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Independent contributions of the orienting of attention, fixation offset and bilateral stimulation on human saccadic latencies

Abstract In a series of experiments we examined the effects of the endogenous orienting of visual attention on human saccade latency. Three separate manipulations were performed: the orienting of visual attention, the prior offset of fixation (gap paradigm) and the bilateral presentation of saccade targets. Each of these manipulations was shown to make an independent contribution to saccade latency. In experiments 1 and 2 subjects were instructed to orient their attention covertly to a location by a verbal pre-cue; targets could appear in the attended hemifield (valid) or in the non-attended hemifield (invalid) together with a no-instruction (neutral) condition. Saccades were made under fixation gap and overlap conditions, to either single targets or two bilaterally presented targets which appeared at equal and opposite eccentricities in both hemifields. The results showed a large increase (cost) of saccade latency to invalid targets and a small non-significant decrease (benefit) of saccade latency to valid targets. The cost associated with invalid targets replicates the "meridian crossing effect" shown in manual reaction time experiments and is consistent with the hemifield inhibition and premotor models of attentional orienting. The use of a "gap" procedure produced a generalised facilitation of saccade latency, which was not modified by the prior orienting of visual attention. The magnitude of the gap effect was similar for saccades made to attended and non-attended stimulis. This suggests that the gap effect may be due to ocular motor disengagement, or a warning signal effect, rather than to the prior disengagement of visual attention. When two targets were presented simultaneously, one in each hemifield, saccade latency was slowed compared with the single target condition. The magnitude of this slowing was unaffected by the prior orienting of visual attention or by the fixation condition. The slowing was examined in more detail in experiment 3, by presenting targets with brief offset delays. The latency increase was maximal if the two targets were presented simultaneously and decreased if the distractor appeared at short intervals (20–80 ms) before or after the saccade target onset. If the non-attended stimulus was presented at greater intervals (160, 240 ms) before the saccade target, then a facilitation effect was observed. This demonstrates that the onset of a distractor in the non-attended hemifield can have both an inhibitory and a facilitatory effect on a saccade production.

Key words Eye movements · Saccade · Attention Gap effect · Human

Introduction

One of the most well-defined attributes of the human attentional system is its capacity to select a part of the total stimulus information potentially available from the environment. In the visual modality, one way in which this selection is achieved uses *overt* movements of the eyes to direct the gaze at a particular location. It has been recognised at least since the time of Helmholtz that a second, *covert*, form of selective attention is also possible even when the eyes are held still. Instructions to attend to a part of the visual field away from the point of fixation can be demonstrated to have behavioural consequences. Following such instructions, stimuli that appear in the attended region are responded to more rapidly than those in non-attended regions (Posner 1980) and are in general more efficiently perceived (Eriksen and Hoffman 1972; Eriksen 1990).

It is generally believed that, although the covert and overt attentional processes can operate separately, they are not totally independent. For example Shepherd et al. (1986) showed that, immediately before a voluntary saccadic eye movement towards a particular location in the visual field, subjects made faster detection responses to targets in this region, when the most likely target location coincided with the direction in which the saccade was cued. When the saccade direction was opposite to

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the direction in which attention was cued, it was found that saccade preparation dominated and responses were faster for probes in non-attended locations that coincided with the desired saccade direction. This suggests that preparing to move the eyes involves a shift of attention to a location and that it is not possible to orient attention in a direction opposite to that in which a saccade is prepared, indicating a link between the eye – attentional orienting systems. Such a suggestion had been made earlier (Klein 1980; Remington 1980), but, on the basis of somewhat complex experimental paradigms, both these workers had argued for dissociation between the processes of covert and overt attention (see also Klein et al. 1992).

More recently, Rizzolatti et al. (1987) have proposed a specific "premotor hypothesis" in which covert attentional orienting and overt attentional orienting are strictly linked. They suggest that covert orienting involves the preparatory stages of saccade generation with the execution of the movement being withheld. Support for their theory came from a manual reaction time (RT) experiment. In this experiment, targets could occur in four possible positions and the fastest responses were found when the target appeared at the cued location (*valid* trials). *Invalid* trials with the target occurring in other positions than the cued position elicited slower responses. Targets in the opposite hemifield to the cue elicited much slower responses (about 45 ms slower than on valid trials) than those obtained when an invalid target was presented in the attended hemifield (about 20 ms slower than valid trials). A similar extra cost was found for invalid targets across either the horizontal or the vertical meridian. This pattern has been termed the "meridian crossing effect".

Rizzolatti et al. (1987) interpreted the meridian crossing effect as reflecting the extra time required to cancel an existing motor program, plus the time required to prepare to make a motor response in a different direction. However, an alternative explanation of the meridian crossing effect has been proposed by Hughes and Zimba (1985) which makes no reference to oculomotor programming. In this *hemifield inhibition* model it is suggested that directing attention to a location in one hemifield produces a broad area of inhibition over the whole of the non-attended hemifield. This produces a pattern of small (often non-significant) benefits for targets in the attended hemifield and large costs for targets in the non-attended hemifield. Hughes and Zimba (1987) obtained experimental results showing that the meridian effect is obtained with crossings of both the vertical and the horizontal meridian, thus suggesting that the inhibitory effect of directed visual attention is distributed in terms of the visual quadrants.

The hemifield inhibition and premotor theories of attentional orienting both predict a cost when attention is cued to one hemifield and the target appears in the opposite hemifield. However, the predictions may be different for targets presented on an axis that does not pass through the central fixation point. Consider for example the case when targets are presented along a horizontal axis located some degrees above fixation. Attention is oriented to one quadrant (e.g. upper left) and targets can appear in either the upper left, or the upper right, quadrants. According to the hemifield inhibition model, directing attention to the upper left quadrant should produce equal levels of inhibition throughout the upper right quadrant. The cost obtained for an attentional crossing to a target presented in the upper right quadrant should be similar to that shown when targets are presented on a horizontal axis level with fixation. The premotor model accounts for the cost of a shift into the non-attended hemifield as being due to a cancellation of the saccade direction programme. Work on saccade programming discussed in the next paragraph suggests that a complete reprogramming may not be required when the direction of a saccade undergoes a small change from an upper left to upper right location, even though the horizontal component of the eye movement is different in the two cases. If a complete reprogramming is not required then a reduction in the size of the meridian crossing effect will be observed in comparison with that on the horizontal axis level with fixation.

The critical question concerns the extent of reprogramming required to make a small change in saccade direction. Some models of saccade generation (Becker and Jürgens 1979; Findlay 1983; Abrams and Jonides 1988) have suggested that the direction component of a saccadic response is separately programmed from the exact distance (amplitude). However, these models have been based on results from saccades along the principal axes only. When saccades in oblique directions are considered, more support is found for a model in which saccades are programmed by activating a broad region of a two-dimensional spatial map. Findlay and Harris (1984) carried out a double-step tracking experiment. In one condition, the second target position was in the opposite hemifield to the first target position, but both positions were displaced vertically from the original fixation point. Under these circumstances, saccades were often directed to intermediate positions with normal latencies, rather than the delay and reprogramming pattern found in cases where the two positions straddle the fixation point on the horizontal meridian. Similar results were found by Aslin and Shea (1987). Additionally, Ottes et al. (1984) showed that delays could occur when the two steps were both on the same axis in the same hemifield but with a wide spatial separation. This supports models of saccade programming where saccade direction is not programmed in a separate stage (Findlay 1987, 1992; Van Gisbergen et al. 1987; Becker 1989).

If attentional effects are closely related to oculomotor programming, then similar effects should be evident when eye movements are measured, to those obtained with manual RT's. Such an approach was recently adopted by Crawford and Müller (1992). Crawford and Müller failed to obtain the meridian crossing effect with manual reaction times following prior attentional orienting. However, they used peripheral cueing in which the cue

indicating where to direct attention is actually presented at the target location. As Umiltá et al. (1991) pointed out, a complication may occur with peripheral cueing because of a form of 'inhibition of return' resulting from the need to abort oculomotor responses potentially evoked by the cue. Reuter-Lorenz and Fendrich (1992) showed that when peripheral cues were used to orient attention there was no effect of the vertical meridian on saccade latency or manual reaction times. Central cues did produce the meridian effect with both manual and saccadic responses. Further dissociations were observed between manual reaction times and saccade latencies with peripheral cues, which suggests that the link between the attentional orienting system and the saccadic system is only apparent when central cueing procedures are used. In this study we examine the effect of central cueing of attention on saccade latencies, extending earlier studies (Posner et al. 1978; Michard et al. 1974).

In the present paper, we re-examine the relationship between oculomotor programming and attention in the light of recent developments in our understanding of saccade programming. We present three experiments employing the standard procedure of requiring subjects to respond to targets presented in the visual periphery, but measure a saccadic, rather than a manual, response. We used a *central cueing* procedure, whereby attention was oriented by a verbal instruction. This may be expected to operate on the sustained orienting system comparable with a central arrow or digit cue, with the advantage that it does not require cognitive interpretation on every trial (Tassinari et al. 1987). The premotor hypothesis implies that the latency to saccade to a peripheral target would be affected by attentional instructions in exactly the same way as the latency to make a manual response. The effects of the prior orienting of visual attention on saccade latency is the first manipulation considered in the present study. The importance of targets located away from the principal axes in distinguishing between different theoretical predictions has been discussed above. Consequently we have also used an *upper-axis* condition in which targets are all on a horizontal axis located above the fixation point.

