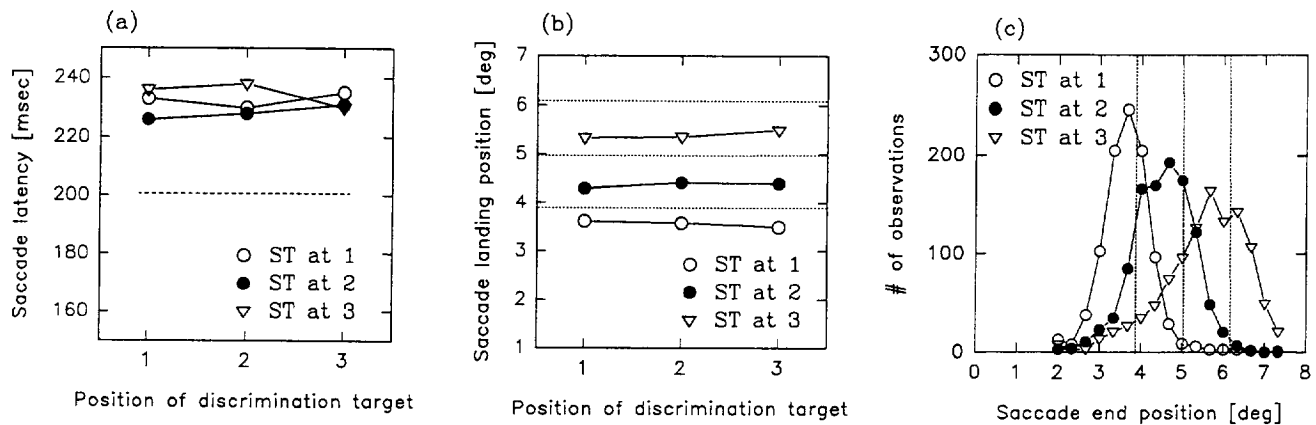


FIGURE 2. Experiment 1: (a) Saccadic latency as a function of discrimination target (DT) position, given separately for saccades directed to one of the three saccade target (ST) positions. The horizontal dashed line indicates saccadic latency in the “No discrimination–saccade only” control condition. (b) Mean saccadic landing positions. The horizontal dashed lines indicate the respective ST positions. (c) Distribution of saccadic landing positions for the various ST positions.

Overall accuracy of the eyetracker for static fixation positions was better than 0.1 deg. Dynamically, however, the eyetracker records considerable artifactual overshoots of the eye at the end of each saccade, due to the movement of the eye lens relative to the optical axis of the eye (Deubel & Bridgeman, 1995). In order to determine veridical direction of gaze, an off-line program for the evaluation of saccade parameters searched the saccade record for the end of the overshoot and then calculated eye position as a mean over a 40 msec time window.

EXPERIMENT 1. SACCADE CONTROL AND VISUAL ATTENTION: OBJECT-SPECIFIC COUPLING?

Experiment 1 was designed to analyze the nature of the coupling between saccades and visual attention. The saccade was guided by a central, symbolic cue that indicated the saccade target (ST) within a string of letters. The subject had to report the identity of a discrimination target (DT) presented tachistoscopically in the string before the eye movement.

Procedure

A block of 216 experimental trials for which the experimental conditions were selected at random followed the calibration procedure. Figure 1 shows an example for the sequence of stimuli in a single trial. Each trial started with the presentation of a small fixation cross in the center of the screen, with a size of 0.15 deg. Simultaneously, two strings of premask characters appeared left and right of the central fixation, each consisting of five “E”. The width of each item was 0.52 deg of visual angle, its height was 1.05 deg. The distance between the items was 1.09 deg, with the central item of the five letters being presented at an eccentricity of 5 deg. The three central items of each letter string appeared on ellipses of red, green, and blue color, as indicated in the figure. In the following graphs presenting the experimental data, these positions will be numbered consecu-

tively as position 1, 2, and 3, respectively. Color intensities were adjusted by flicker-photometry to appear about equally salient.

Initially, the subject fixated a central fixation cross. After a delay of 700 msec, a central, symbolic cue in the form of a red green or blue triangle appeared in the center of the screen and pointed either to the right or to the left side. Thus, color and pointing direction of the triangle unequivocally indicated a specific item, the saccade target (ST), within the string. The subject was asked to saccade to this target item, but only upon disappearance of the central triangle, which occurred after a further delay selected randomly between 500 and 1000 msec. This time is sufficient to complete the programming of the saccade to the ST object. Thus, disappearance of the central cue served as the “Go”-signal for the prepared saccade. Sixty milliseconds after triangle disappearance, the premask characters changed into nine distractors and one discrimination target. The distractors were randomly selected among “E” and “S”. One of the three central items on the side indicated by the cue was replaced by the DT which was either “E” or “S”. The positions of ST and DT were varied independently within the string; all experimental conditions occurred with equal probability. Thus, the cue provided a valid indication of the side where the DT would appear, but was neutral as to the position of DT within the string. The target and distractors remained visible for 120 msec. Then, the items were removed and only the colored ellipses remained. Consequently, the discrimination target was no longer available 180 msec after the “Go”-signal. As a result of this stimulus timing most saccades were initiated well after the disappearance of target and distractors. In order to eliminate occasional responses that occurred too early, the off-line data analysis discarded saccades with latencies shorter than 180 msec. Also, in this and the following experiments, trials with primary saccades smaller than 2 deg were not considered in the analysis. This occurred in less than 4% of trials.

