

Programming Saccadic Eye Movements

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This article addresses questions about the preparatory processes that immediately precede saccadic eye movements. Saccade latencies were measured in a task in which subjects were provided partial advance information about the spatial location of a target fixation. In one experiment, subjects were faster in initiating saccades when they knew either the direction or amplitude of the required movement in advance compared to a condition with equal uncertainty about the number of potential saccade targets but without knowledge of the parameters required to execute the movement. These results suggest that the direction and amplitude for an upcoming saccade were calculated separately, and not in a fixed serial order. In another experiment, subjects appear to have programmed the saccades more holistically—with computations of direction and amplitude parameters occurring simultaneously. The implications of these results for models of eye movement preparation are discussed.

In viewing a complex visual display, an observer often needs to extract more information than is available from a single fixation. To accomplish this, saccades are periodically executed, bringing the fovea to a new portion of the scene. This fixation-saccade-refixation sequence plays a crucial role in the construction of an internal representation of the visual environment (Rayner, 1978). One aspect of this behavior that is of considerable interest involves the preparation of the saccades themselves: Once a new fixation location has been selected, what decisions and computations must be made in order to execute a saccade to that location? This issue was the focus of the present research.

Preparation for a saccade can be described in terms of the construction of a motor program (cf. Keele, 1968). When viewed this way, an important question becomes, What information must be contained in the motor program, and how is that information specified? Following the lead of other researchers, we have chosen to characterize a saccade in terms of the spatial coordinates of the direction and amplitude of the new, desired fixation location relative to the current position of gaze (e.g., Becker & Jurgens, 1979; Hou & Fender, 1979; Komoda, Festinger, Phillips, Duckman, & Young, 1973; Megaw & Armstrong, 1973). Thus, preparing a motor program for a saccade, or "programming" a saccade, involves the specification of values for two parameters: the direction in which the eye is to move and the distance through which the eye must move.¹

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From this perspective, questions about the preparation of saccades can be made more explicit. For example, are values for the direction and amplitude parameters specified in series or in parallel?² If values are specified serially, are they specified in a fixed or a variable order? Are the specification times for the two parameters different? We review previous research and report new results that bear on each of these questions.

Research on Saccade Programming

Most of the previous research on saccade programming has focused on the latency with which subjects produce saccades as they follow a visual stimulus that moves abruptly from one point to another. Because subjects do not know precisely when and where the target will move, the latency includes the time needed to specify values for the direction and amplitude parameters that will produce the desired movement.

When the target for a saccade steps unexpectedly, latency generally does not depend on the number of alternative possible target locations if the number is two or more (Megaw & Armstrong, 1973; Miller, 1969; Ohtani, 1968; Saslow, 1967). But when subjects are provided with some advance information about where the target will be appearing, they are able to reduce their latencies and sometimes even anticipate the target's movements (Findlay, 1981; Stark, Vossius, & Young, 1962). The few attempts to separately assess the utility of advance information about either amplitude or direction have not been definitive. Some evidence suggests that advance information about the amplitude of a required

¹ We don't mean to imply that these parameters are necessarily the relevant ones at the level of the muscles. Rather, we mean that the production of a particular saccade from among all possible saccades can be conveniently characterized as having arisen from decisions about the direction and amplitude of movement. Specifying values on these two dimensions unambiguously distinguishes one saccade from all others (given a common origin).

² By "parallel" specification we mean that the direction and amplitude of a *single* saccade are computed simultaneously. Others have used this term differently.

movement may yield reduced latencies (Viviani & Swensson, 1982). However, others have reported that saccade latencies depend on directional uncertainty but are independent of uncertainty about amplitude (e.g., Megaw & Armstrong, 1973).

More detailed information about the organization of the saccadic control system comes from experiments using "double-step" stimuli. In these studies, the subject is also required to follow a moving target as soon as possible after the target moves to a new location. However, on some trials the target is displaced a second time before the eye has begun to move. When that happens, the subject must attempt to modify or cancel the program for the first saccade and make a saccade only to the final target position.

