



The Role of Attention in the Programming of Saccades

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Accurate saccadic programming in natural visual scenes requires a signal designating which of the many potential targets is to be the goal of the saccade. Is this signal controlled by the allocation of perceptual attention, or do saccades have their own independent selective filter? We found evidence for the involvement of perceptual attention, namely: (1) summoning perceptual attention to a target also facilitated saccades; (2) perceptual identification was better at the saccadic goal than elsewhere; and (3) attempts to dissociate the locus of attention from the saccadic goal were unsuccessful, i.e. it was not possible to prepare to look quickly and accurately at one target while at the same time making highly accurate perceptual judgements about targets elsewhere. We also studied the trade-off between saccadic and perceptual performance by means of a novel application of the "attentional operating characteristic" (AOC) to oculomotor performance. This analysis revealed that some attention could be diverted from the saccadic goal with virtually no cost to either saccadic latency or accuracy, showing that there is a ceiling on the attentional demands of saccades. The links we discovered between saccades and attention can be explained by a model in which perceptual attention determines the endpoint of the saccade, while a separate trigger signal initiates the saccade in response to transient changes in the attentional locus. The model will be discussed in the context of current neurophysiological work on saccadic control.

Saccades Attention Attention operating characteristic Eye movement

INTRODUCTION

Selective attention is the gateway to conscious experience, affecting our ability to perceive, distinguish and remember the various stimuli that come our way (James, 1890). In contemporary usage, selective attention denotes the allocation of limited processing resources to some stimuli or tasks at the expense of others (Norman & Bobrow, 1975; Reeves & Sperling, 1986; Shaw, 1982, 1984; Sperling & Doshier, 1986). Most of what is known about selective attention concerns its effects on perception or memory, but selective attention may also be a significant contributor to motor control, determining which of the various objects in the visual field is to be the target used to plan and guide movement. This paper examines the role of selective attention in the programming of saccadic eye movements.

Understanding the role of selective attention in saccadic programming is important for understanding how it is possible to direct a saccade accurately to a chosen visual object in a highly structured visual display. The difficulty encountered when scanning such displays is that

the saccadic system must "know" which of the many available objects is to be the target. *In this paper, we asked whether the saccadic system "knows" which is the effective target by means of the same attentional mechanism that serves perception.* In effect, we asked whether the saccadic target is selected by shifting perceptual attention to the saccadic goal, or, alternatively, whether it is possible to shift perceptual attention to one location while simultaneously invoking a separate selective mechanism that will direct the saccade elsewhere. Determining whether separate selective mechanisms serve perception and eye movements, or, alternatively, whether a single mechanism serves both, will shed light on the nature of the central mechanisms that control high-level aspects of saccadic planning and execution and will contribute to the understanding of the processing steps leading up to the execution of an accurate saccade.

A role for perceptual attention in saccadic programming is often assumed because of the intuitively appealing observation that people prefer to shift attention to where they are about to look (e.g. Hendersen, Pollatsek & Rayner, 1989). This may be a sensible strategy to use while reading or while scanning complex displays, but by itself the observation reveals nothing about the role of attention in saccadic control. Shifts of attention preceding saccades might serve a variety of purposes unrelated to saccadic control, such as to evaluate whether a particular

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eccentric target is a suitable goal for the saccade, or (as Hendersen *et al.*, 1989, proposed) to get a head start on processing the next item in a sequence.

Analogous arguments apply to the physiological literature. Links between attention and saccades are often assumed based on findings in monkey of pre-saccadic activity in neurons implicated in attentional control. Such neurons have been found in areas such as inferior temporal cortex (Chelazzi, Miller, Duncan & Desimone, 1993), pulvinar (Petersen, Robinson & Morris, 1987; Robinson & McClurkin, 1989), and parietal cortex (Andersen, Essick & Siegel, 1987; Gnadt & Andersen, 1988; Andersen & Gnadt, 1989). This pre-saccadic activity might play an essential role in setting the spatial parameters of the saccade. Alternatively, this activity might have no functional role in saccadic programming at all, but might instead serve to enhance purely perceptual or cognitive aspects of the animal's task, such as target detection, localization or recognition, that happen to coincide with saccadic planning.

The behavioral and physiological experiments described above provide evidence that shifts of attention precede saccades, but do not reveal the function of these pre-saccadic attentional shifts. Determining the role of attention in saccadic programming requires psychophysical and oculomotor experiments expressly designed to discover whether attention shifts are necessary to program accurate saccades. Unfortunately, the methodological obstacles to obtaining an unambiguous answer to this question have proven to be formidable. Prior attempts to study the role of attention in saccadic programming have led to conflicting results, and, in some cases, to artifactual outcomes (issues to be reviewed in more detail below).

The indeterminate outcome of the prior work leaves open broad and basic questions about saccades and attention, such as:

- Does perceptual attention play any role in saccadic control? If so, how great a demand does saccadic programming place on limited attentional resources and at what stage of saccadic programming does attention come into play?
- If perceptual attention is not responsible for the selection of saccadic targets, then what sort of selective mechanism is doing the job?

Our study addressed all of these issues.

Our approach was influenced by three aspects of prior work:

- (1) prior research demonstrating a relationship between *smooth* eye movements and attention;
- (2) prior studies showing saccadic errors during the scanning of structured visual displays (where attentional allocation might be needed to select the target); and
- (3) the conflicting outcomes of prior experiments on saccades and attention.

These three influences are reviewed below.

Attention and smooth eye movements

Investigators since Dodge and Fox (1928) and Ter Braak (1957) have found that smooth eye movements can be used to maintain an accurate line of sight on either stationary or moving targets in the presence of background stimuli moving at a different velocity (e.g. Dubois & Collewijn, 1979; Murphy, Kowler & Steinman, 1975; Ter Braak & Buis, 1970). The influence of the backgrounds on eye velocity can be as small as 2–4% (Kowler, van der Steen, Tamminga & Collewijn, 1984). This high degree of selectivity is due to attention: Khurana and Kowler (1987) showed that perceptual judgments are better for tracked targets than for untracked backgrounds. Their study, which controlled for differential effects of retinal image speed and position, showed that a *single* attentional filter determines the input both to smooth eye movements and perception, i.e. it is not possible to fully attend one target and at the same time accurately pursue another. The present study raises analogous questions about saccades.

Saccades in structured visual displays

Given the effective selection of the target for smooth eye movements just described, it is surprising to discover that the effectiveness of target selection for saccades has been questioned. Several investigators have reported that short-latency saccades made in structured visual fields can be inaccurate, landing near the center of the entire stimulus configuration, rather than at the designated target within the configuration (Findlay, 1982; Ottes, Van Gisbergen & Eggermont, 1985; Coeffe & O'Regan, 1987). These saccadic errors (which would be disastrous if they occurred during natural scanning) inspired the proposal that there is a low-level, automatic, averaging mechanism that determines saccadic endpoints, at least when saccadic latency is short (Findlay, 1982; Ottes *et al.*, 1985; Wise & Desimone, 1988).

Low-level averaging, however, is unlikely because the endpoints of the so-called short-latency "centering" saccades can be biased by high-level factors, such as the probability of the target appearing in one or another location (He & Kowler, 1989), or voluntary effort (He & Kowler, 1991). A more plausible explanation of the saccadic errors observed in highly-structured visual fields is that they were not "errors" in the usual sense. Instead, saccades were programmed while attention was distributed across wide regions of the visual field in an attempt to locate the designated target accurately. According to this view, spatially-selective attention determines the effective input to saccades (He & Kowler, 1989, 1991; also Coeffe, 1987). This suggestion was only tentative, however, because despite many prior attempts to do so (see below), a clear link between attention and saccadic eye movements has not been demonstrated.

Prior attempts to link attention with saccades

The basic idea behind the prior attempts to study the role of attention shifts in saccadic programming was to

evaluate performance on a perceptual task carried out while saccadic preparation was in progress. The critical variable in such experiments was the location of the perceptual target relative to the intended endpoint of the saccades. If shifts of attention precede saccades, then: (1) perceptual performance should be better for targets located at the saccadic goal; and (2) drawing attention to one region of space should reduce the latency of saccades made there at the expense of saccades made elsewhere.

Experiments using this logic have produced diametrically opposite results. Posner (1980), for example, summarized two studies, one in which reaction time to detect the appearance of a stimulus was shorter at the saccadic goal, and the other in which reaction time was shorter at a location opposite to the saccadic goal. Posner (1980) rejected strong links between attention and saccades, concluding instead that movements of attention depend on the importance of the target, not on the occurrence of saccades.

Remington (1980) also rejected strong links between saccades and attention on the basis of his finding (Experiment 3) that detection of a brief luminance increment was equally accurate regardless of the location of the increment relative to the goal of the saccade. But inspection of his data shows that saccadic latencies were prolonged when the luminance increment and saccadic goal were in different places, calling into question the independence he had proposed. Klein (1980) and later Klein, Kingstone and Pontefract (1992), kept alive the notion of independence by finding that cues signaling the likely location of a target for a manual response did not influence subsequent saccades. They speculated, however, that while their results rejected a role for saccades in the control of attention, their experiments were insufficient to rule out the involvement of attentional shifts in what they referred to as "saccadic execution".

Shepherd, Findlay and Hockey (1986) believed that they had evidence showing that shifts of attention preceded saccades. This was based on their finding of shorter manual reaction times to the appearance of a target at the saccadic goal. But this result was not likely to have had anything to do with attention at all because the manual response occurred well after the saccade brought the line of sight to the target. Thus, the results could be attributed to effects of retinal eccentricity, rather than to attention.

Subramaniam and Hoffman (1992), who did remove the target before the saccade occurred, thus eliminating confounding effects of retinal eccentricity, found that identification of a target letter was more accurate at the intended goal of the saccade than elsewhere. Their results provide the most convincing demonstration to date of a saccadic and attentional link. However, the issue still remains open because they did not explicitly ask subjects to try to make a saccade to one place while shifting attention to another. In the absence of such instructions, subjects may have chosen to attend to where they were told to look rather than to make the explicit effort to dissociate the locus of attention from the designated goal of the saccade. If instructed to do so, subjects might have

been able to make the dissociation—or, at the very least, improve identification of targets at non-goal locations.