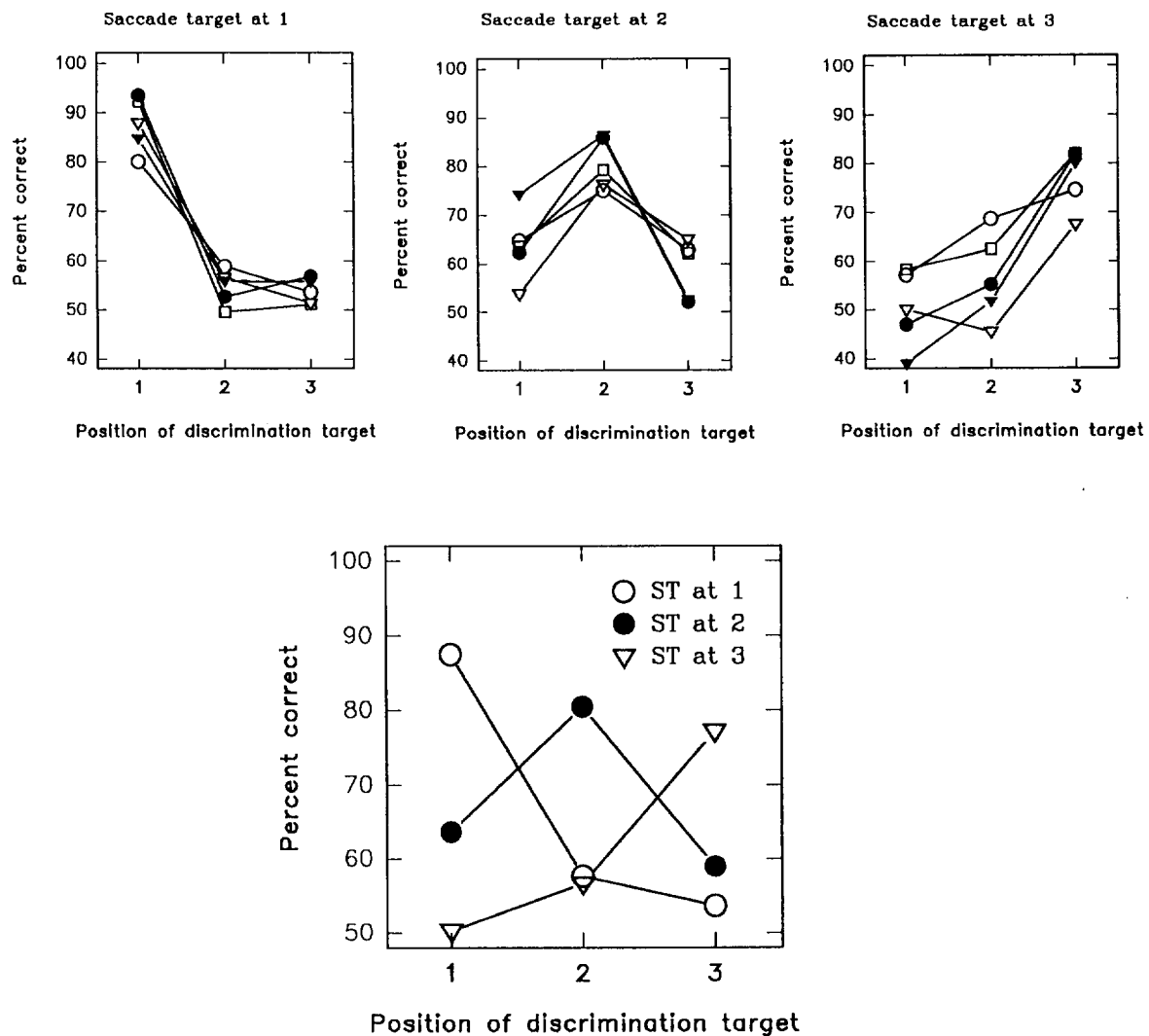


FIGURE 3. Experiment 1. Top row: Discrimination performance for each of the five subjects as a function of DT position, given for the saccade cued to ST positions 1, 2, and 3, respectively. Performance is best when ST and DT positions coincide. The lower panel summarizes the data for all five subjects.

After the saccade the subject had to indicate, without time pressure, the identity of the discrimination target (“E” or “Э”) by pressing one of two buttons [two-alternative forced choice (2AFC)-task]. The central fixation cross reappeared after the subject’s decision and the next trial was initiated by the computer.

A control task (“No discrimination–saccade only” single task condition) served to discern saccadic reaction times in a single task situation. For this purpose, the subject was asked to saccade to the ST, but was not required to discriminate. Each subject performed three sessions of this control task.