We have been particularly concerned with the interaction of attention produced by voluntary instructions with two other manipulations which are known to modify the latency of saccades to visual targets. The first of these has been termed the "gap effect" and was first demonstrated by Saslow (1967). A subject is asked to fixate a point until a peripheral visual target appears and then make an eye movement to the target as rapidly as possible. The latency of the saccade measured from the instant of target appearance, may be substantially reduced if the fixation point is extinguished before the onset of the saccade target, leaving a gap with no stimulation. The effect is optimal with gaps in the 100- to 200-ms range and results in reliable latency decreases of as much as 80 ms. Saslow did not suggest an attentional interpretation of this finding. However, more recently Fischer and Breitmeyer (1987) have used the terminology introduced by Posner et al. (1984) to suggest that the result occurs because the gap allows time for attention to be "disengaged" from the fixation point. It has also been suggested that a part of the speeding obtained by fixation offset is due to a warning signal effect that enables some aspects of the saccade program to be partially completed before the target onset (Ross and Ross 1980, 1981), and the alternative explanations have recently received much discussion (Fischer and Weber 1993 and commentaries). The gap effect forms the second attentional manipulation of the current investigation. We were particularly interested to examine whether the gap effect could be modified by prior attentional instructions. If the gap effect works by disengagement of attention, then it might be expected that prior instructions to attend elsewhere could reduce or eliminate the effect.

The third effect occurs with *bilateral presentation* of saccade targets. This term indicates the situation where two targets appear simultaneously on opposite sides of the fixation point. Lévy-Schoen and Blanc-Garin (1974) found that even when subjects are given instructions which allow them to saccade to either target, bilateral presentation results in saccades whose latencies are increased by about 30–40 ms in comparison with single targets. A similar latency increase was found by Findlay (1983) in a rapid, automatic step tracking task. A simple explanation of the slowing observed with bilateral simultaneous targets is that it is due to a conflict in the choice of saccade direction. A saccade can be made to either of the two targets so an extra decision process is required to select one instead of the other. If this is the case then the slowing should not be observed when attention is cued in one direction, as the saccade direction is then pre-specified by the attentional instruction. This possibility is examined by presenting blocks of unilateral single and bilateral simultaneous targets, in both attentional and neutral trials.

In the three following experiments, we confirm the previously found effects of these manipulations on saccadic reaction times. We also show that neither the decrease in latency produced by the presence of a gap nor the increase produced with bilateral presentation is substantially modified by the instruction to attend voluntarily to a specific peripheral region. Thus all three effects contribute independently to the saccade latency.

Experiment 1: directing attention covertly on the horizontal axis, in a gap and overlap condition

Materials and methods

Subjects

Six undergraduate students (three male, three female) from the Psychology department at Durham University participated in the study. All had normal or corrected-to-normal vision.

Apparatus

The subject viewed a VDU monitor at a distance of 50 cm. A chin rest was used to maintain a stable head position and was adjusted so that the subjects' eyes were level with the central fixation point. Stimuli were generated using a BBC microcomputer. Eye movements were recorded using the Skalar IRIS infrared limbus reflection device (described by Reulen et al. 1988). The analogue signal from the eye movement recorder was sampled at 5-ms intervals and digitised by an Apple Macintosh II computer with a National Instruments interface. Sampling of the analogue signal started as the saccade target was presented on the VDU and was synchronised with a signal sent from the BBC microcomputer to the Macintosh. Sampling stopped 500 ms later and the digital record was saved for later off-line analysis. Saccades were detected by a semiautomatic program, which detected the start of a saccade using a velocity criterion of 30°/s across two consecutive samples. Each record was also examined individually and, if it was distorted by blinks or other artefacts, could be aborted; any saccades incorrectly detected by the algorithm could be adjusted by hand. The resulting saccade latencies were saved for later analysis.

The stimulus display (modified from that of Findlay et al. 1993) consisted initially of a fixation cross (0.57°) located at the centre of the screen. The saccade target appeared at a fixed interval of 1000 ms after the onset of the fixation cross. The target could occur at any of four positions, at 5.5° or 9.5° eccentricities left or right of fixation. The saccade targets were outline squares of 0.57° visual angle formed by illuminated single pixels around the border of a square. The saccade target was presented for 100 ms. After a further 100-ms delay, an indicator stimulus then appeared at the target location for a further 300 ms. The indicator was identical to the saccade target except that it contained either one or two small dots (1 or 2 pixels) inside its border. On bilateral target trials the indicators on each side were different. Subjects were required to discriminate between 1-pixel and 2-pixel displays and report by using a hand-held button box. This discrimination required foveation, thus ensuring that the subject made saccades to the target location as quickly as possible, and also helped maintain the subjects' interest in the task. The discrimination responses were nor further analysed. Following the indicator display, the display reverted to the empty target box. The stimulus presentation sequence is shown in Fig. 1.

Procedure

Subjects were tested under three experimental conditions, run in separate testing blocks: overlap, +100–ms gap and overlap-upper axis. In the overlap condition the fixation cross remained on throughout the trial and saccade targets were presented on the horizontal axis, level with the fixation cross. In the +100-ms gap conditions the fixation point went off 100 ms before the onset of the saccade target. Targets were again presented level with fixation on the horizontal axis. In the overlap-upper axis condition the fixation

point remained on throughout, but targets were presented on the horizontal axis 5° above fixation in the upper visual field.

Each experimental condition (overlap, +100-ms gap and overlap-upper axis) contained 84 unilateral left targets, 84 unilateral right targets and 84 bilateral simultaneous targets, giving a total of 252 trials in each condition. On unilateral single target trials, a saccade target appeared at one of the two eccentricity locations, left or right of fixation. On bilateral simultaneous target trials two targets appeared simultaneously at equal and opposite eccentricities left and right of fixation. The order of presentation of unilateral left, unilateral right and bilateral targets was randomised throughout each block.

Each subject completed three blocks of trials (neutral, attend left, attend right) for each of the three experimental conditions (overlap, +100-ms gap and overlap-upper axis), producing a total of nine blocks of 84 trials each in total. The order of presentation of these blocks was randomised and counterbalanced across subjects. In each block, one-third of trials were left single targets, one-third were right single targets and one-third were bilateral targets. In the neutral (no attentional instructions) blocks the subjects were instructed to saccade to the target when it appeared and then to report the number of dots observed in the indicator stimulus. When bilateral targets were presented in the neutral blocks, subjects were free to saccade to either one of the targets. In the attend left/right blocks of trials, subjects were instructed to direct their attention covertly, to either the left- or right-sided target locations. The direction of attention remained constant throughout the block.

The instructions given to the subject were:

Please try to keep your head as still as possible on the chin rest and avoid altering your position during eye movement recording. At the start of each trial a small fixation cross will appear at the centre of the screen, following which a small target will appear at one of two possible eccentricities. The targets will either be located to the left or right of the fixation cross, or two targets will appear simultaneously left and right of centre. On the double target trials you are free to move your eyes to either target. Your task is to keep your gaze on the central fixation cross and then move your eyes as quickly as possible to the target location when the target appears. You will see one or two small dots inside the target square. Move the switch on the button box left for one dot and right for two dots. Try to be as accurate as possible; a bleep indicates an incorrect response. Return your eyes to the central location ready for the next trial. In the attentional blocks you will be asked to direct your attention to the left/right sides of the screen. Keep your eyes on the fixation cross as before, but attend to the left/right target location.

Results

Subjects found the task straightforward and executed a saccade on all occasions. Saccades with a latency of less than 80 ms (0.3% of total) were rejected as being antici-