The conflicting results of the prior work illustrate how difficult it is to study, *inside* the laboratory, a task that people are continually doing *outside* the laboratory, namely, making saccades and perceiving objects at the same time. Part of the difficulty is finding a perceptual task that is sufficiently sensitive to the allocation of attentional resources. Indeed, the role of attention in the detection of targets (the task used in most of the prior studies of saccades and attention described above) has been controversial. Many investigators have argued that detection occurs at a "pre-attentive level" and attention, in the sense of allocation of processing resources, does not influence target detection at all (Shaw, 1984; Sperling & Doshier, 1986; Norman & Bobrow, 1975; Kinchla, 1992; Palmer, 1994). These investigators have developed formal models showing how effects of location probability on the time to detect an abruptly-appearing target can be attributed to adjustments in decision criteria, rather than to changes in allocation of processing resources. To the extent that the prior work on saccades and attention has been dominated by studies of detection tasks, whose attentional demands are uncertain at best, the diverse pattern of results obtained in the prior work may not be surprising.

OVERVIEW

We did three sets of experiments to determine the role of attention in the programming of saccades. These experiments, like the prior attempts to address this issue, made concurrent measurements of saccadic and perceptual performance. But unlike nearly all of the prior attempts, the perceptual task we used (letter identification) is known to be sensitive to the allocation of attention, when attentional allocation is governed by means of either visual or verbal cues (Sperling & Melchner, 1978; Krose & Julesz, 1989). (Our own results will verify the effectiveness of such cues.) In addition, each set of experiments added conditions that allow increasingly more stringent control of the strategies employed by the subject, something we found to be of critical importance for interpreting the patterns of results we obtained as we proceeded with the work.

The first set of experiments (*1A,B: Drawing attention to an eccentric target*) measured the latencies of saccades made in or opposite to the location of an eccentric target that summoned attention. The second set of experiments (*2 and 3: Central cue*) used a central cue to direct saccades while perceptual performance was assessed at the saccadic goal and elsewhere. The last experiment (*4: Attentional operating characteristic*) measured the trade-off between attentional allocation at the saccadic goal and elsewhere when subjects were required to assign different weights to the saccadic and perceptual task.

The bottom line is that saccades require shifts of attention, but there is a clear ceiling on the attentional demands of saccades, leaving considerable attentional resources available for processing perceptual material.

GENERAL METHODS

Subjects

Two subjects were tested, EK, one of the authors, and MC, who was naive about the purpose of the experiment. MC had some prior experience as an eye movement subject in a prior study dealing with different aspects of saccades (He & Kowler, 1992).

Apparatus

Stimuli were generated on a display monitor (Tektronix 608, P4 phosphor) located directly in front of the subject's right eye. Displays were refreshed every 20 msec, a rate high enough to prevent visible flicker. The intensity was set so that an array of 40×40 points subtending 2.2×2.2 cm on the display had a measured intensity of 100 cd/m^2 at the 20 msec refresh rate. This works out to a luminous directional-energy of $12 \text{ cd-}\mu\text{sec}$ per point (Sperling, 1971). Displays were controlled by a minicomputer (LSI 11/24).

The stimuli were seen against a dim (3.7 cd/m^2), homogeneous background produced by a raster on a second display monitor located perpendicular to the first. The views of the two displays were combined by a pellicle beam splitter. The combined displays were viewed in a dark room through a collimating lens which placed them at optical infinity. Subject EK, who is myopic, viewed the displays through a negative lens, placed between the eye and collimating lens, which kept the stimuli in sharp focus.

Eye movement recording

Two-dimensional movements of the right eye were recorded by a Generation IV SRI Double Purkinje Image Tracker. The left eye was covered and the head was stabilized on a dental biteboard.

The voltage output of the tracker was fed on-line through a low pass 50 Hz filter to a 12 bit analog-to-digital converter (ADC). The ADC, under control of the computer, sampled eye position every 10 msec. The digitized voltages were stored for subsequent analysis.

Tracker noise-level was measured with an artificial eye after the Tracker had been adjusted so as to have the same first and fourth image reflections as the average subject's eye. Filtering and sampling rate were the same as those used in the experiment. Noise level, expressed as a standard deviation of position samples, was 0.4 min arc for horizontal and 0.7 min arc for vertical position.

Recordings were made with the Tracker's automatically movable optical stage (auto-stage) and focus servo disabled. These procedures are necessary with Generation IV trackers because motion of either the auto-stage or the focus-servo introduces large artifactual deviations of Tracker output. The focus-servo was used, as needed, only during intertrial intervals to maintain subject alignment. This can be done without introducing artifacts into the recordings or changing eye position/voltage analog calibration. The auto-stage was permanently

disabled because its operation, even during inter-trial intervals, changed the eye position/voltage analog calibration.

Analysis of eye movement data

The onset and offset of saccades were detected by means of a computer algorithm employing an acceleration criterion. The criterion was determined by examining a large sample of analog records of eye position. Saccades, as small as the microsaccades that may be observed during maintained fixation (Steinman, Haddad, Skavenski & Wyman, 1973), could be reliably detected by this algorithm. Saccade size was defined as the difference between eye position at saccade onset and saccade offset.

Experiment 1a,b: Drawing Attention to An Eccentric Target

In this experiment the locus of attention was controlled by presenting an eccentric stimulus that summoned attention. The stimulus was a single numeral presented in a display of letters. The logic was that if saccades require shifts of attention to the saccadic goal, then latency should be longer for saccades made opposite to the numeral than for saccades made to the numeral because additional time would be needed to shift attention from the numeral to the saccadic goal. If, on the other hand, saccadic endpoints are determined by a separate selective system, unrelated to perceptual attention, then the numeral would simply act to provide information about where the saccade should be directed and no special advantage should accrue to saccades made in or opposite to its location.

On the face of things, the "opposite" condition seems similar to Hallet (1978) "anti-saccade" task. But there was an important difference. A visible stimulus (a letter) was presented at the location opposite the numeral, so that, unlike the typical anti-saccade task, saccades never had to be directed into a blank region of the visual display. The addition of a visible stimulus is important because difficulties in making anti-saccades, reported in the past, could have stemmed from the need to choose a saccadic endpoint within the blank region of the display, rather than from any involvement of attention.

We used a single numeral located among letters to summon attention, rather than the eccentric boxes or lines favored by other investigators, because we wanted the stimulus summoning attention to be equivalent on a sensory level to the other characters in the array. This would allow us to be sure that any effect of the numeral on saccades would be attributable to attention, rather than to sensory differences among the target locations in the display. Such differences would be troublesome because they might affect saccades independently of any attentional involvement (see Palmer, 1994, for a discussion of an analogous issue in research on perceptual attention). A brief psychophysical experiment, described in the Methods section, will confirm the assumption that the numeral was indeed effective in summoning attention.

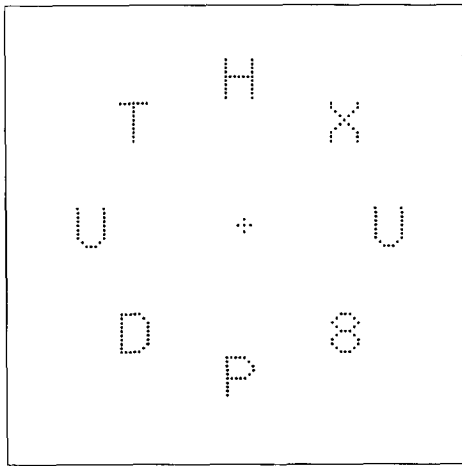


FIGURE 1. An example of the character array used in Experiment 1 containing 7 letters and a single numeral.

Experiment 1A will report the effect of the numeral on saccades. Then, following the presentation and brief discussion of these results, Experiment 1B will be described. Experiment 1B includes a perceptual task to be performed concurrently with the saccadic task.

Experiment 1a: Methods

Stimulus

Stimuli were arrays of 8 characters (21' wide \times 30' high), located at equal intervals along the perimeter of an imaginary circle with radius of 2 deg. In the center was a small (5') fixation crosshair.

Three frames were presented on each trial. Frame 1 was the *pre-mask* (duration 500 msec) and consisted of 8 letters. Frame 2 was the *critical frame* (200 msec) containing 7 letters and a single numeral. An example of this array is shown in Fig. 1. Frame 3 (500 msec) was the *post-mask* and contained all letters.

The identity of the letters, the identity of the numeral (0–9), and the location of the numeral were selected randomly and independently, without the knowledge of the subject.

The letters B, I, G, O, Q, S and Z were not included in the critical frame because of their strong resemblance to the numerals 3, 1, 6, 0, 0, 8 and 2.

Procedure

The subject looked at the crosshair and started a trial by pressing a button when ready. 100 msec later the sequence of 3 frames was shown. The subject was instructed to make a single saccade either in the direction of the numeral or to the character opposite to the numeral. The subjects had to identify the numeral, by means of a button press, at the end of each trial.

Experimental sessions

EK was run in 4 and MC in 8 sessions containing 60 trials each. In half the sessions, the instructions were to look in and in the other half to look opposite the numeral. In and opposite sessions were alternated.

Eliminated trials

Trials containing episodes in which the eyetracker lost "lock" (4% for MC) were eliminated. We also eliminated those trials in which the subject did not appear to have made a genuine attempt to look at the target. These included trials with no detected saccades (6% for MC), trials with latencies < 100 msec (0.6% for MC) and trials in which the error of the first saccade was $> 50'$ (i.e. $> 40\%$ of the distance to the target) (6% for EK and 5% for MC). Finally, we eliminated trials in which the numeral was not identified correctly (4% for EK and 17% for MC) because in such trials the subject could not have been able to follow the instructions to look at or opposite to the numeral.

The results reported were based on the remaining 217 trials for EK and 323 trials for MC.

Trials with more than one saccade

The results described are based on the first saccade of the trial. The majority of trials (78% for EK and 88% for MC) contained only a single saccade. For those trials with 2 or more saccades, a larger proportion (63% for EK and 71% for MC) occurred under instructions to look opposite the target.

Verifying the effectiveness of the numeral in summoning attention

We did a psychophysical experiment, before the saccadic experiments were performed, to test our assumption that the numeral captured attention. We added a *test frame* (100 msec duration) after Frame 2. This test frame—Frame 3 in the sequence—contained 7 letters and a single numeral either in the same or in the opposite location as the numeral in Frame 2, which was assumed to be summoning attention. The identity and location of the test numeral were chosen randomly. If the numeral in Frame 2 really did capture attention, then the test numeral in Frame 3 should be identified more accurately when it was in the same location as the numeral in Frame 2 than when it was in the opposite location. We tested EK in 200 and MC in 500 trials. For trials in which the numeral in Frame 2 was identified accurately (84% for EK and 74% for MC), the accuracy of identifying the test numeral in Frame 3 *did* depend on location. A numeral in the same location as the numeral in Frame 2 was identified more accurately (92% for EK and 90% for MC) than a numeral in the opposite location (66% for EK; 59% for MC). This outcome verifies our assumption that the numeral in Frame 2 captured perceptual attention and paves the way for doing the saccadic experiment, whose results are described below.