Results and discussion

The subjects reported that they had no difficulties in saccading quickly to the indicated target item in the string. However, they were initially very uncertain about their ability to discriminate between the DT items. Performance improved considerably after some practice. Therefore, the first session served for training and was not included in the data analysis. After the experiment, the

subjects were asked for their subjective impression and for how they solved the task. They reported that the peripheral items that were indicated as saccade targets seemed to “light up” in a row of an almost unstructured visual field. Also, they had the impression that they could exactly identify the distractor (“Э” or “Е”) when it appeared at the intended saccade target position. Interestingly, some subjects were surprised to hear that the discrimination stimulus had disappeared before they moved their eyes; rather, they had the subjective feeling that they were “on target” when the test stimulus was presented.

One central rationale of the experimental approach was that the discrimination task should not interfere in a specific way with the saccade task. An analysis of saccadic latencies and amplitudes suggests that this is indeed the case. Figure 2 provides latencies and amplitudes of the saccadic responses, pooled over the five subjects. Figure 2(a) shows mean saccadic latency (defined as the time between central cue offset and saccade onset) as a function of the position of the

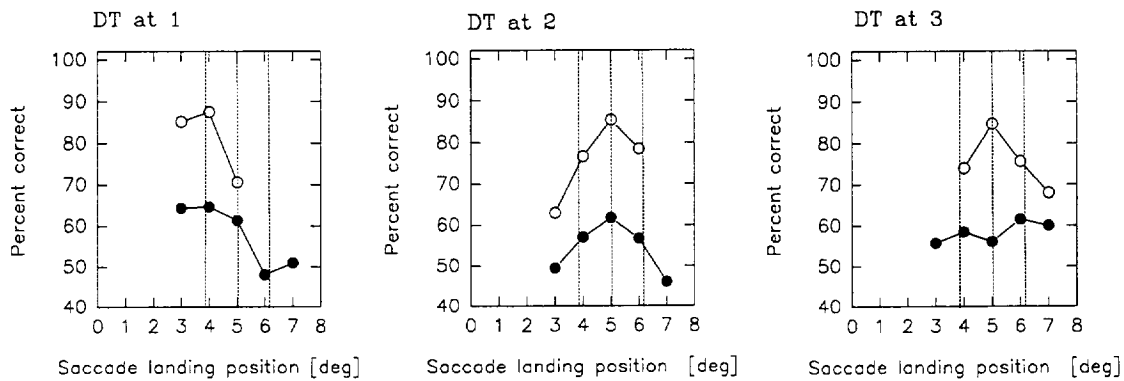


FIGURE 4. Experiment 1: Discrimination performance as a function of the actual saccade landing positions, given separately for the cases when DT and ST coincided (open circles), and when ST and DT positions differed (solid circles). The data are presented for the three DT positions in separate diagrams. Bin width is 1 deg; only data including more than eight reactions per bin are shown.

discrimination target. Saccadic latency is found to be independent of DT position ($F(2,8) = 4.18$; $P > 0.05$) and of ST position ($F(2,8) = 0.19$); the interaction is also non-significant ($F(4,16) = 0.65$). The overall mean latency is 225.5 msec. The dotted horizontal line indicates mean saccadic latency in the “No discrimination–saccade only” control task, which was 201 msec.

Figure 2(b) presents saccadic amplitudes as a function of DT position. Obviously, the subjects follow the symbolic instruction about the to-be-foveated target with reasonably high accuracy. The saccadic responses exhibit an undershooting to the instructed target of 10–15% of target eccentricity. It is important to note that the saccadic amplitudes are independent of the position of the discrimination stimulus ($F(2,8) = 0.74$) but dependent on ST position—as required by instruction ($F(2,8) = 49.48$; $P < 0.001$). Again, the interaction was non-significant ($F(4,16) = 0.76$).

Figure 2(c) presents the distribution of saccadic landing positions in the item string. The data reveal standard deviations of 0.81, 1.21, and 1.41 deg for ST1, ST2 and ST3, respectively, with a tendency for a negatively skewed distribution for the more peripheral targets.

Secondary corrective saccades followed on 64% of all trials. Analysis of the amplitudes and directions of these follow-up saccades revealed that they are indeed corrective in the sense that they bring the eye, on average, to the indicated saccade target position. We found no indication that secondary saccades were directed to the location of the discrimination target, when DT and ST positions differed. We attribute this to the fact that DT was no longer present when the programming of the corrective saccades occurred.

Our indicator for the momentary allocation of attention is the accuracy with which the test items can be identified. The subjects performed the key press to indicate target identity when their gaze was already on the cued location. On average, they responded 697 msec after their primary saccade; manual reaction time showed

large interindividual and intertrial differences. The three diagrams in the upper row of Fig. 3 show discrimination performance separately for the five subjects who participated in this experiment, measured as percent correct decisions, and given as a function of DT position. The graphs give the data for the saccade cued to the inner, central and outer of the three possible target positions, which are indicated as position 1, 2, and 3 in the graph, respectively (see also Fig. 1). It is immediately obvious that the subjects’ performance consistently depends on the relation between position of the discrimination stimulus and the location of the indicated saccade target position. Performance is by far best when ST and DT positions coincide. When the saccade is not directed to the test item, performance decreases steeply, sometimes hardly exceeding chance level (50%). Superimposed on this pattern is a tendency for discrimination performance to deteriorate for the more peripheral DT position (DT3) as compared to the more foveal one (DT1).