Fig. 1 The timing sequence of stimuli presentation used in experiment 1
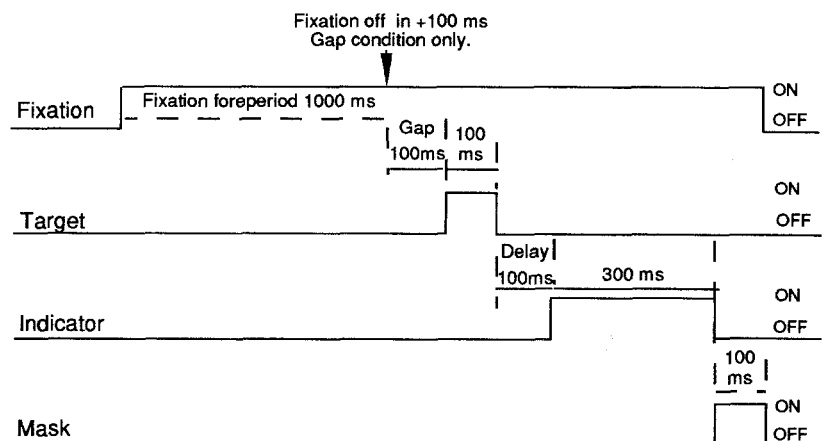
Fig. 2 Mean saccade latency obtained to single and bilateral targets in experiment 1, in the overlap, +100-ms gap and overlap-upper axis conditions. The *error bar* is typical of those obtained for all data points
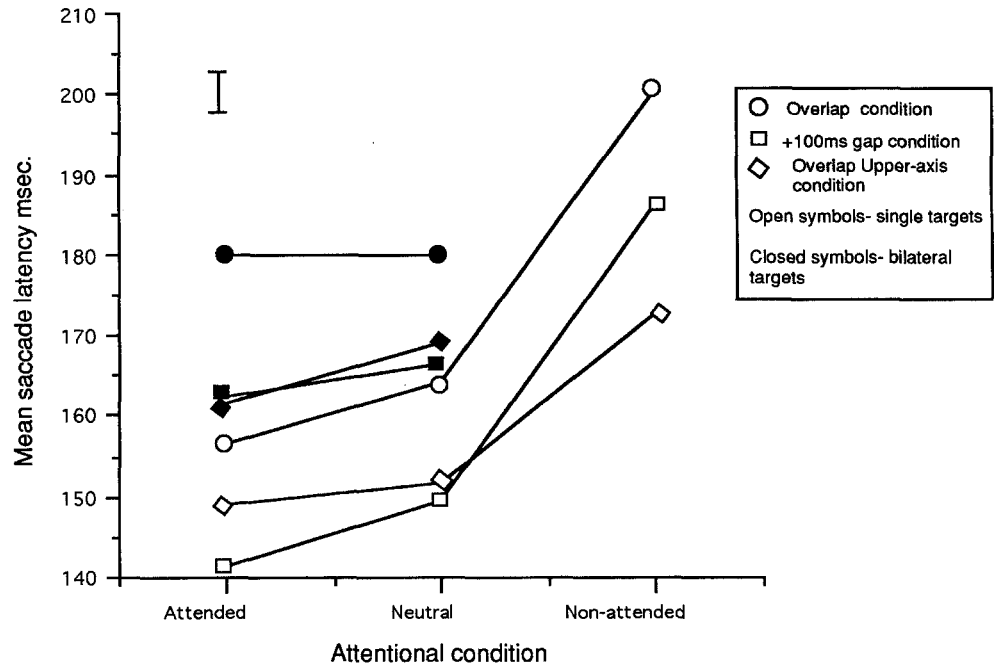
patory (Wenban-Smith and Findlay 1991), and saccades with a latency of greater than 300 ms (4.0% of total) were rejected as not being stimulus elicited. In the blocks with attentional instructions, all saccades on bilateral trails were made to the target in the hemifield to which attention was oriented.

The mean latencies obtained for the two target eccentricity locations were combined (as latency was shown to be unaffected by target eccentricity) and are displayed in Fig. 2. An examination of Fig. 2 shows that saccade latency is shorter in the +100-ms gap conditions than in the overlap condition for saccades made to single and bilateral targets in the attentional and neutral conditions. Saccade latency is also shorter in the overlap-upper axis condition than in the overlap condition. A second observation is that there is a small benefit for saccades made to single targets in the attended direction compared with saccades made to single targets in the neutral condition (attended mean – neutral mean). The greatest effect on saccade latency is the large cost shown for saccades made to targets in the non-attended hemifield (non attended mean – neutral mean).

A three-factor ANOVA compared the mean latencies obtained to single targets in the +100-ms gap and overlap conditions, under the three attentional conditions. The factors were condition (gap, overlap), attention (valid, invalid, neutral), and target eccentricity (near, far). The mean latencies obtained to bilateral targets were not included as there were no "non-attended" bilateral targets. There was a significant effect of condition ($F_{(1,5)}=14.5$, $P<0.02$) and a significant effect of attention ($F_{(2, 10)}=47.4$, $P<0.001$). There was no effect of target eccentricity ($F<1$) and no significant interaction effects. Post hoc analysis (Newman-Keuls) showed that the attentional mean did not differ from the neutral mean ($F<1$), but the non-attentional mean was significantly slower than the

neutral mean ($P<0.01$). The analysis confirmed that the +100-ms gap condition produced a significant reduction of saccade latency compared with the overlap condition. The orienting of visual attention did not result in a significant facilitation effect for targets in the attended direction, but did produce a significant slowing on latency for targets in the non-attended direction.

A second, similar three-factor ANOVA compared the mean latencies obtained with single targets in the overlap and overlap-upper axis condition. The factor of condition was significant ($F_{(1,5)}=14.1$, $P<0.02$), as was the factor of attention ($F_{(2,10)}=38.8$, $P<0.001$). Post hoc analysis (Newman-Keuls) showed that the attentional mean did not differ from the neutral mean ($P>0.05$), but the non-attended mean was significantly slower than the neutral mean ($P<0.01$). A significant two-way interaction effect was shown between the factors of attention and target eccentricity ($F_{(2,10)}=6.5$, $P<0.02$). An examination of Table 1 shows that the two-way interaction effect can be explained by the smaller costs for saccades made to invalid targets at the near-invalid location than when made to the far-invalid location (near-invalid 180 ms, far-invalid 193 ms). The reduction in the cost for near eccentricity targets is much greater in the overlap upper-axis condition (near-invalid 164 ms, far-invalid 182 ms) than in the overlap condition (near-invalid 196 ms, far-invalid 205 ms). Although this trend was apparent in the data of all six subjects in the upper-axis condition, the three-way interaction effect was not significant.

The final observation is that the mean saccade latency when targets are presented bilaterally and simultaneously is substantially slower than the mean obtained with unilateral single-target presentation. The slowing of saccade latency obtained with bilateral target presentation is shown in both attentional and neutral trials, in all three experimental conditions. To examine the slowing that bi-

Table 1 Mean saccade latency (*Mean lat*) and within-subjects SDs obtained in experiment 1, as a function of attention and target type. Latency is collapsed across hemifields and displayed in terms of the attended, neutral and non-attended targets and shown separately for the three experimental conditions

	Attended				Neutral				Non-attended	
	Single		Bilateral		Single		Bilateral		Single	
Overlap										
Eccentricity	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near
Mean lat (ms)	155	157	174	185	162	166	172	187	205	196
SD	29	25	30	31	31	32	30	29	37	32
+100-ms Gap										
Eccentricity	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near
Mean lat (ms)	138	144	165	160	147	152	162	171	185	187
SD	21	27	29	24	27	24	29	28	32	32
Overlap-upper axis										
Eccentricity	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near
Mean lat (ms)	147	151	162	161	152	151	178	160	182	164
SD	28	32	28	26	28	25	29	29	36	32

lateral target presentation had on saccade latency, three separate three-factor ANOVAs were performed on the means obtained in the overlap, +100-ms gap and overlap-upper axis conditions, respectively. The main factor of attention had only two levels (attended and neutral); the non-attended means were not included as there were no non-attended bilateral target trials. The factor of target had two levels (unilateral and bilateral) and the factor of eccentricity had two levels (near and far).

The factor of attention reached significance in the +100-ms gap condition only ($F_{(1,5)}=14.1$, $P<0.02$). The factor of target type was shown to be significant in the overlap ($F_{(1,5)}=79.8$, $P<0.001$), +100-ms gap ($F_{(1,5)}=20.0$, $P<0.01$) and overlap-upper axis ($F_{(1,5)}=14.9$, $P<0.02$) conditions. There were no significant effects of target eccentricity and no significant interaction effects in any of the analyses. The three analyses have confirmed that the presentation of bilateral simultaneous targets results in a highly significant slowing of saccade latency. This inhibitory effect of bilateral target presentation was shown to be comparable in the attentional and neutral blocks.

Discussion

In experiment one, we examined the effects of orienting visual attention covertly (sustained attentional orienting) on the latency of target-elicited saccadic eye movements. Saccades were made in a fixation overlap, +100-ms gap and overlap-upper axis condition, to unilateral single targets and bilateral simultaneous targets. The differences in latency between the attentional conditions and the neutral condition were the focus of interest.

The use of a cost/benefit analysis in attentional experiments is complicated by the difficulty of assigning a neutral condition (Jonides and Mack 1984). We used a design similar to that employed by Tassinari et al. (1987), with separate blocks of neutral and attentional trials. We felt that this would result in a saccade latency measure that is uncontaminated by subjects having to interpret a cue on every trial. A second consideration was to obtain an accurate neutral mean on bilateral target trials. If attentional and neutral cues are mixed within a

block then be choice of a bilateral target on a neutral trial may be influenced by the direction indicated by the preceding attentional cue. Jonides and Mack (1984) claim that blocked and unblocked designs do affect the neutral means obtained in a manual reaction task, but they do not offer any empirical evidence to help choose between the two procedures. In experiments not reported here in detail (Walker 1992), similar costs and benefits were obtained when attentional and neutral cues were mixed within blocks of trials. We believe this justifies the use of a cost-benefit analysis.

Saccades made to a unilateral single target in the attended hemifield showed a small (3–8 ms) speeding effect when compared with those in the neutral condition. This speeding was shown in all three experimental conditions, but failed to reach significance in all but one comparison. The greatest effect of orienting attention was shown on the latency of saccades made to targets presented in the non-attended hemifield. Here saccade latency was slower than that in the neutral condition, which produced a highly significant "meridian crossing effect". The presence of this meridian crossing effect suggests that the primary consequence of sustained attentional orienting is inhibitory in nature. The large costs with minimal benefits which we obtained are not consistent with either the spotlight or zoom lens, explanations which would predict significant benefits for responses made to attended targets.

The small benefits and large costs obtained in the present experiment are consistent with the premotor model of Rizzolatti et al. (1987), who suggested that a common neural system is used to covertly orient attention and make an overt saccadic eye movement. According to this model, orienting attention covertly preprograms the direction of the saccade prior to the onset of the target. If the target appears in the attended hemifield a small benefit may be expected due to the initiation of the direction component. In our paradigm the exact amplitude of the saccade is not pre-specified by the cue and so the amplitude component cannot be computed until after the onset of the target. When a target is presented in the non-attended hemifield the direction program has to be cancelled and a new program initiated. The cancella-

tion of any preprogrammed components of the saccade and the computation of the new target direction are thought to account for the extra cost obtained with crossing the vertical meridian. The presence of the meridian crossing effect in our data supports the premotor model and suggests that Crawford and Müller's (1992) failure to obtain the effect on saccade latency may be due to the peripheral cueing procedure they used.