Experiment 1a: Results

It was easier to look in the direction of the numeral summoning attention than to look opposite to the numeral. Very large saccadic errors, which we defined as a directional error of > 67 deg (i.e. 1.5 times the directional separation of adjacent targets) were more

frequent in opposite trials [Fig. 2(c)]. Of the remaining trials, in which directional errors were < 67 deg, saccades made to the numeral had shorter latencies [Fig. 2(a)] and smaller directional errors [Fig. 2(b)] than saccades made opposite to the numeral. Directional error was used as the index of saccadic accuracy because saccade vector magnitude, unlike direction, was about the same for saccades made in and opposite to the numeral (mean vector magnitude = 104° for EK and 118° for MC). Figure 2 also shows individual differences: MC's saccadic latencies were longer than EK's and his latency differences between in and opposite saccades were smaller. MC's latency difference, although smaller than EK's, were statistically reliable ($Z = 2.76$; $P < 0.003$).

Experiment 1a: Discussion

Saccades made to a stimulus that captures attention have shorter latencies and better accuracy than saccades made to a target 180 deg away. The greater difficulty encountered when looking opposite to the numeral might

reflect the cost of having to shift attention away from the numeral to the saccadic goal. If these differences were really due to the attentional shift, we would expect to find some sign of this attentional shift in perceptual performance.

To test this idea, we repeated the experiment with the addition of a concurrent perceptual task. Subjects had to identify the letter located opposite to the numeral. We chose letter identification because it is sensitive to the allocation of attentional resources, i.e. when attention is controlled by means of visual or verbal cues, performance is better at attended than at unattended locations (Sperling & Melchner, 1978; Shaw, 1984; Krose & Julesz, 1989; Reeves & Sperling, 1986). If shifts of perceptual attention precede saccades, then identification of the letter should be better when saccades were directed opposite to the numeral, and in the direction of the letter, than when saccades were directed to the numeral. If perceptual attention and saccades can be dissociated, identification should be equally accurate regardless of saccadic direction.

Experiment 1b: Methods

Stimuli and procedure

Stimuli were the same as in Experiment 1A except that the duration of Frame 2, containing the numeral, was selected at random to be either 200, 300 or 400 msec. The additional, longer durations were included because we wanted to be sure of allowing the subject enough time to complete all aspects of the task before the frame was removed, i.e. locate the numeral, plan the saccade and identify the letter. Subjects were asked to make the saccade as soon as they had determined the location of the numeral, and not to wait until the end of the frame.

Subjects were required to report the letter located opposite to the numeral on each trial. The letter opposite to the numeral was randomly selected from a set of 10 (J, K, L, M, N, T, U, V, W or X) and, once again, letters closely resembling numerals (B, I, G, O, Q, S and Z) were not included in the critical second frame. Feedback was given after each trial by displaying the frame containing the numeral and the critical letter.

Four 60-trial sessions for EK and two for MC were run under each of the instructions, namely, to look in and to look opposite the direction of the numeral. In a third condition (no saccade) (4 sessions for EK and 2 for MC), the subjects were asked to identify the letter while keeping the line of sight stationary and not making saccades during the trial. The 3 types of sessions (in, opposite and no saccade) were tested once each day, with different orders used on different days.

Eliminated trials

Trials were eliminated as follows: loss of eye tracker "lock" (9% for EK and $< 1\%$ for MC), error of the first saccade greater than 50° (6% for EK and 8% for MC) or angular error greater than 67 deg (5% for EK and 2% for MC) and numeral not identified correctly (2% for EK and 6% for MC).

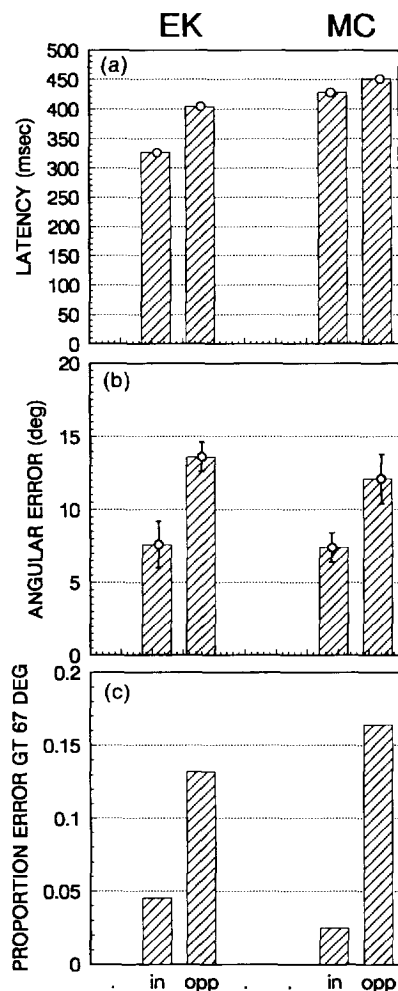


FIGURE 2. Saccadic latency (a), angular error (b), and proportion of trials with an angular error of > 67 deg (c) as a function of the direction of the saccade relative to the location of the numeral. Saccades were made either *IN* the direction of the numeral or *OPPOSITE* the numeral. Each bar is based on approx. 200 trials for EK and 150 trials for MC. Standard errors (SE) are shown by the vertical lines. The circular symbols without error bars signify that the SEs were smaller than these symbols.

The results reported were based on the remaining 217 trials for EK and 323 trials for MC.

Experiment 1b: Results

Saccadic performance, shown in Fig. 3, can be compared to that obtained in the prior experiment (1A) with the same duration (200 msec) of Frame 2. Only MC's performance changed. Both the mean latency and mean angular error of his saccades in the direction of the numeral increased relative to the values observed in Experiment 1A, and differences between latencies and angular errors of saccades in and opposite to the numeral were abolished. Figure 3 also shows that EK's saccades in the direction of the numeral had shorter latencies and smaller angular errors than did the saccades made opposite to the numeral, with performance not changing with increasing frame duration. MC's latencies increased with duration.

Analysis of variance confirmed these trends, with MC showing significant effects of duration on both latency [$F(2,193) = 38, P > 0.001$] and angular error [$F(2,193) = 3.02, P < 0.05$] but no significant effect

of instruction (i.e. in vs opposite). EK, on the other hand, showed a significant effect of the instruction on both latency [$F(1,361) = 92, P < 0.001$] and angular error [$F(1,361) = 14, P < 0.001$] but no significant effect of duration. None of the interactions (duration \times instruction) reached significance.

Figure 4 shows the perceptual performance. It is based only on those trials in which the saccade did not occur until after the critical Frame 2 was replaced by the mask (81% of the trials for EK and 99% for MC). EK identified the letter accurately only under the opposite instruction, when she was preparing to look at the letter (opposite to the attention-catching numeral). Similar results were obtained when she shifted attention to the letter while the eye was stationary. MC's performance was completely different. He identified the letters equally well regardless of where he looked or whether he made any saccades at all. This pattern of extreme individual differences has implications both for interpreting the prior literature and for planning new experiments to discover the role of attention in saccades.

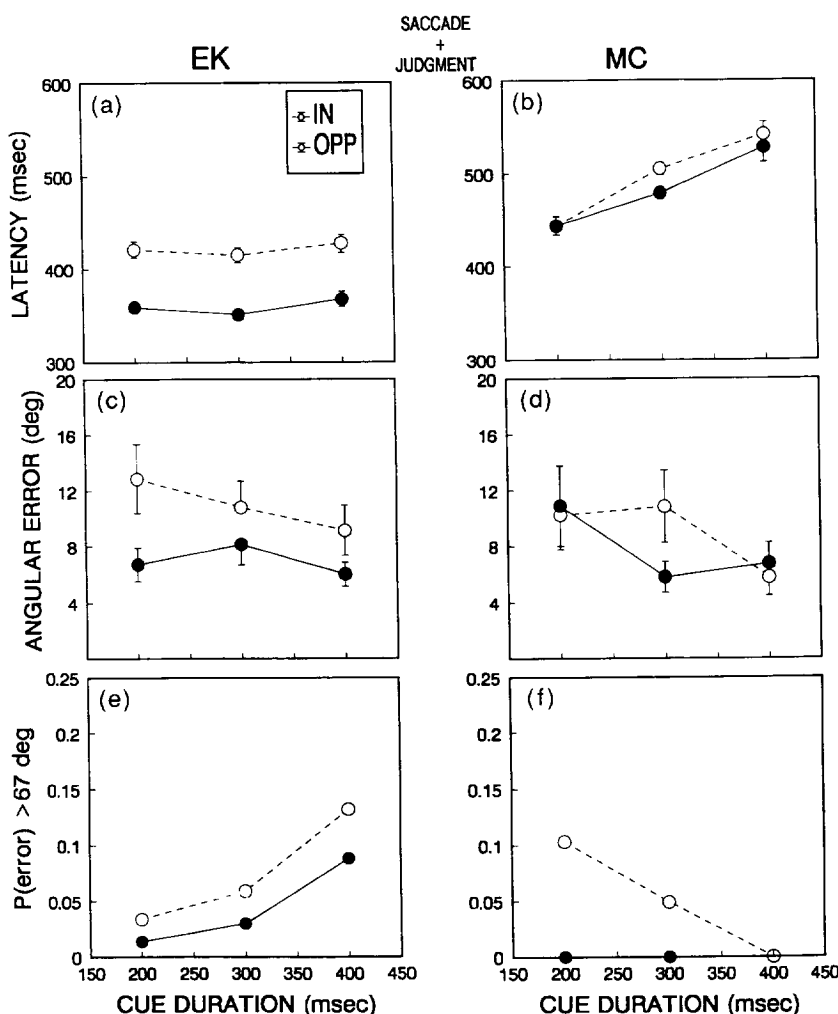


FIGURE 3. Saccadic latency (a and b) and mean angular error (c and d), and proportion of trials with an angular error of > 67 degrees for saccades made *IN* the direction of the numeral (●) and *OPPOSITE* to the numeral (○) as a function of the duration of Frame 2. Each datum point is based on approx. 60 trials for EK and 30 trials for MC. Error bars represent 1 SE.