The lower panel of Fig. 3 summarizes the data for all subjects. For ST1, discrimination performance is close to perfect (89%) when the test item is presented at the ST location, but drops to 58% and finally to chance level for DT2 and DT3, respectively. This amazing difficulty identifying non-saccade target items is also obvious in the cases where the test item is located more foveally than the saccade target. So, when the saccade is directed to the central item (ST2), discrimination accuracy drops from 80.5 to 63.7% with DT2 and DT1 being tested. ANOVA shows a highly significant interaction between ST and DT positions ($F(4,16) = 32.45$; $P < 0.001$). Furthermore, discrimination performance does not depend on ST position ($F(2,8) = 3.54$; $P > 0.05$) but, to some degree, on DT position ($F(2,8) = 8.01$; $P < 0.02$).

The question arises whether best discrimination performance is (spatially) linked to the *actual* landing position of the eye or, rather, to the *instructed* saccade target position. The relatively broad distributions of the saccade amplitudes, as shown in Fig. 2(c), allowed for a dissociation of these two aspects. Figure 4 provides

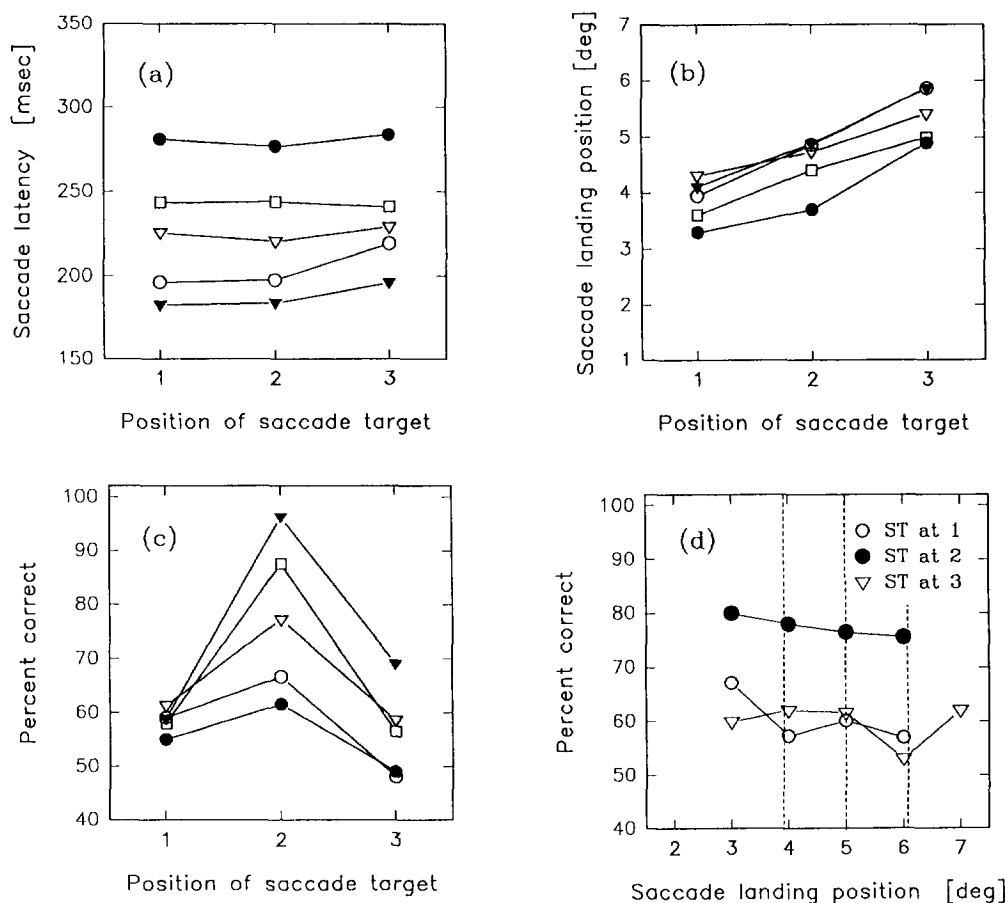


FIGURE 5. Experiment 2: DT always at position 2. (a) Mean saccadic latency as a function of ST position, given separately for the five subjects. (b) Mean saccadic landing positions for the five subjects. (c) Discrimination performance as a function of saccade target position. (d) Discrimination performance as a function of actual saccade landing position, averaged over the subjects. Only data including more than eight reactions per bin are shown. Parameter is the indicated saccade target position. The vertical dashed lines display the various ST positions.

discrimination performance as a function of the actual saccadic landing positions, given separately for the cases when DT and ST coincided (open circles) and when ST and DT positions differed (solid circles). The data are presented for the three DT positions in separate diagrams. For cases DT1 and DT2 the data indeed suggest that performance is slightly improved when the eye lands on the test item. A two-factorial ANOVA was performed in which the first factor determined whether ST was equal to DT, and the second factor was whether the eye landed on the amplitude bin before, at, or after DT position. The analysis reveals a non-significant effect of landing position ($F(2,8) = 0.22$, $P > 0.05$). More interestingly, however, Fig. 4 shows that the effect of the *instructed* target position clearly prevails over the *actual* landing position: the curves for the cases where ST and DT differed are consistently below the open symbols where ST and DT coincided. This means that, even in cases where the eye actually lands precisely on the DT position, performance is strongly deteriorated when this position is different from the instructed ST position. Accordingly, ANOVA revealed a highly significant effect of the

second factor, that is ST/DT coincidence ($F(1,4) = 113$). Interaction was non-significant ($F(2,8) = 1.3$, $P > 0.05$).