The costs and benefits obtained are also consistent with the "hemifield inhibition" model proposed by Hughes and Zimba (1985, 1987). According to Hughes and Zimba, orienting attention into one hemifield produces a broad inhibition for the whole of the non attended hemifield. A target appearing in the non attended hemifield produces a slower response due to the presence of this inhibition. The presence of a substantial meridian crossing effect in our experiment is thus consistent with both the hemifield inhibition and premotor models of attention. The meridian crossing effect was reduced in the overlap-upper axis condition for saccades made to the near target eccentricity, although this did not reach significance in the ANOVA. Our initial hypothesis for the upper-axis condition was based on the supposition that the motor maps of the colliculus contain "movement fields" which are oval in shape (see McIlwain 1986). If this is the case then when attention is directed to one hemifield, specific movement fields may become activated, and a target presented in the opposite hemifield is more likely to fall into a separate movement field which is inhibited. A target which crosses the vertical meridian above fixation (upper-axis condition) at a near eccentricity location may, however, fall within the attended movement field. A far eccentricity target on the axis above fixation would be more likely to fall into a different movement field and would be subject to inhibition. We wonder if our failure to significantly reduce the meridian crossing effect in the upper-axis condition was because the near target eccentricity was simply too great to fall within the movement field activated by directed attention.

In the +100-ms gap condition a speeding effect of 15 ms was shown for saccades made to single and bilateral targets in the neutral, attended and non-attended trials. The size of the gap effect is smaller than has been observed in some experiments using gap conditions (e.g. Saslow 1967). This may be attributed to the use of a 100 ms gap and the use of a fixed SOA between fixation and target onset. The fixed SOA provides a warning signal. Reuter-Lorenz et al. (1991) showed that part of the latency reduction in the gap effect may be due to such a warning signal effect. They showed that an acoustic warning signal reduces the size of the gap effect, but it does not diminish it altogether. Reuter-Lorenz et al. obtained a 25-ms gap effect using a 200-ms gap and an acoustic warning signal. We feel that the rather small gap effect that we observed could be for these reasons (we are grateful to an anonymous reviewer for raising this issue).

In the gap condition, prior fixation offset produced a generalised facilitation effect, which did not interact with target type or with the prior orienting of visual attention. It has been claimed that, before visual attention can be moved to a peripheral location, it must be disengaged from the location of the current fixation (Posner et al. 1984; Fischer 1987; Fischer and Weber 1993). In our experiment subjects were instructed to orient their attention away from fixation before the target appeared. In these attentional trials subjects might be expected to have already disengaged their attention from fixation and oriented attention to the cued hemifield. In neutral trials subjects would be expected to be attending to fixation. This leads to the prediction that the size of the gap effect may be smaller in the attentional blocks, when attention had been disengaged and moved away from fixation, than in the neutral blocks, when attention should be located at fixation. Our results revealed no such interaction effect. The size of the gap effect was as large in the attentional blocks as was shown in the neutral blocks and a similar speeding was also observed when the saccade was made to a target in the non-attended hemifield. The facilitation effect is consistent with other explanations of the gap effect that enables a triggering of the saccade program (Ross and Ross 1980, 1981; Findlay 1993). Reuter-Lorenz et al. (1991) suggested that the gap effect results from a reduction in inhibition produced by active fixation.

Saccade latency was substantially slower when two targets were presented bilaterally and simultaneously in both hemifields than when a single target was presented. This slowing was shown for saccades made in neutral and attentional trials and was apparent under all three experimental conditions. The slowing produced by bilateral target presentation was greatest in the overlap and +100-ms gap conditions and smallest in the overlap-upper axis condition. In the attentional blocks saccade direction is pre-specified by the attentional instruction, so the subject will always saccade to the bilateral target in the attended hemifield, thus reducing the conflict of saccade direction. The magnitude of the slowing was not reduced in attentional blocks, suggesting that it is not an extra decision process required to select a saccade direction that causes the increase in latency. An alternative explanation is that the onset of a target produces inhibition within the orienting system for the "contralateral" motor map involved in computing saccade parameters (cf. McIlwain 1986). With bilateral target presentation there could be inhibition acting on both motor maps which increases saccade latency for a saccade made in either direction.

Experiment 2: directing attention covertly on the vertical axis, in an overlap fixation condition

In experiment 1, a crossing of the vertical meridian was shown to result in a large increase in saccade latency when the saccade was made to a target in the non attended hemifield. A similar cost has been shown to occur with crossings of both the horizontal and the vertical meridians in similar covert orienting manual RT experi-

ments (Hughes and Zimba 1985, 1987; Rizzolatti et al. 1987). The presence of the meridian effect with a crossing of both the horizontal and the vertical meridians was central to Rizzolatti et al.'s (1987) premotor model of attentional orienting. This cost was attributed to the time required to cancel an existing saccade program to make a saccade in the non-attended direction, even though the final decision to make the saccade is vetoed when only a manual response is required. In experiment 2, the effects of directing attention along the vertical axis on saccade latency were examined, to see whether a similar pattern of costs was produced on saccade latency as occurred with attentional orienting on the horizontal axis. This experiment is a modified version of the overlap condition of experiment 1. Attention is again oriented covertly by a verbal cue into the upper and lower visual fields and saccades made to single and bilateral targets presented at two eccentricities above and below a central fixation point.
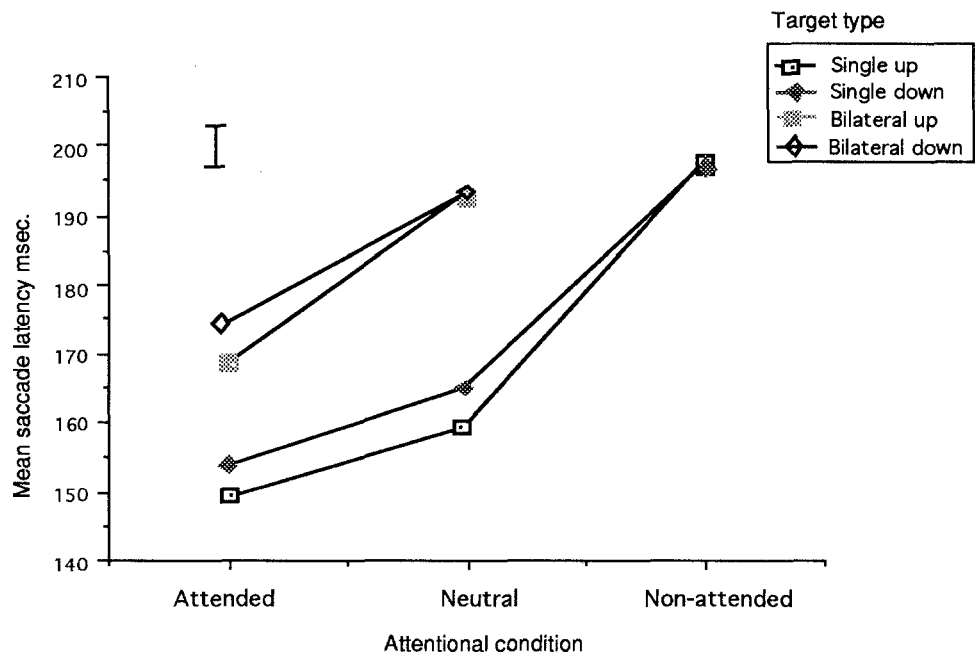
Materials and methods

Subjects

Six postgraduate students (two male, four female) from the psychology department acted as subjects. All had normal or corrected-to-normal vision and were not aware of the nature of the experiment.

Apparatus

The apparatus was identical to that used in experiment 1; the one difference being that the VDU screen was now placed on its side, so that the timing of targets presented above and below fixation was not affected by the screen raster scan.

Procedure

The timing and presentation of stimuli was identical to that used in the overlap condition of experiment 1. The same instructions were also used, except that subjects were now told to direct their attention covertly above or below the central fixation point. There were three blocks of trials: attend up, attend down and neutral, and the order of these was counterbalanced across subjects. Single and bilateral targets were presented on a vertical axis centred on the fixation point at either 5.5° or 9.5°. Bilateral targets appeared simultaneously above and below fixation, at equal and opposite eccentricities.

Results

Saccades with latencies under 80 ms and over 300 ms were rejected from the final analysis (less than 5%). Mean latencies obtained to targets in the upper and lower hemifield were collapsed in terms of the attended and non-attended hemifields and are shown, with standard deviations, in Table 2. Mean saccade latency is displayed for saccades made to targets above and below fixation, under the three attentional conditions (combining the two eccentricities) in Fig. 3.

Table 2 Mean saccade latency (*Mean lat*) and within-subjects SDs obtained in experiment 2, collapsed across hemifields and displayed in terms of the attended neutral and non-attended targets

	Attended				Neutral				Non-attended	
	Single		Bilateral		Single		Bilateral		Single	
Eccentricity	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near
Mean lat (ms)	152	150	178	169	164	160	203	186	208	182
SD	29	24	41	35	31	23	44	35	46	51

Fig. 3 Mean saccade latency obtained to single and bilateral targets in experiment 2, with attention oriented to the upper and lower hemifields and targets presented on the vertical axis. The *error bar* is typical of those obtained for all data points

Figure 3 shows that a large cost was incurred when a saccade was made to a target presented in the non attended hemifield. Saccade latency was also increased when two targets were presented bilaterally and simultaneously above and below fixation. There is some suggestion that saccade latency is slower when made to a target presented in the lower visual field than when made to a target in the upper visual field.