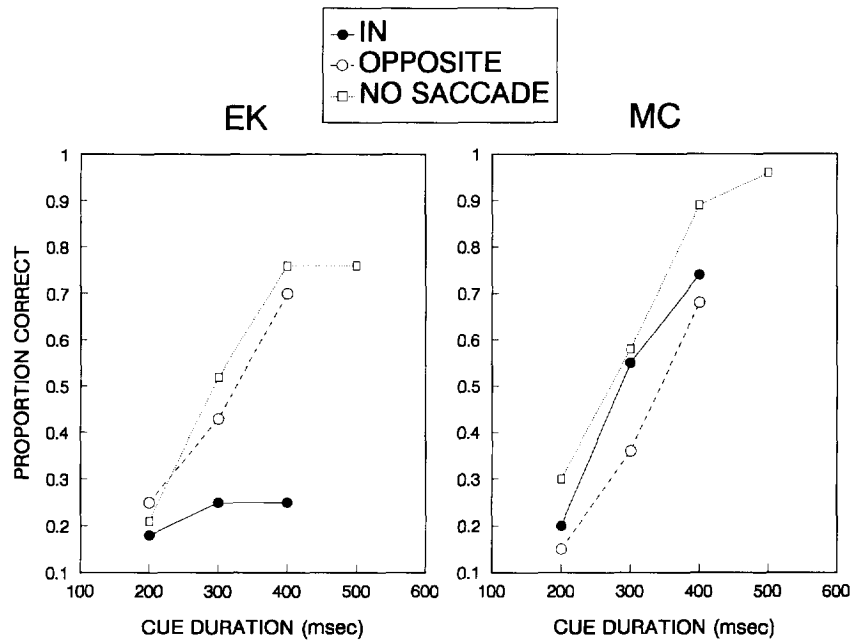


FIGURE 4. Proportion of letters identified correctly when making a saccade *IN* the direction of the numeral (●), *OPPOSITE* to the numeral (○), or when not making saccades at all (□), as a function of cue duration. Each datum point was based on approx. 60 trials for EK and 30 trials for MC.

Experiment 1b: Discussion

The logic behind this experiment was the same as that employed in prior work on saccades and attention summarized in the *Introduction*, namely: Finding superior perceptual performance for targets at the goal of the saccade supports the involvement of attentional shifts in saccadic programming. Equivalent performance for targets at goal and non-goal locations would suggest independence of saccades and attention. The prior experiments (e.g. Posner, 1980; Klein, 1980; Klein *et al.*, 1992; Remington, 1980; Shepherd *et al.*, 1986; Subramaniam & Hoffman, 1992) obtained conflicting results, some supporting a link between saccades and attention and others supporting independence. We obtained the same pattern of conflicting results within a single experiment. MC's pattern of performance was like that in prior studies in which independence of saccades and attention was observed, while EK's pattern of performance was like that in prior studies in which evidence for attention shifts preceding saccades was found.

Individual differences as large as those we observed are usually regarded as falling somewhere between a nuisance and a disaster, but in this case the outcome proved to be fortunate because it forced us to devise new and better methods. The best guess about the source of the individual differences is that shifts of attention do precede saccades, but the subjects used different strategies: EK kept latency short at the expense of letter identification while MC increased latency in order to identify the letter correctly. If this interpretation is correct, then the key to developing a method to study the relationship between saccades and attention will be to encourage each subject to adopt each of the two strategies. This will allow determination of the increase in saccadic latency that is required in order to

identify target letters correctly at non-goal locations. Finding any increase at all indicates a role for perceptual attention in saccadic programming. The magnitude of the increase is an index of the extent to which saccades require attentional resources.

The remaining experiments required subjects to adopt different strategies. We began by simplifying the stimulus and expanding the instructions in ways that seemed likely to be able to place strategies under experimental control. In doing so, we hoped to determine conclusively whether shifts of attention do or do not precede saccades and, in addition, assess the attentional demands of the saccades by comparing performance under instructions to emphasize either the saccadic or the perceptual tasks.

Experiment 2: Central Cues

Once again, concurrent saccadic and perceptual tasks were performed. The main new feature is that a simple central cue—a single pointer directed to one of the letters—was used to designate the saccadic goal instead of an eccentric numeral. Identifying the orientation of this pointer is easier and faster than the numeral search task used in Experiment 1. By switching to this easier and faster task, there would be less opportunity for subjects to sneak attentional glimpses of the eccentric targets, a trick that could improve perceptual performance without cost to saccades.

Performance was compared under two different conditions. In the *Random report* condition, the subject had to make the saccade as soon as possible following the appearance of the central pointer and, after the trial, identify a letter chosen at random from the 8 letters in the display. If shifts of attention precede saccades, then identification should be better for letters located at the saccadic goal than for letters located elsewhere. Of course,

subjects may simply decide to shift attention to the saccadic goal even if they do not have to. To test this possibility, a *Fixed report* condition was included in an attempt to force a dissociation between saccades and attention. In the *Fixed report* condition, subjects were asked to try to identify a letter at the same location on each trial, sacrificing saccadic latency if necessary, *but only as much as necessary*, to identify the letter. Any increase in saccadic latency in the *Fixed report* condition relative to that in the *Random report* condition would reflect the cost of having to move perceptual attention from the perceptual target location to the goal of the saccade or, alternatively, the cost of having to attend to two locations (saccadic and perceptual targets) concurrently. On the other hand, if accurate perceptual reports in the *Fixed report* condition were obtained with no increase in saccadic latency, we would have evidence that perceptual attention was *not* required in order to program saccades, and that a subject could program saccades to one location while paying attention to a stimulus located elsewhere.

Experiment 2: Method

Stimulus

Three frames were presented, all containing 8 letters. Frames 1 and 3 were masks (duration = 500 msec). The critical frame was Frame 2 (200 msec), which contained a 30' centrally-located pointer directed to the letter that was to be the target of the saccade (see Fig. 5). One of the letters in Frame 2 (selected at random) would have to be reported at the end of the trial. This letter was chosen from the same set (J-N; T-X) used in Experiment 1B. The other display locations could contain any letter, including those in this set. Feedback was given by displaying Frame 2 for 500 msec after the response was given.

Procedure

In the *Random report* condition, subjects were instructed to make a saccade as quickly as possible to the letter designated by the central pointer. At the end of the trial, a letter Q appeared at one of the 8 display locations, chosen at random. The subject had to report the letter that had appeared in that location by means of a button press. If attentional shifts precede saccades, perceptual identification should be better for a letter located at the saccadic goal than for letters located elsewhere.

In the *Fixed report* condition, the subject was required to report correctly the letter in the rightmost location of the display. Saccadic latency was to be sacrificed, if necessary, but *only as much as necessary*, to achieve perfect perceptual identification.

Two conditions were included in which *no saccades* were made. This was done in order to compare the effectiveness of attention shifts made while the eye was stationary with the effectiveness of any attention shifts preceding saccades. In the *Random report/no saccade* condition, subjects were instructed to shift attention to the letter indicated by the central cue while the line of sight remained fixated at the center of the display. The letter to

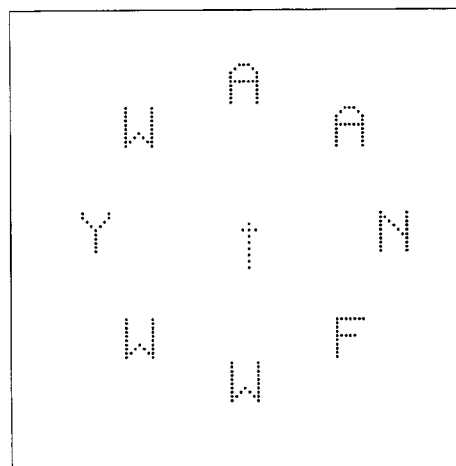


FIGURE 5. An example of the character array used in Experiments 2 and 3. The central pointer (in this example directed downward) indicated the target of the saccade.

be reported was selected randomly at the end of the trial. In the *Fixed report/no saccade* condition, the letter in the righthand location was reported while the line of sight remained at the center of the display. Letter identification in the *Fixed report/no saccade* condition was perfect, confirming that the letters could be resolved clearly and that any perceptual errors observed in the remaining 3 conditions (*Random report*, *Fixed report* and *Random report/no saccade*) were due to inattention, not to poor visual acuity. Results from the *Fixed report/no saccade* condition will, therefore, not be described further since this experimental condition had served its intended purpose.

Random and *Fixed report* conditions were tested in separate experimental sessions (100 trials each). Each subject was tested in 3 replications of the 3 types of sessions (*Random report*, *Fixed report* and *Random report/no saccade*), with the sessions ordered haphazardly within a replication. Both then ran one additional *Fixed report* session to allow further observation of practice effects.

Eliminated trials

Trials were eliminated as follows: loss of eye tracker lock (5% for EK and <1% for MC), error of the first saccade > 50' (4% for EK and 11% for MC) and directional error > 67 deg (3% for EK and 2% for MC). The results reported were based on the remaining 498 trials for EK and 683 trials for MC.

Trials with more than one saccade

In an attempt to keep saccadic latency as short as possible, the instruction used in Experiment 1 to reach the goal with a single saccade was relaxed. As expected, this new instruction caused an increase in the proportion of trials containing more than one saccade for MC, whose proportion rose to 0.29 from his previous values of 0.12 in Experiments 1A and 1B. The proportion of trials with more than 1 saccade was 0.25 for EK, about the same as her previous values of 0.22 (Experiment 1A) and 0.27 (1B).

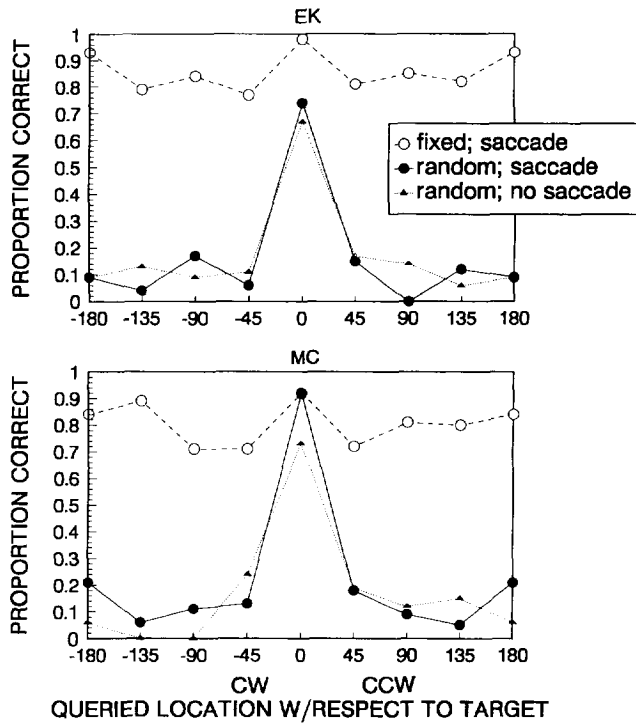


FIGURE 6. Proportion of letters identified correctly as a function of letter location with respect to the saccadic target. ○, Performance when the letter to be reported was in a fixed (righthand) location throughout the session; ●, when the location was selected randomly. ▲, Performance when the reported location was random and no saccades were made. Each datum point represents approx. 30–40 trials.