In summary, the preparation of a saccade entails that during eye movement programming—and before saccade execution—discrimination and recognition capabilities are selectively coupled to the object to be foveated by the saccade. They are, however, to some degree independent of the actual landing position of the saccade.

EXPERIMENT 2. SACCADE CONTROL AND VISUAL ATTENTION: OBLIGATORY COUPLING?

A central question concerning the relationship of saccades and visual attention is to what extent this coupling is obligatory, i.e., whether subjects are indeed unable to move their eyes to one location while attending to another. In normal scene inspection, visual attention and saccadic programming may be coupled, but under certain conditions, e.g. with a high incentive, decoupling might nevertheless be possible. For the previous experiment it might be argued that the exact DT position was not known in advance, and, therefore, it might be difficult to find the DT within the brief presentation time. In order to allow optimal conditions for decoupling of visual

attention and saccade control, we then provided subjects with complete advance knowledge about DT position.

Procedure

The experiment was identical to Experiment 1, but instead the DT always appeared at the central position of the string, on the side indicated by the cue. The subjects were accordingly informed so that they could infer the future location of DT from the direction indicated by the cue. This advance information about DT position creates an optimal condition for decoupling, possibly allowing the saccade to be programmed while the location of the future DT can be attended. The waiting time of 500–1000 msec before the “Go”-signal (the offset of the central arrow) should provide sufficient time for completing these processes.

Results and discussion

Figure 5 presents the experimental results. The basic parameters of the saccadic responses were very similar to Experiment 1. Mean saccadic latency was 227.6 msec [Fig. 5(a)]. Analysis of variance proved saccadic latencies to be dependent on ST position ($F(2,6) = 7.32$; $P < 0.03$). Mean saccade magnitudes were 3.85, 4.51 and 5.34 deg for ST 1–3, respectively [Fig. 5(b)]. ANOVA proves these differences to be significant ($F(2,6) = 19.6$; $P < 0.01$).

The dependence of discrimination performance on indicated saccade target position is shown in Fig. 5(c), again separately for the five subjects. Although subjects differ in their overall performance level, it is obvious that preknowledge about test stimulus position (DT 2) does not improve performance when this position is not the cued saccade target location: the discrimination rate is still far superior when DT and ST coincide, and drops drastically at the adjacent positions. The differences are significant ($F(2,6) = 11.6$; $P < 0.01$). This demonstrates that discrimination performance is here again strictly limited to the object indicated as the saccade target. In consequence, we conclude that the subject is not able to allocate attention to the central item while saccading to one of the adjacent objects.

Finally, Fig. 5(d) analyzes discrimination performance as a function of the actual landing positions of the saccade. As in the previous experiment, performance depends on the coincidence of ST and DT position, but is largely independent of the actual landing position of the eye.

GENERAL DISCUSSION

Summary of main results

The central finding of this study is that the capability for object recognition is tightly limited to the intended saccade target position, producing best performance when the eye is directed to the object that has to be identified. Discrimination performance declines steeply when ST and DT refer to items at different locations. This also holds when, as in Experiment 2, the subject knows in

advance where in the string the DT will appear. These results clearly argue against the decoupling hypothesis, i.e., the ability to direct visual attention to one location while simultaneously preparing a saccade to another location. Instead, the results suggest that both processes are strictly coupled, both temporally and spatially. Moreover, the attentional allocation is found to focus on the *intended* saccade target object rather than on the precise location that is finally going to be foveated with the saccade. Taken together, the results provide evidence for the coupling of saccade target selection and visual attention in the form of prioritized visual processing.

In the following discussion, we will first identify distinct properties of our experimental approach that might be of importance to understand the findings. Then, the results will be discussed in relation to various previous reports. Finally, theoretical implications on the role of visual selective attention in saccade target selection will be discussed.

Extant properties of the experimental paradigm

Our dual-task paradigm meets a number of requirements that we deem important for investigating the relationship between visual attention and saccade target selection. As a measure of attentional focusing, we believe that it is important to use a 2AFC discrimination task instead of the frequently applied reaction time paradigms. A reaction time paradigm requires the subject to prepare and execute a manual response nearly simultaneously with the saccade, which entails the possibility of additional motor- or response-related interferences. These effects, known as the psychological refractory period (PRP, for an overview see Pashler, 1993), arise when the interval between two motor reactions (such as manual key press and saccade) is short. A frequent observation is that the second reaction is then delayed as compared to conditions of a single reaction or a long interval. Wolf *et al.* (1984) and Pashler *et al.* (1993) have demonstrated PRP effects for certain combinations of manual key press reactions and saccades. Accordingly, PRP effects could potentially mask effects of the coupling between visual attention and saccades. Indications for unusually prolonged saccadic and manual responses can indeed be found in comparable paradigms in the literature (e.g., in Shepherd *et al.*, 1986).