A three-factor ANOVA was performed on the mean latency obtained to single targets under the three attentional conditions. The factors were attention (valid, neutral, invalid), hemifield (upper, lower) and eccentricity (near, far). The factor of attention was found to be highly significant ($F_{(2,10)}$=78.4, $P<0.001$). The factor of hemifield was not significant ($F<1$) and the factor eccentricity was also not significant ($F<1$). There were no significant interaction effects. A post hoc analysis (Newman-Keuls) examined the attentional effect and showed that the valid mean (151 ms) was significantly ($P<0.05$) faster than the neutral mean (162 ms), and the invalid mean (203 ms) was significantly slower than the neutral mean ($P<0.01$).

A three-factor ANOVA was performed to examine the effect of bilateral target presentation. The analysis had two levels of attention (attended, neutral), two levels of target (single, bilateral), and two levels of eccentricity (near, far). The main effect of attention was significant ($F_{(1,5)}$=6.6, $P<0.05$), showing that mean latency obtained for targets in the attended direction (162 ms) was significantly faster than when made on the neutral trials (178.2 ms). The factor of number of targets was highly significant ($F_{(1,5)}$=76.5, $P<0.001$), showing that the bilateral target mean of 183.8 ms is significantly slower than the single targets mean of 156.5 ms. There was also a significant two-way interaction effect between number of targets and eccentricity ($F_{(1,5)}$=23.1, $P<0.01$). This appears to be due to a greater slowing produced by bilateral targets at the far eccentricity location than at the near eccentricity location (means 202.8 ms and 185.9 ms respectively). Latency to single targets was not affected by target eccentricity. There were no significant three-way interactions.

Discussion

In experiment 2 a similar pattern of costs and benefits were produced when attention was oriented on the vertical axis, as was shown when attention was oriented on the horizontal axis. When attention was directed above or below fixation a small but significant facilitation effect was observed on saccade latency. When two targets appeared bilaterally and simultaneously above and below fixation, saccade latency was significantly increased compared with the single target mean latency. An increase in latency was shown when the saccade was made to targets in the non-attended hemifield (meridian crossing effect). A similar result has been shown to occur with manual RTs and attentional crossings of the horizontal meridian (Rizzolatti et al. 1987; Hughes and Zimba

1987). The implication is that the meridian crossing effect cannot be explained in terms of the time required for signals to cross from one hemifield to another, as the delay also occured with a crossing of the horizontal meridian. The premotor theory explains the cost in terms of the time required to change the saccade direction program, and the hemifield inhibition model accounts for the cost in terms of inhibition in the visual quadrant opposite to the attended quadrant; the inhibition being restricted spatially to areas separated by the horizontal and vertical meridians.

The increase in latency for saccades made to targets in the lower visual field has been reported previously (Heywood and Churcher 1980). As yet there is no straightforward explanation for this slowing. Honda and Findlay (1992) recorded saccades made to targets presented at different depth planes and showed that the lower field slowing effect could be reduced under monocular viewing conditions. They rejected the hypothesis that the slowing results from a link with the convergence eye movement system. Interestingly, a 100-ms gap condition was shown to produce equal facilitation effects on latency for saccades made to targets in both the upper and the lower hemifields. This suggests that the gap effect acts independently of many other characteristics of the saccadic system, as we observed in experiment 1.

In both experiment 1 and experiment 2, we have confirmed that bilateral target presentation results in longer saccade latencies. The magnitude of this slowing was not affected by prior instructions to attend in a particular direction. In neither case, however, was it possible to predict completely the direction of the required saccade because of the presence of single targets in the unattended hemifield. In experiment 3, we investigated a situation in which subjects are presented with bilateral targets but the direction of the required saccade was held constant. We also examined the time course of the slowing effect by presenting bilateral targets with varying temporal offsets.

Experiment 3: an examination of the time course of the inhibitory influence of bilateral target presentation

Experiment 3 was performed to examine the time course of the inhibitory effect of bilateral target presentation. The results from experiments 1 and 2 showed that the bilateral simultaneous appearance of two saccade targets produced a 20- to 30-ms increase in mean saccade latency. Although the attentional instructions were expected to eliminate the "conflict" factor with bilateral targets, it might be argued that this elimination was not effective, because of the requirement to saccade into the non-attended hemifield when a single target occurred there. In experiment 3 this apparent conflict is reduced by keeping the direction of saccades constant throughout each block of trials. Subjects were instructed to direct their attention to the *right* of fixation and always saccaded to a target stimulus presented to the *right* of the fixation point (on

the horizontal axis). A second, distractor, stimulus appeared on the left at some time before, simultaneous with, or after the appearance of the saccade target. This experiment was performed to examine the time course of the inhibitory effect that bilateral target presentation has on saccade latency by altering the time that the non attended (left) stimulus appeared in relation to the saccade target. The saccade targets appeared in the presence of a continuously displayed fixation point (overlap condition) to keep other facilitatory/inhibitory influences to a minimum.

In contrast to the inhibitory effect occuring when a target is accompanied by an opposite hemifield distractor, it could be expected that the *prior* appearance of a stimulus before a saccade target onset may produce a facilitation effect. This may be expected owing to a warning signal effect, which enables some preprogramming of the saccade parameters before the onset of the saccade target. Ross and Ross (1980, 1981) showed that the onset or offset of fixation prior to target onset reduced saccade latency. However, the onset of fixation 50–150 ms after the onset of the target produced an intereference effect which increased saccade latency. Ross and Ross (1981) showed that the interference effect was specific to a visual onset and did not occur with an auditory onset. The interference effect of visual onset was shown for a stimulus presented at fixation and for stimuli presented in the periphery. Braun and Breitmeyer (1990) examined the effects of the reappearance of visual stimuli on saccade latency. They showed that if the fixation point reappeared at intervals over 100 ms before the target onset, then latency was facilitated compared to an overlap condition where the fixation point remained on. However, the reappearance of the fixation point at intervals 100 ms before to 150 ms after target onset increased saccade latency to a mean comparable to that shown in the overlap condition. It appears that the reappearance of a previously attended fixation point interferes with the ongoing saccade program and increases saccade latency. Braun and Breitmeyer showed that the inhibitory effect was also shown with a peripheral (4°) stimulus onset, but the effect was not as strong as shown for the onset of fixation at the fovea.

A further point noted by Braun and Breitmeyer was that the timing of events at the fixation affected the frequency of saccades with a very short latency, termed "express saccades". This term was first used to describe very short latency saccades found in monkeys (Fischer and Boch 1983) and subsequently in humans (Fischer and Ramsperger 1984). Much recent work has elaborated the conditions under which these short-latency saccades are produced, but the issue of whether they constitute a separate population is still unsettled (Wenban-Smith and Findlay 1991; Fischer and Weber 1993; Kingstone and Klein 1993a).

Experiment 3 was designed to find whether a similar pattern of facilitation and inhibition is produced on saccade latency with the onset of a target in the non attended hemifield, as has been shown with the reappearance of stimuli at the fovea and locations close to the fovea (Ross and Ross 1980, 1981; Braun and Breitmeyer 1980). In the "baseline" condition a single saccade target was presented 1000 ms after initial fixation onset, at either 4.5° or 8.5° eccentricity, to the right of fixation. Subjects were instructed to direct their attention to the right of fixation and to ignore any targets in the non attended hemifield. In this case the eccentricity of the non-attended stimulus is much greater than was used by Braun and Breitmeyer (1990), or Ross and Ross (1981). In the bilateral target condition the right saccade target again appeared 1000 ms after initial fixation and a second (non-attended) stimulus appeared in the opposite (left) hemifield, *simultaneously* with the onset of the saccade target; or at various intervals (20, 40, 80, 160, or 240 ms) *before* or *after* the saccade target onset. Single and bilateral targets were presented randomly throughout the block of trials. Since, in this experiment, saccades were always made in the same direction, a check was made to ensure that the amplitudes were appropriate for the targets at different eccentricities.
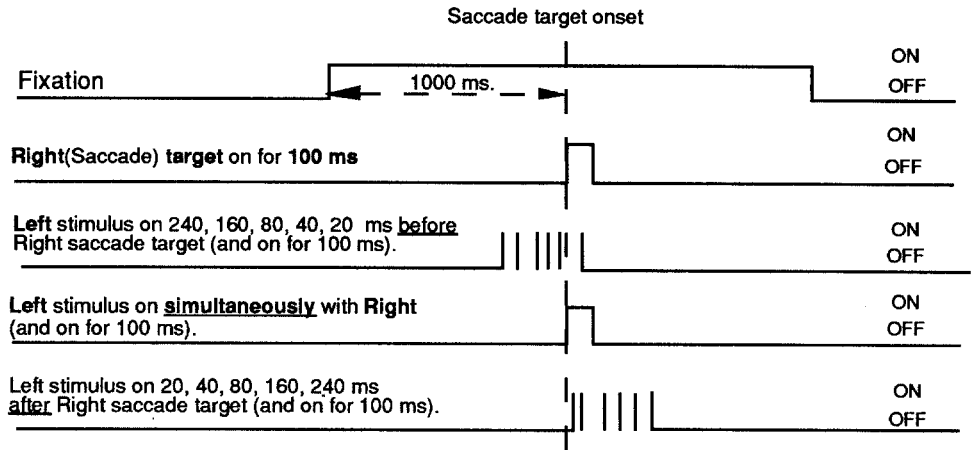
Materials and methods

Subjects

The subjects were six students from the Psychology department at Durham University. Five subjects had all taken part in experiments similar to experiment 1 and one subject had not taken part in any other saccade experiments.