Experiment 2: Results

Random report

In the *Random report* condition, letters at the saccadic goal were identified accurately in 70–90% of the trials,

while performance was near chance levels for letters located elsewhere (Fig. 6, filled circles). Stated differently, subjects usually remembered only one of the 8 displayed letters, with the particular letter remembered coinciding with the goal of the saccade. This suggests that perceptual attention does shift to the intended endpoint of the saccade (see Reeves & Sperling, 1986, who show how attention can be modeled as the “gateway” to visual memory). Performance was almost the same when the line of sight remained stationary and the subject was instructed to shift attention to the letter indicated by the pointer (Fig. 6, triangles). This shows that attentional shifts before saccades were no more or less effective than attentional shifts made while the eye was stationary.

Fixed report

In the *Fixed report* condition, subjects were told to identify the letter in the rightmost location, even if a sacrifice in saccadic performance was needed to accomplish this. We found that, in accordance with these instructions, identification of the letter in the rightmost location was very accurate (70–100% correct) (see Fig. 6, open circles). The important result was that this excellent perceptual performance was achieved at the cost of an increase in saccadic latency for both subjects of 50–75 msec, and, in addition, an increase in average angular error (up to 5 deg) for EK, as is shown in Fig. 7.

Two additional analyses

(1) *Latencies as a function of location.* Was there better performance in the *Fixed report* condition when the randomly-selected saccadic target happened to fall at the rightmost location, where attention had been directed at the start of the trial? EK’s saccadic latencies were shortest

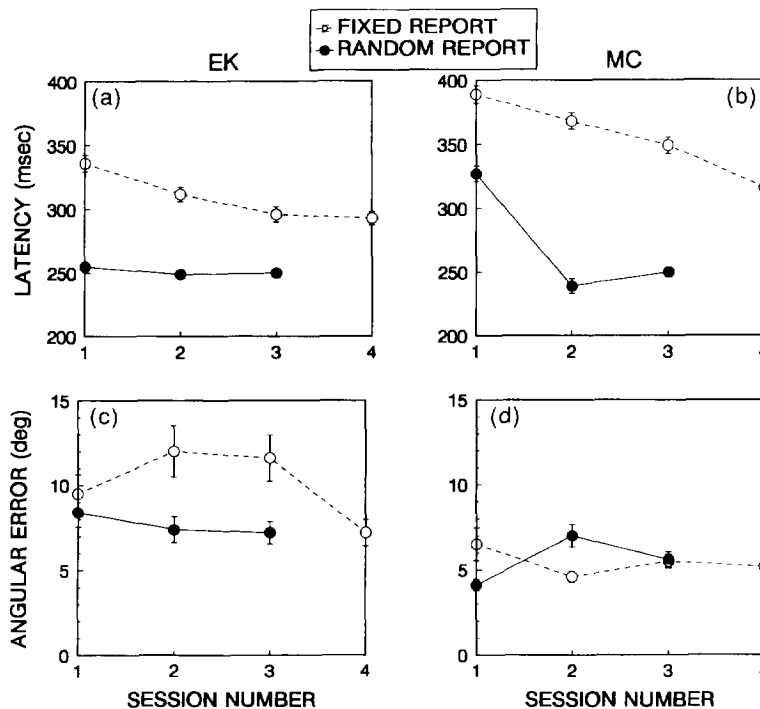


FIGURE 7. Saccadic latency (a and b) and average unsigned angular error as a function of session number. Each datum point is based on approx. 85 trials. Error bars represent 1 SE.

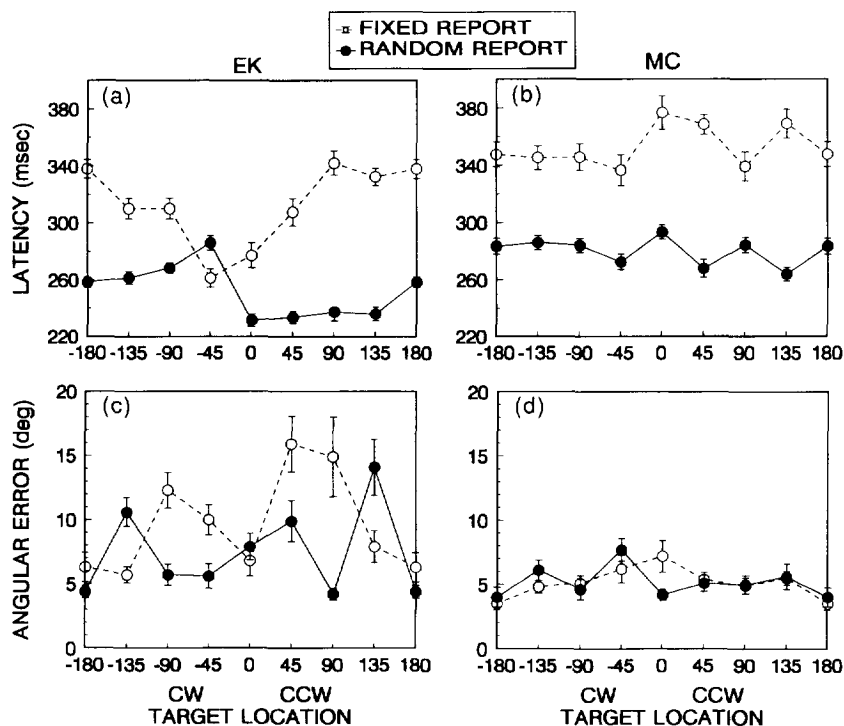


FIGURE 8. Saccadic latency (a and b) and average unsigned angular error (c and d) when the letter to be reported was at a fixed (○) or random (●) location as a function of the location of the saccadic target. Zero on the abscissa represents the righthand location. Each datum point is based on approx. 30–40 trials. Error bars represent 1 SE.

and directional errors smallest when she looked in the rightmost location (indicated by 0 on the abscissa of Fig. 8). But MC's latencies for the rightmost location were among his longest. MC was not asked to prepare for the rare trials in which he would be asked to look where he was already attending, and such trials may have had longer than usual latencies because they represented an infrequent (12.5%), hence, unexpected, event.

(2) *Directional errors.* The signed directional errors of saccades were quite small (5 deg) and not biased toward the rightmost location containing the perceptual target. But the rare trials (2–3%) eliminated because of very large directional errors (>67 deg; see *Methods*) showed a different pattern. All of the large errors occurred in the *Fixed report* condition, showing that the attempt to dissociate saccades and attention disrupted saccadic accuracy on at least a small proportion of the trials. EK's errant saccades had very short latencies (<200 msec) and were usually directed toward the perceptual target. But most of MC's saccades with large directional errors had long latencies (about 400 msec), and were usually directed either upward or downward. Thus, his large saccadic errors on a few rare trials were due to confusions about where to look rather than to the diversion of attention to the perceptual target.

Experiment 2: Discussion

There were two main results. The first was that in the absence of information about which letter would have to be identified (*Random report*), perceptual performance was accurate at, and only at, the goal of the saccade.

Performance at other locations was near chance. This result, by itself, suggests a saccadic/attentional link. The second main result was that attempts to dissociate the locus of perceptual attention from the saccadic goal (*Fixed report*) were unsuccessful. Subjects preparing to make a saccade in the direction of a randomly-oriented pointer had to prolong latency (by 50–75 msec) whenever they were also required to identify a letter at a different location. The crucial aspect of the task that led to the longer latencies was the different locations of the perceptual and saccadic target, not the requirement to identify a character, because characters at the saccadic goal were identified equally well in both the *Random* and *Fixed report* conditions. The difference between *Random* and *Fixed report* latencies is consistent with the idea that attention must be allocated to the goal of the saccade. The results also suggest that the attentional demands of saccades, although real, may be relatively modest, given that increases in latency of <75 msec produced substantial benefits to perceptual performance at locations different from the saccadic goal.

The next experiments (3 and 4) follow-up two aspects of the demonstration that attention is allocated to the saccadic goal. Experiment 3 deals with the spatial extent of the region attended preceding saccades. Experiment 4 will employ a more elaborate methodology, drawn from the attentional literature, to examine the relationship between perceptual attention and saccades, and to obtain a more precise description of the demands that saccadic programming and execution place on attentional resources.

Experiment 3: Cue Between Two Characters

This experiment was the same as the *Random report* condition of Experiment 2 except that the central pointer was directed between two letter locations and subjects were required to identify either of the two letters (selected at random). We wanted to find out whether attention shifted to the precise location of the saccadic endpoint (in which case, neither letter would be identified accurately), or, alternatively, whether attention shifted to a larger region surrounding the saccadic goal (in which case both letters might be identified accurately). If the results turned out to favor the attentional-regions hypothesis, it would mean that perceptual attention, by itself, is not the only factor determining the precise location of the saccadic endpoint. Instead, precise positioning of the saccade would depend either on a separate, non-attentional mechanism, or else on a lower-level process that determines the saccadic endpoint by pooling information within spatially attended regions.

Experiment 3: Method

Stimulus and procedure

Stimuli and procedure were the same as those of the *Random report* condition in Experiment 2, except that the pointer was directed midway between two randomly selected letters. Subjects were instructed to make a saccade to the location indicated by the pointer. At the end of the trial, one of the two letters surrounding the pointer, selected at random, had to be identified. Each subject ran in one 100-trial session.

Eliminated trials

Trials were eliminated as follows: loss of eye tracker lock (8% for EK), error of the first saccade $> 50'$ (2% for EK and 20% for MC) and directional error > 67 deg (1% for MC). The results reported were based on the remaining 90 trials for EK and 79 trials for MC.

Experiment 3: Results

Saccades directed midway between a pair of letters were less accurate than those directed to a letter. Average angular error was 12 deg for EK (in comparison to an error of 8 deg for saccades to a letter in the *Random report* condition of Experiment 2) and 9 deg for MC (in comparison to an error of 7 deg in *Random report*). Nevertheless, these angular errors were substantially smaller than half the inter-letter separation (which was 22.5 deg), showing that saccades, for the most part, landed in between the letter pairs, rather than at one or the other letter.

If attention were confined to the precise location of the saccadic endpoint, then we would expect perceptual identification of the letters to be poor. Perceptual identification was not poor. Subjects were correct about half the time (see Fig. 9), regardless of which letter they were asked to report. In other words, they were usually able to identify one of the two letters surrounding the saccadic goal, which was located midway between them.