Our paradigm used a short-term presentation of a target-distractor string in combination with a forward mask. Such an experimental approach is assumed to limit the visual processing to about the time of stimulus presentation and allows access to the momentary content of the attentional focus. In a reaction time paradigm with continuous stimulus presentation, on the other hand, reaction time may also reflect the time required to shift attention from item to item until the target is found. However, our paradigm allows us to determine the momentary focus of attention, while providing only a minor possibility of shifting attention between the items.

Further, before test stimulus presentation, we wanted to provide a prestructured field of objects. This is

important for several reasons. First, it is known that the sudden appearance of an item in an empty field can automatically attract attention (Jonides, 1981; Yantis & Jonides, 1984). The disappearance of features that occurs when switching from the premask to the target and distractors, on the other hand, is known not to have such a strong 'automatic' attentional effect (e.g., Yantis & Jonides, 1984). Also, the short-term presentation of the discrimination target should not *per se* attract attention (and thus interfere with the saccade target selection process). For this reason, the same amount of transient change (removing two lines) was applied for the target element, as well as for all distractor elements. Furthermore, it was important that the targets did not "pop out" from the distractors because of figural reasons, which would again entail an automatic attraction of attention to the discrimination target. Comparable approaches were used by Cheal & Lyon (1988) and Nakayama & Mackeben (1989).

Finally, the timing of the stimulus sequence assured that the discrimination targets had disappeared before the eye could start to move. In order to maintain stable oculomotor reaction throughout the sessions, the subject received postsaccadic feedback about the target location. Ideally, saccadic programming itself should not be affected by the perceptual test of visual attention. Our data show that this is only partly the case: amplitudes and latencies are independent of DT position, but shorter latencies are found for the "No discrimination-saccade only" task, suggesting that the discrimination task exerts a nonspecific influence on saccade programming.

Spatial selectivity: Object-specific focusing of attention

Our results demonstrate that discrimination performance during saccade preparation is essentially restricted to the intended saccade target location. The amount of spatial selectivity reflected in our data is indeed surprising. We assume that this selectivity reflects the current spatial location of the visual attention mechanism. The underlying assumption is that recognition of an object presupposes selective attentional allocation to that object (see, e.g., LaBerge & Brown, 1989; Schneider, 1995); in other words, only attended objects can be discriminated and recognized. The fact that spatial selectivity becomes so obvious in our experiments is probably due to the brief presentation time of the stimuli that may prevent additional attentional shifts. Investigations using reaction paradigms where attentional shifts cannot be excluded, therefore, often reveal a rather broad gradient of attentional effects as the result of peripheral cuing (e.g., Downing & Pinker, 1985).

The coupling of visual attention and saccade target selection is obligatory

The data of Experiment 2 reveal that the coupling of attention and saccade target selection is obligatory. Subjects had ample time to prepare the saccade to the indicated ST object, while allocating visual attention to the DT object. Nevertheless, discrimination is accurate

only when DT coincides with ST, demonstrating that it is not possible to keep or direct attention on an object while performing a target-directed saccade to another location. This is in line with the findings of Shepherd *et al.* (1986), Hoffman & Subramaniam (1995), and Kowler *et al.* (1995). Shepherd *et al.* (1986) demonstrated that directing a saccade to one hemifield and performing a manual reaction to an object in the opposite hemifield generated substantial costs for both actions, reflected in prolonged saccade latencies and manual reaction times. In contrast to our experimental approach, Hoffman & Subramaniam (1995) held the saccade target location constant within a block, but varied the probable location of the discrimination target which appeared with a likelihood of 80% at the position indicated by a central cue. Discrimination performance was always best when saccade target and discrimination target coincided, no matter where the cue directed attention. Kowler *et al.* (1995) (Experiment 2) presented a circular array of eight letters for 200 msec, together with a central pointer indicating the letter to which the saccade was required. Then masking stimuli appeared for 500 msec. At the end of the trial, a letter Q was presented at one of the eight display locations, and the subject had to report the letter that had appeared in that location. In the first type of task (Random report), the location of the target letter was unpredictable. The main result was that perceptual performance was accurate only at the goal of the saccade, being at chance at other locations, which is in close correspondence to our data. However, since the "Q" was provided long after the disappearance of the test stimulus, accurate performance would have required the subject to memorize eight letters and their locations for more than 500 msec, a task that is probably beyond the encoding limits of short-term memory. Therefore, the subjects could have adopted the strategy to limit processing and memorizing to the letter at the saccade target position. In the second type of task (Fixed report), the subjects knew in advance the location of the letter to be identified. Here, discrimination performance improved dramatically for all saccade locations, while saccade latency increased by 50–75 msec. This indicates that subjects preparing a saccade to one location have to prolong latency when they are also required to identify a letter at a different location. In agreement with our data, these findings suggest that the locus of attention cannot be easily dissociated from the saccade goal.

The hypothesis of a strict coupling seems to contradict the observation that primates can shift visual attention without moving the eyes (e.g. Eriksen & Hoffman, 1972a, b; Posner, 1980). Along with the suggestion by Rizzolatti *et al.* (1987) we think that the strict coupling holds for the preparation and programming of the saccade but does not necessarily require, or entail, overt initiation of the saccade. Therefore, in cases where visual attention but not the eye moves, we assume that the spatial parameters for the potential saccade are available and provided by the attentional mechanism, but that the saccade is prevented from being converted into overt

action owing to the missing release of a fixation signal (Munoz & Wurtz, 1992; Hoffman & Subramaniam, 1995).