Apparatus and stimuli

The apparatus was identical to that used in experiment 1. The fixation cross was presented continuously throughout each trial (overlap), and the saccade target appeared 1000 ms after fixation onset. The stimulus presentation and timing of bilateral targets was different to that used in experiment 1. On single target trials the saccade target was presented to the right of fixation, at an eccentricity of either 4.5° or 8.5°. On bilateral target trials a second stimulus was presented at an equal and opposite eccentricity to the left of fixation in the non-attended hemifield. The non-attended (left) stimulus was presented either: *simultaneously* with the onset of the saccade target: at intervals 20, 40, 80, 160 and 240 ms *before* the onset of the saccade target (left target before right; LBR); and at intervals of 20, 40, 80, 160 and 240 ms *after* the onset of the saccade target (right target before left; RBL). The timing sequence of bilateral target presentation is shown in Fig. 4. The saccade target was presented for 100 ms and then went off leaving a delay of 100 ms, after which time an indicator and mask were presented, as used in experiment 1. The non-attended stimulus was also presented for 100 ms, but was not followed by an indicator or mask. The fixation point was extinguished and an inter-trial delay of 1000 ms occurred between each trial.

A calibration routine was used before and after each block of trials to enable the later off-line computation of saccade amplitude. Subjects were required to track a stimulus circle (1.5° diameter) as it stepped from the central fixation location, to positions 3° and 6° left and right of fixation. The calibration stimulus was presented for 1.5 s at each location and appeared at the five locations in a random sequence. The calibration records were later examined off line using a semi-automatic procedure. A cursor was used to select each of the five fixations and the change in the eye position signal for the 3° and 6° steps calculated. Changes in the eye position signal were translated into degrees of visual angle (a lin-

Fig. 4 The timing sequence of the stimuli presentation in experiment 3. The fixation point was presented continuously (overlap) throughout each trial. The left (non-attended) stimuli and the right (saccade) targets were presented for 100 ms. The saccade target appeared 1000 ms after the onset of the fixation point. The left (non-attended) stimulus appeared at one of 11 gap intervals before and after the onset of the right (saccade) target

Saccade target onset

Fixation — 1000 ms. — | ON / OFF

Right(Saccade) target on for 100 ms | ON / OFF

Left stimulus on 240, 160, 80, 40, 20 ms before Right saccade target (and on for 100 ms). | ON / OFF

Left stimulus on simultaneously with Right (and on for 100 ms). | ON / OFF

Left stimulus on 20, 40, 80, 160, 240 ms after Right saccade target (and on for 100 ms). | ON / OFF

ear relationship between eye position and target eccentricity was assumed). The amplitude of each saccade made in the experimental trials could then be calculated in relation to the calibration information. As subjects used only a chin rest the resulting saccade amplitudes were measured with reduced precision, but we estimate a worst case accuracy of $+/-1°$.

Procedure

Each block contained 96 single target trials and 16 trials for each of the 11 offset intervals used (8 for each eccentricity location), giving 272 trials in total. Each subject completed two blocks on two separate days. Prior to each block subjects were verbally instructed to "Look at the fixation cross when it appears and then direct your attention covertly to the right of fixation, on every trial. One some trials a target will appear in the opposite side of the screen (left side), which you should ignore. In effect you will always make a saccade to the right (attended) target". They were also instructed to report the presence of the indicator stimulus by using the hand-held button box (as in experiment 1). Subjects were asked to saccade to the target as quickly as possible and were not informed about the timing of the non-attended stimulus onset.

Results

A total of 4% of records were discarded from the initial analysis due to blinks or multiple saccades being made to locate the final target position. Saccades with latency of over 300 ms (7%) and under 80 ms (1.7%) were also excluded from the final analysis.

Initial analysis showed no effect of target eccentricity and the data from the two target eccentricities were combined to increase the amount of data obtained for each of the bilateral target presentation intervals. Figure 5 shows the mean saccade latency combined from the six subjects. The mean latency obtained to single targets was 168 ms and is shown as a "baseline" mean. With bilateral simultaneous stimuli a slowing of 18 ms was observed compared with the single target mean. When non attended stimuli were presented 20, 40, or 80 ms before or after the onset of the saccade target, saccade latency was greater than when a single target appeared. When non at-

Fig. 5 Mean saccade latency with error bars (1 SEM), as a function of the gap interval between the onset of the non-attended stimulus and the saccade target, obtained in experiment 3; also, the mean latency obtained to a single target presented in the attended hemifield
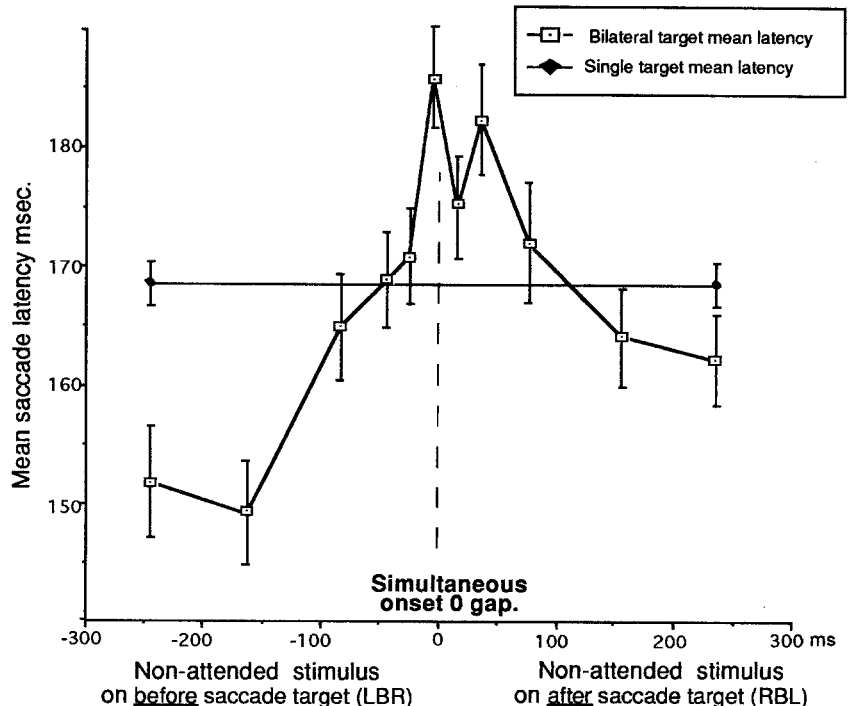
tended stimuli were presented 160 ms or 240 ms before the onset of the saccade target, saccade latency was decreased compared with the single target mean, by some 16 ms. A non-attended stimulus presented at 160 ms or 240 ms after the onset of the saccade targets resulted in a mean comparable with that obtained to single targets.

A two-factor ANOVA was performed on the mean saccade latencies obtained with *bilateral* target presentation. There were 11 levels of target gap interval and two levels of target eccentricity. The factor of target eccentricity was not significant ($F<1$). There was, however, a significant effect of gap interval ($F_{(10,50)}=4.6$, $P<0.001$). The two-way interaction was not significant ($F<1$). A post hoc analysis (Newman-Keuls) was performed to further examine the effects that the gap intervals had on saccade latency. The analysis confirmed that the mean obtained when a non-attended stimulus appeared 160 ms and 240 ms before the saccade target was significantly faster than when two targets appeared simultaneously ($P<0.01$) and was also faster than when the non-attended stimulus appeared 20 ms and 40 ms after the onset of the saccade target ($P<0.05$). The means obtained in all other gap intervals did not differ significantly from each other.

Paired t-tests were performed to compare the facilitation and inhibitory effects of bilateral target presentation to the baseline mean obtained with single target presentation. The mean latency obtained with bilateral simultaneous presentation 185 ms was shown to be significantly slower than the single target mean of 168 ms ($t=2.8$, 5 df, $P<0.02$). Saccade latency was also significantly slower when a non-attended stimulus appeared 40 ms after the onset of the saccade target ($t=3.3$, 5 df, $P<002$). Saccade latency was significantly faster than with a single target when a non-attended stimulus appeared 160 ms before the onset of the saccade target ($t=2.3$, 5 df, $P<0.05$). However, the speeding observed when a non-attended stimulus appeared 240 ms before the saccade target did not reach significance. The analysis has confirmed that there are both facilitatory and inhibitory effects produced by presenting a non-attended stimulus at intervals before and after the onset of a saccade target compared with the single target condition.