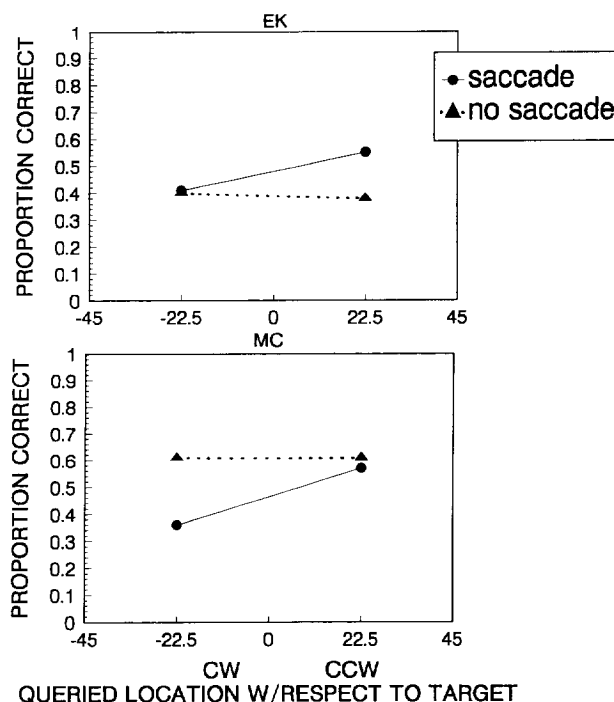


FIGURE 9. Proportion of letters identified correctly as a function of letter location relative to the saccadic target location when saccades were aimed between two letters (●) and when saccades were not made (▲). Each datum point is based on approx. 40 trials.

This was about the same as perceptual performance when saccades were not made and subjects were simply required to shift attention in the direction indicated by the pointer (Fig. 9). Both subjects were slightly better when asked to identify the letter that was counterclockwise with respect to the saccadic goal, but there was no counterclockwise bias for judgments made when saccades were not made.

Figure 10 shows the relationship between letter identification and the endpoint of the saccade. When subjects were asked to identify the letter located clockwise with respect to the pointer, they were more likely to be correct when the angular error of the saccades was in a clockwise direction. Similarly, when identifying the letter located counterclockwise with respect to the pointer, they were more likely to be correct when the saccadic error was counterclockwise.

Experiment 3: Discussion

The ability of subjects to identify one of the two letters surrounding the saccadic goal shows that attention need not be confined to the precise locus of the saccadic endpoint. Either dissociations between the locus of attention and the endpoint of the saccade are possible when saccadic and perceptual targets are close together, or alternatively, attention is allocated to an extended region of space and a lower-level sensorimotor process determines the precise saccadic endpoint by pooling information in the attended region. The relationship between the angular error of saccades and the accuracy of letter identification (Fig. 10) lends support to the latter (attentional regions) hypothesis, however, additional work is needed to resolve the issue completely.

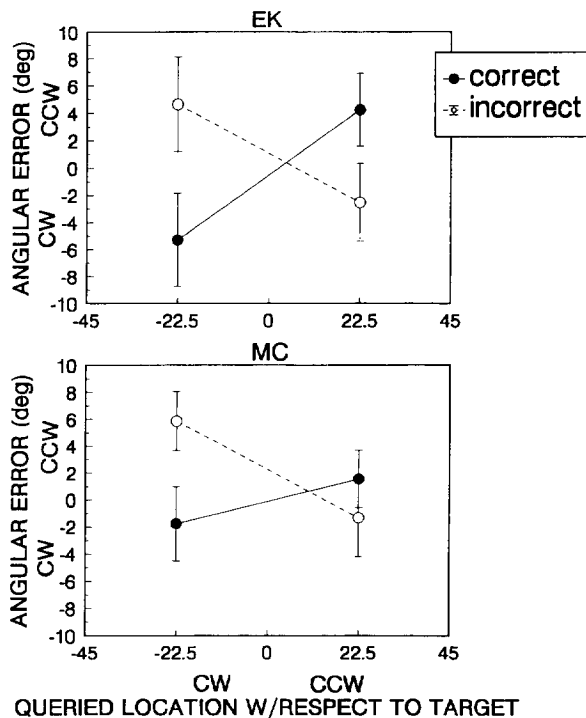


FIGURE 10. Mean unsigned angular error of saccades as a function of the location of the reported letter relative to the saccadic target for correct (●) and incorrect (○) reports. Each datum point is based on approx. 20 trials. Error bars represent 1 SE.

Experiment 4: Attentional Operating Characteristic

In this experiment, we take a closer look at the sacrifices of saccadic performance that are needed in order to identify targets accurately at locations other than the saccadic goal. We found such sacrifices in Experiment 2, when subjects increased saccadic latency by 50–75 msec in an attempt to follow the instruction to avoid any perceptual identification errors at non-goal locations. Increases of this magnitude might not have been necessary. It is possible that a less conservative strategy would have been successful as well, resulting in excellent perceptual performance with a smaller increase in saccadic latency.

To explore the effects of different latency-strategies on perceptual performance, we turned to techniques developed previously for determining whether two perceptual tasks draw on a common pool of attentional resources (Norman & Bobrow, 1975; Navon & Gopher, 1979; Sperling & Melchner, 1978; Sperling & Doshier, 1986). To answer this question, we did experiments that would allow us to determine the “attentional operating characteristic” (AOC), which describes the functional relationship between the performance of two concurrent tasks. The AOCs will allow us to determine whether, and by how much, performance on one task (e.g. making saccades) must be sacrificed for performance on another (e.g. identifying letters). The unique characteristic of the AOC is that performance is measured under instructions to assign different priorities to one or the other task.

Determining an AOC requires a larger number of experimental conditions and trials, and makes a greater

demand on a subject’s ability to maintain consistent assignments of task priorities, than the techniques we (and others) have used so far to study attention and saccades. Despite these challenges, measuring an AOC is appropriate at this stage of the research, once links between saccades and attention have been demonstrated (Experiments 1–3), because the AOC is the best way to study the effects of small changes of strategy on performance. The AOC allows us to avoid confounding the effects of the strategies used to allocate attentional resources from the effects of the resources themselves on the performance of the task. For a detailed treatment of the theoretical bases for interpreting the AOC, and for many examples of AOCs obtained from different perceptual tasks, see Sperling and Doshier (1986).

Experiment 4: Method

Stimulus and procedure: random and fixed saccades

The stimulus was the same set of 3 frames (pre-mask, cue, post-mask) used in Experiments 2 and 3. There were two main conditions, *Random saccades* and *Fixed saccades*.

In the *Random saccade* condition, the subject was always required to report the letter in the rightmost display location and, in the same trials, to make a saccade in the direction indicated by the central cue. The letter in the rightmost location was chosen from the usual critical set (J–N; T–X). The direction of the saccade was selected at random and indicated by the central cue (in Frame 2), which pointed to one of the 8 letters. Subjects ran under 3 types of instructions, which controlled the relative weight subjects were to assign to each of these tasks. The first instruction was to give priority to the perceptual task (P), prolonging saccadic latency if necessary, but only as much as necessary, to achieve perfect perceptual performance. The second instruction was to give priority to the saccadic task (S), which meant keeping saccadic latency as short as possible and sacrificing perceptual accuracy if necessary. The third instruction was to achieve a level of performance intermediate (I) between the two extremes. Each instruction was tested in separate experimental sessions.

In the *Fixed saccade* condition, which was tested after the *Random saccade* testing was completed, both the goal of the saccade (indicated, as usual, by the pointer) and the location of the letter to be reported remained the same throughout the session. In some types of *Fixed saccade* sessions, subjects were required to look upward and report the letter in the leftmost location. In other types of *Fixed saccade* sessions, subjects looked to the left and reported the letter in the top location. Some other changes were made. The critical letter set was changed to A through E and P through T. Also, the durations of the frames were changed to take into account the decrease in saccadic latency that occurs when saccadic direction is known in advance of the trial. Specifically, Frame 2 (containing the pointer and critical letter) was reduced to 130 msec, to avoid having saccades occurring while the critical letter was still displayed. Also, the duration of

Frame 1 (the pre-mask) was random (400–700 msec) to introduce uncertainty about when the saccade would be required, thus reducing the likelihood that the subject would be able to precisely time an accurate saccade to coincide with the onset of Frame 2. The same 3 instructions used in the *Random saccade* condition were again tested in the *Fixed saccade* condition (priority to perception, priority to saccades, intermediate priority).

Single task

To establish a baseline against which any trade-offs between saccadic and perceptual performance can be evaluated, we ran two additional conditions. In one (*saccade only*) either the *Random* or *Fixed* saccadic task was performed by itself and no reports of letters was taken. In the other (*perception only*) the letter in the location tested in the *Random* and *Fixed saccade* conditions was reported, and no saccades were made.

Trying to achieve independence

Two other conditions were tested after the *Fixed saccade* sessions were completed. Subjects were given a final opportunity to try to dissociate saccades and attention after they had experience in doing each of the tasks (saccade-only and perception-only) by themselves. They were asked to try to perform the saccadic and perceptual tasks together as well as they had just performed each task alone. For some of these sessions, the location of the saccadic goal and letter to be identified were *different* (specifically, either look up and identify the letter on the left, or look to the left and identify the letter on top). For the remaining sessions, the locations of the saccadic goal and the letter to be identified were the *same* (either up or left).

Order of testing

Subjects ran in two replications (60 trials/session) of the 5 different conditions for both the *Random* and the *Fixed saccade* sessions. The order of testing in the first replication was: priority to perception, priority to saccades, intermediate priority, saccades only and perception only. The order was the same for the second replication except that “priority to perception” and “priority to saccades” were reversed. *Random saccade* sessions were tested before *Fixed saccade* sessions. The 4 sessions in which the subject was asked to try to perform the saccadic and perceptual tasks together as well as they performed each alone were tested last. These 4 sessions were run over two days, with a session in which the saccadic and perceptual targets were at different locations and one in which the targets were at the same location run on each day.

Eliminated trials

Trials were eliminated as follows: loss of eye tracker lock (2% for EK and 0.6% for MC), latencies < 100 msec (2% for MC), error of the first saccade > 50' (4% for EK and 10% for MC) and directional error > 67 deg (< 1% for EK and 0.4% for MC). The results reported were based on the remaining 1103 trials for EK and 1037 trials for MC.