As shown in both experiments, the intended saccade target, rather than the actual saccadic landing position receives attentional care. This may imply that, while the target is precisely selected from the non-target distractors by means of an attentional selection process, the coordinates provided by the attentional mechanism are not exactly transformed into the appropriate saccade commands, leaving the systematic saccadic undershooting and endpoint variance. We therefore assume that the relatively broad distribution of saccade landing position around the intended target object is mainly due to postattentional low-level motor noise, possibly entering the system only at the level of the brainstem saccade generator. Nevertheless, it is possible that attentional shifts to DT prior to the saccade occurred in a few trials, leading to corresponding shifts of the saccade landing point.

Visual attention and saccade programming: theoretical implications

Our data suggest a close coupling between visual attention on the one hand and saccade programming on the other. This coupling will be discussed in relation to current theoretical suggestions.

Rizzolatti *et al.* (1987) proposed the “premotor hypothesis” of the relationship between visual attention and saccade control. The underlying assumption is that attentional shifts to a stimulus are made on the basis of eye movement programs to that location; therefore, every attention shift is necessarily preceded by an eye movement program. Whether the eyes actually move or not depends on a “Go”-signal for releasing the program into execution. A straightforward application of the premotor hypothesis to our experimental situation is to assume that the eye movement programming keeps visual attention on the ST location and prevents it from a shift to the DT location. Since the premotor hypothesis does not specify the perceptual effects of attention, however, it cannot predict the spatially highly specific discrimination capability at the intended saccade landing point (see below).

Fischer & Weber (1993) made the claim that the occurrence of fast saccades is contingent upon the *disengagement* of attention. In other words, when saccades occur, visual attention must not be engaged at a specific location in the visual field, neither at the fixation point nor at the future target location. This is in contrast to the claims of Henderson (1992), Schneider (1995) and the present experimental data that all stress the function of presaccadic attentional *engagement* for selecting the saccade target location. Unfortunately, Fischer and colleagues have not yet presented direct experimental evidence for their claim of attentional disengagement. Further, the disengagement hypothesis cannot account for the spatially highly selective coupling found in our data.

Henderson (1992) claims that visual attention has to be allocated to the future saccade target location for the eye to move to this location. Visual attention itself is defined as “the selective use of information from one region of the visual field at the expense of other regions of the visual field” (Henderson, 1992; p. 260). Adding the assumption that recognition capabilities depend on attentional allocation, a strict coupling of object recognition and saccade programming can indeed be predicted.

Schneider (1995) has recently proposed a neurocognitive model for functions and mechanisms of visual attention in the primate brain, called VAM—“Visual Attention Model”. Two functions of a common visual attention mechanism are postulated, namely selection-for-object-recognition (e.g., LaBerge & Brown, 1989) and selection-for-action (e.g., Allport, 1987). More precisely, the main functions of this mechanism are to select information from an object for space-based motor actions—computed within the dorsal “where”-pathway areas (e.g., posterior parietal cortex)—and to select information from the same object for visually based and “capacity-limited” object recognition—computed within the ventral “what”-pathway (e.g., inferior temporal cortex). In other words, whenever visual attention is allocated to an object, this object can be recognized and its spatial parameters are computed for eventual motor actions such as saccades, grasping etc. In contrast to the premotor theory, saccade programming is a *consequence* of attentional allocation and not its antecedent. Furthermore, in contrast to other attentional theories, not only can “where”-based information of the dorsal pathway be utilized in controlling the allocation of attention (e.g. van der Heijden, 1992), but also “what”-based information of the ventral pathway. In short, VAM suggests a shift in the theoretical treatment of the relationship between saccades and visual attention. Following this model, the question is not how visual attention and saccades are related, but whether there exists a common selection mechanism, visual attention, for saccades and for object recognition (and other “what”-based capabilities). Our data suggest a positive answer.

Neurophysiological correlates for the coupling of attention and saccades

Further evidence for the close coupling between saccades and object recognition comes from recent neurophysiological data by Chelazzi *et al.* (1993). These authors trained awake macaque monkeys to saccade to a target object among several distractor objects. Simultaneously, the activation of cells within the inferior temporal cortex was recorded. The inferior temporal areas are commonly assumed to be the neural sites for object recognition processes (e.g., Desimone & Ungerleider, 1989; Tanaka, 1993). The data show that 90–120 msec before saccade onset, most cells that represent distractor objects reduce their firing rates, almost down to the level of spontaneous activation. Simultaneously, the cells representing the saccade target increase their firing up to a maximum level. Thus, saccade target selection

and object recognition seem to be closely coupled at the neural level.