In this experiment the distributions of saccade latency are of interest. Figure 6 shows the frequency distributions of saccade latency obtained from the six subjects, to a single target, with bilateral simultaneous target presentation and when a non-attended stimulus appeared 240 ms before or 240 ms after the onset of the saccade target. Single targets resulted in a peak in the latency distribution at about 130 ms, indicating the presence of many "fast regular"saccades. With bilateral simultaneous targets the peak in the distribution occurs later at about 180 ms. So, it appears that the simultaneous appearance of a stimulus in the non-attended hemifield results in many "slow regular" saccades. When the non-attended stimulus appeared 240 ms *before* the saccade target the

Fig. 6A–D Frequency distributions of saccade latency obtained from the six subjects in experiment 3. Distributions are shown for: **A** the single target condition, **B** when the two targets appeared simultaneously, **C** when a non-attended stimulus appeared 240 ms before the saccade target, and **D** when a non-attended stimulus appeared 240 ms after the saccade target
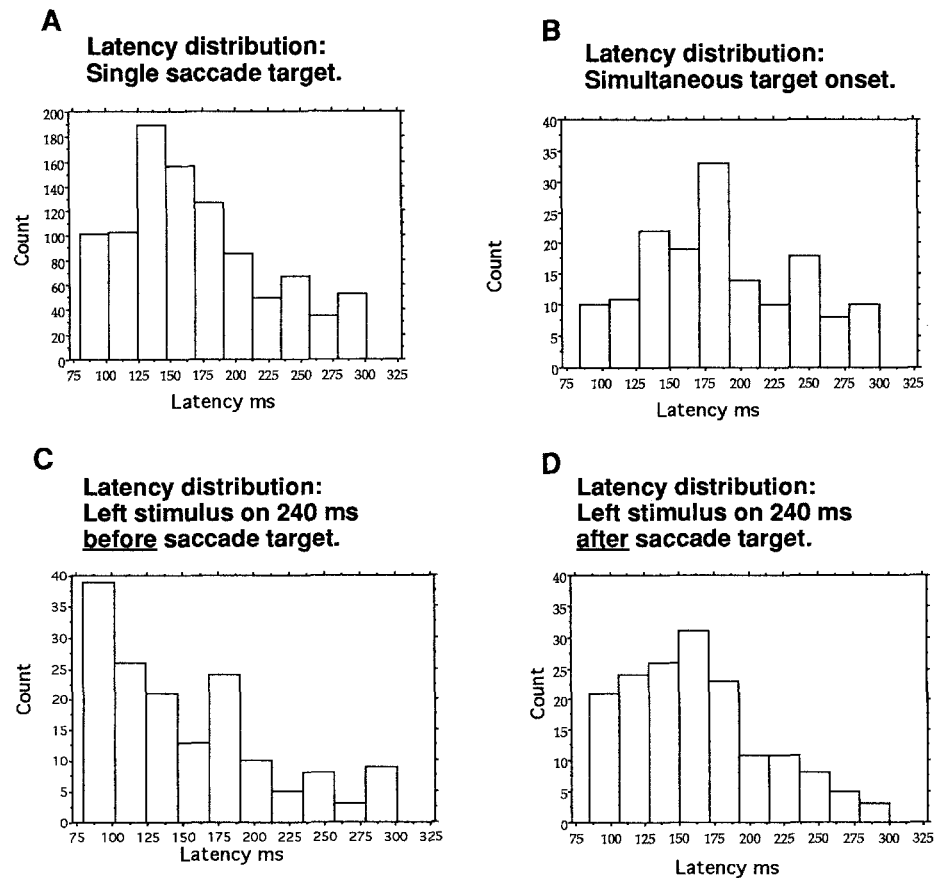
peak in the distribution is shown at a very fast 90 ms. This indicates that the early onset of a target in the non-attended hemifield produced a population of saccades of very short latency. An examination of the frequency distributions of saccade latency from the −160 ms and −240 ms gap conditions revealed very few anticipatory saccades. Only 2% of saccades had a latency of less than 60 ms, while 52% of saccades had a latency of between 60 and 150 ms. The frequency distributions from individual subjects were also examined for the −240 ms gap condition and showed no evidence of bimodality for five of the six subjects. One subject's distribution did show evidence of bimodality with a first peak of express saccades at about 110 ms and a second peak occurring later at about 185 ms. The issue of bimodality is a controversial one in the express saccade literature (Wenban-Smith and Findlay 1991). When the non attended stimulus appeared 240 ms *after* the onset of the saccade target the latency distribution peaks at about 160 ms and was positively skewed. A similar latency distribution is shown for when a single saccade target was presented.

The mean saccade amplitudes obtained to single and bilateral targets are shown in Table 3. In experiment 3 the subject made a saccade to a right-sided target on every trial. Although the exact target location was not predictable, it may have been possible for subjects to anticipate the target onset before it appeared or to employ a strategy of making a saccade to a mid-target location. In both cases saccade amplitude would be expected to be inaccurate, as saccades were not stimulus driven. The mean saccade amplitudes in Table 3 clearly show that subjects made accurate saccades to both single and bilateral targets. Saccade amplitudes were not affected by the early onset of a distractor stimulus in the non-attended hemifield. This is an important point, as it shows that the early onset of the distractor has not resulted in subjects anticipating the saccade target onset, which would result in inaccurate saccades. Table 3 shows that the saccades were appropriately target directed.

Table 3 Mean saccade amplitudes and within-subjects SDs obtained to single and bilateral targets for each onset interval in experiment 3 (six subjects)

| | Target eccentricity | | | |
| | 4.5° | | 8.5° | |
	Mean	SD	Mean	SD
Bilateral targets				
−240	4.3	0.6	7.2	1.3
−160	4.3	0.7	7.0	1.9
−80	4.3	1.0	7.5	1.2
−40	4.2	1.5	7.3	1.7
−20	4.3	0.8	7.4	1.4
Simultaneous	4.2	1.1	7.5	1.6
+20	4.3	0.6	7.3	2.0
+40	4.2	1.7	7.4	1.4
+80	4.3	0.8	7.3	1.8
+160	4.2	1.1	7.6	1.3
+240	4.2	0.9	7.7	1.3
Single targets	4.5	0.8	7.5	1.6

Discussion

The results of the present experiment have extended those of experiment 1 in two respects. They have shown that the latency increase with bilateral targets occurs even if the saccade direction is predetermined and they have established the time course of this bilateral slowing. A slowing of some 20–30 ms, compared with the single target conditions, was observed in this experiment when a stimulus appeared simultaneously with, 20–40 ms before, or a similar period after, the onset of the saccade target. The magnitude of this slowing has not been substantially reduced in this experiment even though the subject directed attention to the saccade target and saccade direction was kept constant throughout blocks of trials. The inhibitory effect of a simultaneous onset of a target in the non-attended hemifield cannot result from the subject having to "choose" a direction in which to make a saccade. It appears that the inhibitory effect of the non attended stimulus is automatic and is outside the influence of covertly oriented visual attention. It is interesting to note that Braun and Breitmeyer (1990) observed a slowing in saccade latency with the simultaneous onset of an attended fixation point. However, in a control experiment they reported that this slowing was not apparent if a distractor stimulus was presented at a non-attended location away from the fixation location. The results of our experiment do not confirm this second finding, as the onset of a target at an equal and opposite eccentricity in the non-attended hemifield has produced a large inhibitory ef-fect.

When a non-attended stimulus was presented at intervals of 160 or 240 ms before the onset of the saccade target, a facilitation effect was observed on saccade latency. This finding is similar to those of Ross and Ross (1980, 1981) and Braun and Breitmeyer (1990), who showed that an abrupt onset of a previously attended fixation point can reduce saccade latency in much the same way that an offset or change can. Braun and Breitmeyer showed that the early onset leads to an increase in the frequency of "express saccades", with very short latencies below 100 ms. A similar increase can be seen in the frequency distributions of latency obtained in the present experiment (Fig. 6). When a non-attended stimulus appeared 240 ms before the saccade target, a peak in the distribution is shown at about 85 ms, indicating that many very fast saccades were being produced in this condition. Ross and Ross attributed this facilitation to a general preparation or alerting process that could either improve the processing of target detection or prepare the early steps of saccade programming. The suggestion is that the early onset of the stimulus in the non-attended location enables the triggering of processes involved in programming the desired eye movement. This non-specific triggering occurs whether or not the direction of the saccade can be anticipated and is recognised as one of the major contributors to the gap effect (Fischer and Weber 1993). The size of this facilitation effect is perhaps surprisingly large in this experiment, as the saccade tar-

get appeared at a fixed interval of 1000 ms after fixation onset. It appears that an onset 100 to 240 ms before the target can still exert a strong additional warning signal effect.

General discussion

The series of experiments discussed above has indicated three separate influences of visual attention on saccade latency. These are: the "central cueing effect", the "gap effect" and the "bilateral target effect". The main findings of the experiments were as follows.

When visual attention was covertly oriented to one hemifield by a *central cueing* procedure, consistent changes to the latency of target-elicited saccades were found. A small latency decrease (benefit) was obtained for saccades made to targets in the attended hemifield, compared with those made under neutral conditions with no explicit attentional instruction. This decrease occurred consistently, although only on one occasion was it statistically significant. In all three experimental conditions a large and statistically significant latency increase (cost) was shown for saccades made to targets presented in the non-attended hemifield.