Experiment 4: Results

The trade-off of processing resources

Figure 11 shows the AOC, with the percentage of correctly identified letters plotted against saccadic latency. Note that the values along the latency axis are

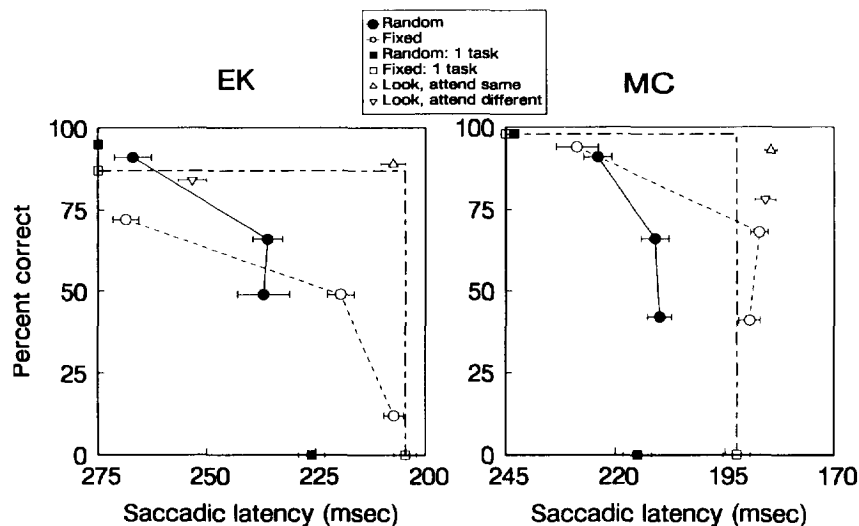


FIGURE 11. Attentional operating characteristic (AOC) curves showing saccadic latency (abscissa) and proportion of correctly identified letters (ordinate). The location of the letter to be reported remained the same throughout the session. The saccadic target was either selected at random (●, ■) or remained fixed throughout the session (○, □, △, ▽). The 3 circles in each function show performance under instructions to give priority to the saccadic task (lower circles), to the perceptual task (upper circles) or to adopt an intermediate priority (middle circles). Squares, plotted on the axes, show performance when doing only one task, either the saccadic or the letter identification task. The intersection of the dashed lines emanating from the open squares represents the independence point, i.e. the point at which there would be no interference in the performance of the two concurrent tasks. The triangles represent attempts to achieve the independence point by trying to minimize latency and maximize letter identification simultaneously. Saccadic and perceptual targets were either at the same (upright triangle) or different (inverted triangle) locations.

Each datum point was based on approx. 100 observations. Error bars represent ± 1 SE.

inverted, in keeping with the convention of representing improvements in performance in AOCs by moving to the right (Sperling & Doshier, 1986). The results show how performance on the saccadic task was traded for performance on the perceptual task. To examine the trade-off, we need to describe Fig. 11 in some detail.

Performance in the *Random saccade* condition is shown by the filled symbols and in the *Fixed saccade* condition by the open symbols. The squares, plotted along the axes, show the performance obtained when either the saccadic or the perceptual task was done alone. The intersection of these "task alone" values is the "independence point" (shown in Fig. 11 for the *Fixed saccade* condition). If the saccadic and perceptual tasks can be done concurrently as well as each can be done alone, then performance will fall at the independence point.

Performance never reached the independence point. To see this, we need to look at the functions (circular symbols) showing how performance varied under the three different attentional instructions that were used. In each function, performance shown by the upper-leftmost circle was obtained under the instruction to give priority to the perceptual task (P), and the lower right-most circle under the instruction to give priority to the saccadic task (S). The performance shown by the circle in the middle was obtained when subjects were asked to adopt a strategy intermediate between these two extremes (I). If saccadic and perceptual tasks do not compete for the same processing resources, performance would fall at the independence point. Figure 11 shows that instead of independence, improvement on the perceptual task was achieved at the expense of performance on the saccadic task. This result was obtained for both the *Random* and *Fixed saccade* conditions.

Random and *Fixed saccades* were somewhat different in that the *Random* saccadic latencies were longer, and the differences among the latencies under the different instructions was smaller, than in the *Fixed saccade* condition. The differences among the 3 latencies in the *Random saccade* condition were smaller for MC than for EK (see Fig. 11). Analysis of variance confirmed that MC's latencies in the *Random saccade* condition were significantly different from one another [$F(2,343) = 6.45$, $P < 0.01$].

Were subjects trying as hard as they could to reach the independence point? The inverted triangles in Fig. 11 show what happened in the *Fixed saccade* condition under the instruction to do both saccadic and perceptual tasks concurrently as well as each could be done alone. Performance missed the independence point when saccadic and perceptual targets were in different locations (inverted triangles). Subjects missed the independence point in different ways. EK's sacrificed saccadic latency (mean = 253 msec, SD = 34, $N = 113$, when trying to reach the independence point vs 205 msec, SD = 27, $N = 109$, when doing the saccadic task by itself). MC sacrificed perceptual performance (78% correct, $N = 98$, when trying to reach the independence point vs 98% correct, $N = 120$, when doing the perceptual task by itself;

the difference was highly reliable; $\chi^2 = 23$, $df = 1$, $P < 0.001$).

Performance fell closer to the independence point in one special case, namely, when perceptual and saccadic targets were the same (upright triangles in Fig. 11). This shows that the observed trade-off was not between making saccades and identifying targets, but rather between the requirement to pay attention to two different locations.

Shifting small amounts of attention to the perceptual target

A striking characteristic of the AOCs in Fig. 11 was that considerable improvement in perceptual identification was achieved at the cost of little or no increase in saccadic latency. This unexpected result can be seen by comparing performance under the "priority to saccades" and the "intermediate priority" instructions (i.e. the middle and lower data points of each AOC). Perceptual performance well above chance was achieved with saccadic latencies that were either the same as (MC) or slightly longer than (EK) the latencies observed when the saccadic task was done alone. Achieving the best possible perceptual performance (which in our task approached 100% correct) required a much larger increase of saccadic latency.

Saccadic accuracy

Examining saccadic accuracy was important because subjects might have chosen to sacrifice saccadic accuracy, as well as latency, in order to improve perceptual performance at non-goal locations. If this were the case, then the latency AOCs, shown in Fig. 11, underestimate the cost of giving priority to the perceptual task and a complete picture requires presentation of accuracy data as well. It is, of course, possible that the saccadic latencies were sufficiently long so that the accuracy obtained in the *saccade only* condition would be maintained even under instructions to give priority to the perceptual task.

Figure 12 shows the AOCs in which the measure of saccadic performance is average unsigned angular error. There was no sacrifice in accuracy in the *Random saccade* condition; errors did not vary with the instruction (S, I or P) and were about the same as those observed in the *saccade only* condition. In the *Fixed saccade* condition, the errors were smaller and the AOCs resembled the latency AOCs (Fig. 11) in that:

- (1) accuracy was sacrificed for improvements in perception;
- (2) a large improvement in perceptual identification was achieved with little or no sacrifice of saccades (instructions S vs I), but achieving maximal perceptual performance (instruction P) required a sacrifice of saccadic accuracy, just as it had required a sacrifice of latency;
- (3) subjects failed to reach the independence point when saccadic and perceptual targets were in different locations.

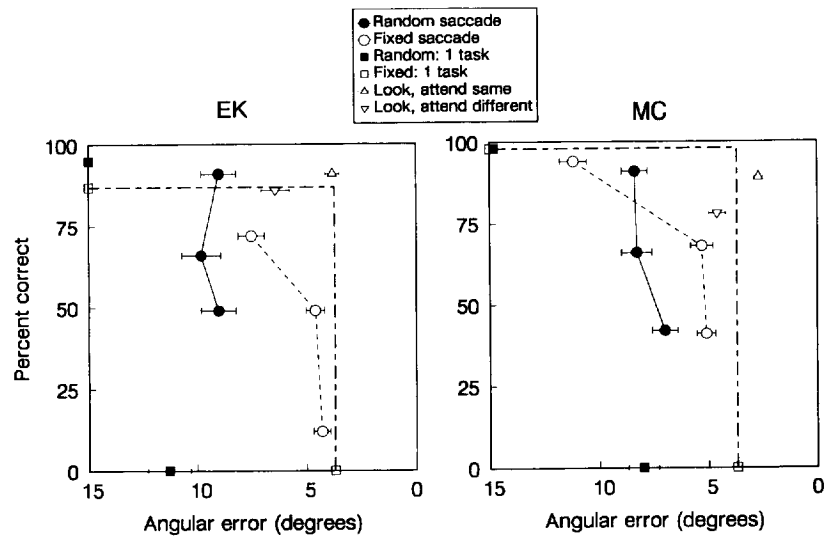


FIGURE 12. Same as Fig. 11, except that unsigned angular saccadic error is plotted on the ordinate.

We assume that saccadic accuracy in the *Fixed saccade* condition under the instruction to give priority to perception would have been better had latency been prolonged even further. Thus, the longest latency shown in Fig. 11 for the *Fixed saccade* condition underestimates the time required to achieve both accurate perceptual performance and accurate saccades.*

Experiment 4: Discussion

It is not possible to prepare to look to one location, while simultaneously, and without cost, making accurate perceptual judgments about an eccentric target located elsewhere. Making saccades requires a shift in perceptual attention to the saccadic goal.

The attentional demands of saccades were observed both when the location of the saccadic goal was known before the trial (*Fixed saccade*) and when the location had to be determined during the trial (*Random saccade*). Finding a trade-off in both of these conditions means that the role of attention is not limited to specifying the initial selection of the saccadic goal. Had it been, then the trade-off between saccadic and perceptual performance would have been found only when the location of the saccadic goal was chosen randomly. In fact, the observed trade-off was weaker in the *Random saccade* condition, as shown by the smaller difference between saccadic latencies under the two extreme instructions (i.e. give priority to the perceptual and give priority to the saccadic

tasks) (Fig. 11) and by the absence of an effect of instructions on accuracy (Fig. 12). The weaker trade-off between saccades and perceptual performance in the *Random saccade* condition implies that at least some of the operations unique to the *Random saccade* task (such as identifying the direction of the pointer on each trial and choosing the saccadic target) may not have interfered with the sampling of information from the perceptual target. Some processing of the perceptual target might have occurred with no cost to saccades while identification of the pointer direction and other high-level aspects of target selection were in progress. Thus, the competition for attentional resources between the saccadic and perceptual target appears to be most acute, not during high-level aspects of target selection, but rather further downstream, closer to the time of construction of the saccadic program for immediate execution.