REFERENCES

- Allport, D. A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In Heuer, H. & Sanders, A. F. (Eds), *Perspectives on perception and action* (pp. 395–419). Hillsdale, NJ: Lawrence Erlbaum.
- Cheal, M. & Lyon, D. R. (1988). Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology*, *43A* (4), 859–880.
- Chelazzi, L., Miller, E. K., Duncan, J. & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, *363*, 345–347.
- Crane, H. D. & Steele, C. M. (1985). Generation-V dual-Purkinje-image eyetracker. *Applied Optics*, *24*, 527–537.
- Crawford, T. D. & Müller, H. J. (1992). Spatial and temporal effects of spatial attention on human saccadic eye movements. *Vision Research*, *32*, 293–304.
- Desimone, R. & Ungerleider, L. G. (1989). Neural mechanisms of visual processing in monkeys. In Boller, F. & Grafman, J. (Eds), *Handbook of neuropsychology* (Vol. 2, pp. 267–299). New York, NY: Elsevier Science Publishers B.V. (Biomedical Division).
- Deubel, H. & Bridgeman, B. (1995). Fourth Purkinje image signals reveal eye lens deviations and retinal image distortions during saccades. *Vision Research*, *35*, 529–538.
- Deubel, H. & Schneider, W. X. (1992). Spatial and temporal relationship of saccadic eye movements and attentional orienting. *Perception*, *21*, Suppl., 106.
- Downing, C. J. & Pinker, S. (1985). The spatial structure of visual attention. In Posner, M. I. & Martin, O. S. M. (Eds), *Attention and performance*, *XI* (pp. 171–187). Hillsdale, N.J.: Lawrence Erlbaum.
- Eriksen, C. W. & Hoffman, J. E. (1972a). Temporal and spatial characteristics of selective encoding from visual displays. *Perception and Psychophysics*, *12*, 201–204.
- Eriksen, C. W. & Hoffman, J. E. (1972b). Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception and Psychophysics*, *11*, 169–171.
- Fischer, B. & Weber, H. (1993). Express saccades and visual attention. *Behavioral and Brain Sciences*, *16*, 553–610.
- Henderson, J. M. (1992). Visual attention and eye movement control during reading and picture viewing. In Rayner, K. (Ed.), *Eye movements and visual cognition* (pp. 261–283). Berlin: Springer.
- Hoffman, J. E. & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception and Psychophysics*, *57*, 787–795.
- Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In Lomng, J. & Badderly, A. (Eds), *Attention and performance IX*. Hillsdale, NJ: Lawrence Erlbaum.
- Klein, R. (1980). Does oculomotor readiness mediate cognitive control of visual attention? In Nickerson, R. (Ed.), *Attention and performance*, *VIII* (pp. 259–276). Hillsdale, NJ: Lawrence Erlbaum.
- Kowler, E., Anderson, E., Doshier, B. & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*, 1897–1916.
- LaBerge, D. & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review*, *96*, 101–124.
- Müller, H. J. & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315–330.
- Munoz, D. P. & Wurtz, R. H. (1992). Role of the rostral superior colliculus in active visual fixation and execution of express saccades. *Journal of Neurophysiology*, *67*, 1000–1002.
- Nakayama, K. & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.
- Pashler, H. (1993). Dual-task interference and elementary mental mechanisms. In Meyer, D.E. & Kornblum, S. (Eds), *Attention and performance XIV* (pp. 245–264). Cambridge, MA: MIT Press.
- Pashler, H., Carrier M. & Hoffman, J. E. (1993). Saccadic eye movements and dual task interference. *Quarterly Journal of Experimental Psychology*, *46A*, 51–82.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.
- Remington, R. W. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *6*, 726–744.
- Reuter-Lorenz, P. A. & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral cues. *Perception and Psychophysics*, *52*, 336–344.
- Rizzolatti, G., Riggio, L., Dascola, I. & Umiltà, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*, 31–40.
- Schneider, W. X. (1993). Space-based visual attention models and object selection: Constraints, problems, and possible solutions. *Psychological Research*, *56*, 35–43.
- Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition and space-based motor actions. *Visual Cognition*, *2*, 331–376.
- Schneider, W. X. & Deubel, H. (1995). Visual attention and saccadic eye movements: Evidence for obligatory and selective spatial coupling. In Findlay, J. M., Kentridge, R. W. & Walker, R. (Eds), *Eye movement research: Mechanisms, processes and applications* (pp. 317–324). Amsterdam: Elsevier.
- Shepherd, M., Findlay, J. M. & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology*, *38A*, 475–491.
- Tanaka, K. (1993). Neuronal mechanisms of object recognition. *Science*, *262*, 685–688.
- Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology*, *40*, 201–237.
- van der Heijden, A. H. C. (1992). *Selective attention in vision*. London: Routledge.
- Wolf, W. & Deubel, H. (1993). Enhanced vision with saccadic eye movements: An artefact due to phosphor persistence of display screens? In *Proceedings of the 15th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 1383–1384). New York: IEEE.
- Wolf, W., Deubel, H. & Hauske, G. (1984). Interaction between saccadic and manual reactions. *Investigative Ophthalmology and Visual Sciences*, *25*, Suppl., 262.
- Wolfe, J. M. & Cave, K. R. (1990). Deploying visual attention: The guided search model. In Blake, A. & Troscianko, T. (Eds), *AI and the eye* (pp. 79–103). New York: John Wiley and Sons.
- Yantis, S. & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Psychophysics*, *10*, 601–620.

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