Rizzolatti et al. (1987) proposed that orienting visual attention to a specific location involved the same neural mechanisms required to produce a saccadic eye movement. According to this model, when visual attention has been oriented following a symbolic cue, the saccadic system prepares to make a saccade to that location. The resulting costs and benefits obtained on manual RTs are interpreted in terms of the time required to program a saccadic eye movement. Previous work used to support the premotor hypothesis of attentional orienting has been based on covert attentional orienting and manual reaction times (Rizzolatti et al. 1987; Tassinari et al. 1987; Umiltá et al. 1991). Our results have demonstrated that orienting attention covertly can produce a similar pattern of costs and benefits on saccade latency. This pattern of large costs and small benefits appeared consistently across all subjects. Further investigation will be required to determine whether cue validities greater than those we used would produce a more extreme pattern of costs and benefits. The pattern of results we obtained supports the view of a close coupling between the system involved in orienting attention and those involved in programming a saccadic eye movement.[1]

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[1] The premotor model of attentional orienting has recently been supported by a series of experiments by Sheliga et al. (1994), who demonstrated that attentional orienting can affect saccade trajectories. Subjects oriented their attention to one of four boxes located horizontally above fixation and, following either a visual or auditory "imperative" signal, they then had to make a saccade to a target located vertically below fixation. The resulting saccade trajectories were shown to deviate in the direction contralateral to that in which subjects were covertly directing their attention. The finding that attentional orienting can affect saccade trajectories provides further support for the idea that a common mechanism is involved in covert and overt orienting.

The introduction of a gap between fixation point offset and target onset always produced a consistent *gap effect*. The +100-ms gap condition produced a generalised speeding effect on saccade latency. This speeding effect showed no interaction with the other effects. It was of equal magnitude for saccades made to single targets either in the attended or in the non-attended direction and for saccades made to bilateral targets. It has been claimed that this gap-effect speeding occurs because attention can be more quickly disengaged from the fixation point (Fischer and Breitmeyer 1987). We suggest that our finding of no interaction between the gap effect and prior attentional instructions rather suggests that two independent effects are at work[2] (Tam and Stelmach 1993). While it seems intuitively appealing to speak of attention being disengaged from the fixation point and moved to a peripheral location, we wish to reject this notion, at least as an explanation of the gap effect. In our experiments subjects voluntarily oriented attention away from fixation to eccentric target locations. This manoeuvre had no effect whatever on the speeding produced by the gap effect. We believe this necessitates the conclusion that the gap effect and voluntary attentional orienting are affecting different parts of the saccade programming system.

The gap effect has excited considerable interest recently, partly because of its connection with the phenomenon of "express saccades" (Fischer and Weber 1993). Express saccades are short-latency saccades produced with the gap paradigm which may form a distinct, separate sub-population in the distribution function of sac-

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[2] A similar conclusion was reached by Kingstone and Klein (1993b) in a paper published after our own paper was submitted for publication. Kingstone and Klein used a dual-task situation where subjects were required to make manual RTs to an "attended" stimulus located above fixation on half the trials and to make a saccade to a stimulus located left/right of fixation on the other trials. The disengagement hypothesis of the gap effect was examined by prior offset of: the attended peripheral stimulus, the non attended peripheral stimulus, or the non-attended foveal stimulus, in a +200-ms gap situation. The manual RT response was included to ensure that subjects were orienting their attention to the upper/lower stimuli following the cueing procedure. In contrast to predictions from the disengagement hypothesis, saccade latency was facilitated with the offset of both the attended and the non attended peripheral stimulus. The greatest facilitation effect was observed with the offset of the non-attended foveal stimulus, which is comparable with the gap effect we observed on attentional trials and to the effects found by Tam and Stelmach (1993). The Kingstone and Klein paper highlights a possible problem with the use of dual task paradigms, a situation which has provided results that are thought to be incompatible with the oculomotor hypothesis of attentional orienting (e.g. Klein 1980: Klein et al. 1992). In Kingstone and Klein's experiment the slowest saccade latencies were obtained in the overlap condition (315 ms) and the fastest obtained in the +200-ms gap condition (220 ms). These latencies are much slower than observed in simple saccade experiments and are very much slower than would be expected in a 200-ms gap condition. This suggests that the dual task situation is adding extra demands on the subject which are drastically slowing saccade latency. This extra interference effect could well be masking subtle attentional effects that are normally observed in simple covert attentional orienting experiments. We feel that more attention should be paid to the absolute values of saccade latencies and manual RTs as well as to the differential values in attentional orienting experiments.

cade latencies. Although, bimodal distributions of saccade latencies indicative of separate populations have been reported (Fischer 1987; Jüttner and Wolf 1992), this bimodality has not always been found and remains a controversial issue (Reuter-Lorenz et al. 1991; Wenban-Smith and Findlay 1991; Kingstone and Klein 1993a). We examined our data for the presence of bimodal distributions and found little evidence for a separable peak in the express range (see experiment 3). In consequence we have based all our analysis on mean latencies rather than attempting to separate out different populations of saccades.

When two saccade targets were presented bilaterally and simultaneously in both hemifields, saccade latency was increased compared with the single target condition. We have termed this effect the *bilateral target effect.* Saccade latency was increased compared with single target mean latency, even when attention had been oriented covertly to one hemifield in attentional trials. The magnitude of this slowing was not modified by such directed visual attention or by the use of a gap procedure. In experiment 3, the bilateral target slowing was observed when the subject always made a saccade in the same direction (to the right) on every trial. The bilateral target effect thus appears to be a third independent effect on saccade latencies. Since it is unaffected by a prior voluntary decision to saccade in a particular direction, it would appear to be an automatic inhibitory effect between two potential saccade targets.

Experiment 3 examined the time course of the bilateral target effect. Bilateral simultaneous or near-simultaneous presentation of a stimulus on the left increased saccade latency even though the task required a saccade to be made to the right target on every trial. In contrast to the increased latency with simultaneous onset, when a stimulus in the non-attended direction appeared more than 160 ms before the onset of the saccade target, a decrease was found in the latency of the saccade, probably because the left target provided a warning-signal-like cue. The presentation of a non-attended stimulus at intervals up to 80 ms after the onset of the saccade target increased saccade latency, but the effect was not as great as with simultaneous or near simultaneous stimulus onset. This suggests that the inhibitory effect is dependent on simultaneous target presentation and is thus short lasting.

Our general conclusion is that we have demonstrated three independent effects on saccade programming. This is concordant with the current theoretical view that attention has multiple manifestations (Rizzolatti and Camarda 1987; Allport 1993) and is also supported by physiological findings.

The attentional effects produced by central cueing are probably the most elusive to account for in terms of detailed neurophysiology. Although the parietal lobes of the cortex are often involved in discussions of spatial attention, the detailed operation remains obscure. Parietal lobe cells are active when an animal is attending to a stimulus and when a stimulus is a saccade target (Yin

and Mountcastle 1977; Andersen et al. 1987). The parietal lobes are known to be connected to the superior colliculi (Lynch et al. 1985), an important centre for saccade generation. It is known that damage to the parietal cortex results in behavioural deficits which are often interpreted as being attentional in nature (Posner et al. 1984; Lynch and McLaren 1989). Patients with parietal lobe damage also have difficulty in making saccades to the hemifield contralateral to the site of damage (Walker et al. 1991). The premotor model of attention (Rizzolatti et al. 1987; Umiltá et al. 1991) requires the existence of a structure which is involved in voluntary saccade generation. It seems possible that central cueing of attention could operate through the parietal pathways.

The gap effects seems most readily accounted for by current physiology in the light of recent work on the rostral region of the superior colliculus, the region in which the fovea is represented in the collicular retinotopic map. Munoz and Wurtz (1992) inhibited the activity of cells in this region in the left superior colliculus of an awake monkey, by a local injection of an inhibitory neurotransmitter (GABA). After the injection the monkey made very fast saccades with a latency of less than 100 ms to a contraversive (right-sided) target. The monkeys were also less able to suppress the initiation of unwanted saccades. These results suggest that the disengagement characteristic of the gap effect may have a physiological substrate, namely the removal of activity from the rostral colliculus. Such a suggestion has been made in several recent models of saccade generation (Munoz et al. 1991; Massone 1993).

The bilateral target effect, in contrast, seems likely to reflect some form of inhibition between structures which spatially map locations. One centre known to be involved in saccade generation is the superior colliculus (Robinson 1972; Sparks and Hartwich-Young 1989). Schiller et al. (1987) showed that removal of one superior colliculus reduced the latency of saccades made in the ipsilesional direction. They suggested that the two superior colliculi are linked by inhibitory cross connections and when one colliculus is active it produes inhibition within the other. Infante and Leiva (1986) found that when a cat was making a saccade in one direction activity in the cells of one superior colliculus increased, while activity in the other colliculus decreased. As well as this inter-collicular inhibition, evidence for intra-collicular inhibition has also been indicated in single-cell recording experiments. Rizzolatti et al. (1974) recorded the response of a single cell in the superior colliculus of an awake cat and found that the cell responded if a stimulus was presented within the receptive field of that cell. A second stimulus presented at various locations within the same hemifield as the first inhibited the cells response. Rizzolatti et al. showed that the strongest inhibitory influence was exerted on a cell when a second remote stimulus was presented simultaneously with the onset of the activating visual stimulus. The inhibitory influence of the second remote stimulus was reduced when it was presented at short intervals before the visual stimulus and was absent when

presented a few seconds earlier. This is entirely in line with our findings in experiment 3, where bilateral simultaneous target presentation produced the greatest increase in saccade latency. A model of saccade generation based on such intra-collicular inhibition has been proposed by Van Opstal and Van Gisbergen (1989).

In summary, we have demonstrated three separate non-interacting effects which modify saccade latency. These effects must be accounted for in any attempt to understand the brain mechanisms of saccade generation and we have suggested possible physiological substrates for each effect. The results we have obtained show considerable similarity with results in which attention has been measured with manual reaction times and we believe provide additional support for the pre-motor model of visual attention.

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