We found strong evidence for the involvement of attention in saccadic programming, but at the same time we found that paying too much attention to the saccadic target was inefficient. We found that when the subject switched from the instruction to give priority to saccades (S) to the instruction to adopt an intermediate priority between saccadic and perceptual tasks (I), substantial improvement in the perceptual task was achieved with little or no cost to saccades. Analogous results have been obtained for smooth pursuit (Khurana & Kowler, 1987). The same was *not* true for our perceptual task. We found no region in which the withdrawal of attention was harmless.

This outcome shows that increasing the amount of attention benefits saccadic performance, but only up to a point. The diminishing returns of allocating increasing amounts of attention to the saccadic task is illustrated in Fig. 13, which shows hypothetical performance–resource functions (Norman & Bobrow, 1975) that might have given rise to the AOCs we observed in Figs 11 and 12. The performance–resource function for the perceptual task is nearly linear, while that for the saccadic task (where performance is represented by latency) levels off with

*It is possible that subjects showed better saccadic performance in the *Fixed* than in the *Random saccade* condition because the two saccadic target locations tested in the *Fixed* condition (left and up) were easier than the other locations. To determine if it was easier to look in these two directions, we examined latency and angular error for the *Random saccade* condition at these two positions, and compared them to the mean latency and angular error across all positions. Differences were small, indicating that the differences between the *Fixed* and *Random* AOC curves were not due to target location.

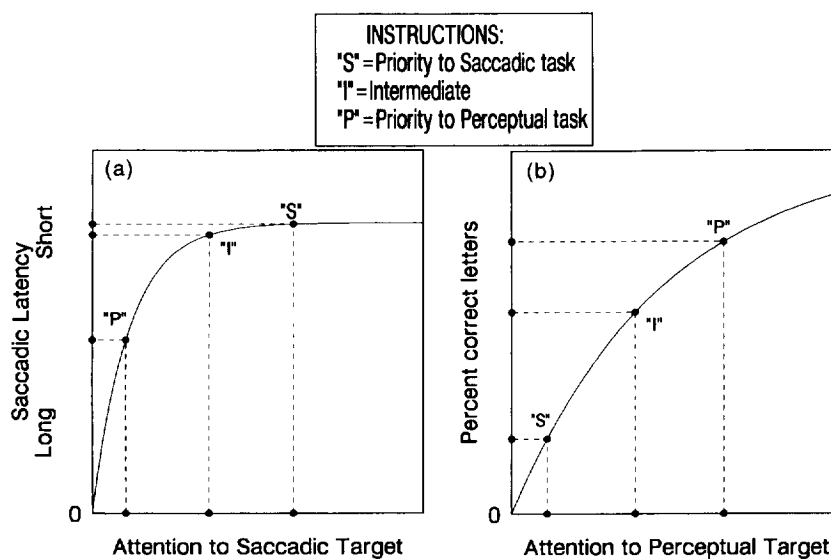


FIGURE 13. Hypothetical performance resource functions demonstrating the effect on task performance of varying attentional allocation. (a) Shows saccadic latency as a function of the amount of attention allocated to the saccadic target; (b) shows the percentage of correctly identified letters as a function of the amount of attention allocated to the perceptual target. The 3 labeled points represent the 3 instructions: give priority to the saccadic task (S), the perceptual task (P) or adopt an intermediate strategy (I).

increasing amounts of allocated attention, i.e. allocating increasing amounts of attention to the saccadic task reduced the latency, but only up to some limit. To illustrate the effect of transferring attention from one target to another, we labeled 3 points S, I and P, to designate the hypothetical relationship between attention and latency under the 3 instructions tested (priority to the saccadic task, S, the perceptual task, P, or intermediate priority, I). When moving from point S to point I, for example, attention is shifted from the saccadic to the perceptual target. Saccadic latency increases only slightly with the drop in allocated attention while perceptual performance improves substantially.

We do not know whether the diminishing returns of allocating increasing amounts of attention is a general characteristic of saccadic tasks, or whether increasing amounts of attention would become more valuable when the difficulty of the saccadic task is increased by, for example, increasing the required precision of the movement. Nevertheless, this is an intriguing result because it suggests that the saccadic system (and pursuit as well; Khurana & Kowler, 1987) protects us against the folly of paying too much attention to motor control and ignoring the very targets that the eye movements are there to help us perceive.

GENERAL DISCUSSION

Accurate saccades require shifts of perceptual attention to the target. We have shown this by finding effects of attention-catching stimuli on saccades (Experiment 1), by demonstrating superior perceptual judgments at the saccadic goal (Experiment 2), and by showing that the locus of perceptual attention cannot be fully dissociated from the goal of the saccade (Experiments 2 and 4). Our experiments differ from prior work, in

which conflicting results were obtained (see Introduction), in that we used a perceptual task that made demands on attentional resources and tested performance while subjects used a variety of specific and explicitly-defined strategies about apportioning effort between saccadic and perceptual tasks. We did this because both the prior work and our own results (i.e. the individual differences observed in Experiment 1B) suggested that, without such instructions, subjects may adopt idiosyncratic strategies, different from those intended by the experimenter. These idiosyncratic strategies preclude understanding the underlying relationship between attention and saccades.

Implications for models of the attentional/saccadic link

Our results are consistent with the idea that the same spatially-selective attentional mechanism that serves perception also determines the goal of the saccade. Attention may select an object or a spatial region as the saccadic goal, while the precise locus of the saccadic endpoint may depend on subsequent operations that pool spatial information exclusively within attended regions of space (see also He & Kowler, 1989, 1991; Morgan, Hole & Glennerster, 1990).

Any model of how attention accomplishes this task, and, in particular a model which is to be plausible at the neurophysiological level, would have to account for our findings that drawing a little attention away from the saccadic goal is harmless, and drawing too much attention away impairs either saccadic latency, accuracy or both. Considering how models would accomplish such a task is worthwhile, not only as a basis to interpret neurophysiological results, but also to understand events during natural scanning, when saccadic and perceptual tasks are being performed concurrently all the time. We

consider two ways of explaining the effects of attention on saccades.

The first we refer to as the *spatial* model. In this model attention can be allocated at the same time to two sites (the saccadic and the perceptual targets) during the entire saccadic latency period, with the subject having control over the strength of attentional activation at each site. In order to explain the reduction in saccadic latency that occurs when too much attention is diverted from the saccadic goal, we would assume that diverting attention slows processing by, for example, reducing firing rates or reducing the number of neurons participating in saccadic generation.

Using the spatial model to account for the effects of attentional diversion on saccadic accuracy, however, has some drawbacks. If the saccadic endpoint is determined by pooling information across all attended regions, then dividing attention between two widely separated regions of the visual display would produce large directional errors on most every trial. But we found that trials with large directional errors were extremely rare (2–3% in Experiment 2; 1% in Experiment 4). For the spatial model to be able to account for such a low error rate, the saccadic system would have to be able to distinguish the saccadic target from the perceptual target even when both regions receive equivalent amounts of attention. Making such a distinction would require yet another signal, in addition to perceptual selective attention, to identify the saccadic goal. Attention, by itself, would not be sufficient.

Another way to distinguish saccadic and perceptual targets working within the assumptions of the spatial model would be to have separate groups of neurons handle saccadic and perceptual selection. In order to account for the long saccadic latencies observed when too much attention was directed to the perceptual target, or the poor perceptual performance observed when too much attention was directed to the saccadic target, these separate groups of neurons would have to be able to inhibit each other's activity when perceptual and saccadic targets were in different places.

The *temporal model* is an alternative, and more straightforward, explanation for the effects of attention on saccades. According to the temporal model, the endpoint of the saccade is determined by the locus of attention during a critical segment of the saccadic latency period when a saccadic "go" signal is issued. Directing attention away from the saccadic goal during non-critical portions of the latency period (perhaps early in the latency period) would have no ill effects. Saccadic errors would result, however, when a saccade was initiated while attention was still at a non-goal location. Saccades would be accurate whenever the saccade was initiated after the shift of attention was completed (see Reeves & Sperling, 1986, for models of the time course of attentional shifts).

The *temporal model*, unlike the *spatial model*, does not require separate attentional areas for saccades and perception, nor does it require special signals to distinguish the saccadic target from non-targets.

It does require a distinction between systems that initiate saccades from those that determine the saccadic endpoint. If saccades are to be accurate while attention hops about the visual field, it is necessary for the saccadic go signal to be issued just as attention has settled at the saccadic goal. Issuing the go signal too early leads to errors; issuing it too late prolongs latency unnecessarily.

The assumption of a separate saccadic initiation area, responsible for relaying a saccadic go signal, but not for setting spatial parameters, is consistent with neurophysiological findings of fixational cells whose activity inhibits saccades and whose silence facilitates saccades. [See Munoz and Wurtz (1993a,b), for an example of such an area in the superior colliculus and a discussion of its possible role in saccadic control, and see Schlag, Schlag-Rey and Pigarev (1992) for a representative description of analogous cells in the cortex (supplementary eye fields).]

The temporal model has one other virtue. If the saccadic go signal could be pre-set to occur automatically in response to a transient change in the locus of attention, then optimal scanning performance would be ensured—optimal in the sense that saccadic errors would be small, latencies would not be unnecessarily prolonged, and on-line, time-consuming decisions would not be required, save for the control of attention itself. Saccadic scanning of complex displays would be easy, effortless and accurate—which is precisely the way things seem to be in everyday life.

SUMMARY

We developed novel methods to evaluate the role of attention shifts in saccadic performance and found that perceptual attention plays an important and necessary role in saccadic programming. It was not possible to plan a saccade to one target while paying full attention to another.

Two aspects of the attentional demands of saccades are noteworthy. First, modest diversions of attention away from the saccadic target were possible with little loss in saccadic performance. This limit on the attentional demands of saccades means that resources will be available for cognitive processing of the visual display. Second, the demands made by saccades on attention appear to concern aspects of saccadic programming itself, rather than "higher-level" decisions about target selection made well in advance of saccadic execution.

We described two models to account for our results, one in which attention is devoted simultaneously to perceptual and saccadic targets (spatial model) and the other in which attention shifts during the saccadic latency period (temporal model). The temporal model seems simpler, is more in line with current evidence from neurophysiological studies, and is able to account for the finely-tuned temporal coordination between attention shifts and saccades that is experienced by all of us.

Finally, our experiments employed new and effective methods, drawn from the attention literature, for studying concurrent perceptual and motor performance. These techniques were more successful than prior attempts to study concurrent saccadic and perceptual performance in that they established more stringent control over subject's strategies and in so doing allowed the attentional demands of the motor task to be determined unambiguously. Such techniques may prove to be of further value for understanding how human beings allocate limited processing resources during the performance of a variety of natural tasks with both perceptual and motor requirements.

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