The double-step paradigm has yielded several important results. First, subjects are sometimes able to suppress a response to the first target step and to move their eyes only to the final target position (Becker & Jurgens, 1979; Komoda et al., 1973; Levy-Schoen & Blanc-Garin, 1974; Wheelless, Boynton, & Cohen, 1966). Second, the time required to reprogram a saccade depends on the spatial relation between the two displacements. Considering only trials in which the eye goes directly to the second target location, when the second displacement calls for a saccade in a direction different from the first, latencies (measured from the time of the second step) are elevated somewhat relative to identical saccades in response to a single target-step (Hou & Fender, 1979; Komoda et al., 1973; Wheelless et al., 1966). However, when the second displacement requires a change only in the amplitude of the saccade, the latency may be somewhat shorter than usual (Becker & Jurgens, 1979; Komoda et al., 1973). Thus, modifying the direction of a saccade program may take more time than programming a saccade from "scratch," whereas changing only the amplitude may actually benefit from the initial partial preparation.³

Taken together, these results have led to a number of inferences about the processes involved in the preparation of saccades. It has been suggested that the additional time needed to change the direction of a saccade reflects a process in which all or part of the original program is canceled or erased (Hou & Fender, 1979; Wheelless et al., 1966). Because saccade amplitude appears to require less time to modify than does direction, researchers have suggested that direction is computed before decisions are made about amplitude (Becker & Jurgens, 1979; Hou & Fender, 1979; Komoda et al., 1973) or that direction and amplitude are programmed in parallel but that direction takes a longer time to specify (Howard, 1982). Thus, on the basis of the models that have emerged from this work, it is generally believed that the computation of direction and amplitude involve separate processes that follow different time courses (e.g., Findlay, 1983).

Limitations of Previous Research

There are some good reasons to question the inferences that have been made about saccade programming in the research described above. One major limitation of the previous research involves the use of suddenly changing visual stimuli to signal the required response and to define the

saccade target. Consider the studies in which the saccade target stepped only once on each trial. In those situations, when subjects were provided with advance information about the saccade that would be required, they also knew something about where the saccade target would be appearing. Evidence from a variety of sources suggests that stimuli are more readily detected if they appear in an expected location (e.g., Posner, Nissen, & Ogden, 1978). Thus, any benefit of the advance information could have been due to advance programming of parameters of the saccade, more rapid detection of the stimulus, or both. On the basis of existing data, it would be difficult to assess separately the contributions of these various components to the latencies.

The use of suddenly appearing saccade targets also limits the conclusions that can be drawn from the results of double-step studies. The difficulty arises in interpreting the additional time required to modify a saccade program when the second step requires a new direction, relative to one in which only amplitude is to be modified. If this difference is to be attributed to a process in which direction is specified before amplitude (as suggested by Becker & Jurgens, 1979; Hou & Fender, 1979; and Komoda et al., 1973), then it must be assumed that the durations of all nonsaccadic processes (e.g., stimulus perception and identification) that intervene between the second target step and the onset of the response do not depend on the spatial relation between the two target steps (i.e., whether a change in direction or amplitude is signaled).

However, it may take longer to perceive a second target-step that calls for a saccade in a different direction than it does to perceive a second step calling for a change only in amplitude. This could happen if the first target-step attracts the subject's attention. As Yantis and Jonides (1984) have shown, the onset of a peripheral stimulus may automatically attract attention toward that stimulus and away from other regions. Furthermore, several investigators have demonstrated that the perception of stimuli is facilitated if the stimuli are located near the target for a saccade (Bryden, 1961; Crovitz & Daves, 1962; Rayner, McConkie, & Ehrlich, 1978; Remington, 1980; Shepherd, Findlay, & Hockey, 1986). In the double-step studies, second steps that required altering only the amplitude of the saccade were usually shorter than those signaling a direction change (e.g., Becker & Jurgens, 1979; Komoda et al., 1973; Levy-Schoen & Blanc-Garin, 1974), and thus a step requiring a change in amplitude might be more easily perceived than one that called for a new direction. Additional support is provided by the results of Hughes and Zimba (1985). They showed that if attention is summoned to one hemifield, then latencies to respond to stimuli appearing in the other hemifield are slower. Because double-step targets

³ A related result involves the fact that saccades often undershoot their target but rarely overshoot (some exceptions to this are reported by Kapoula & Robinson, 1986). As a result, the direction of a corrective movement would typically be the same as that of the primary saccade and would be known in advance, possibly minimizing the time needed to program the correction (Becker, 1972; Henson, 1978). Results from the double-step paradigm suggest that a similar savings is realized when the direction of a reprogrammed saccade (i.e., a saccade modified before execution) can retain its former value.

that differ only in amplitude always remain in the same hemifield (by definition), it might simply take longer to perceive second steps calling for a change in direction. These facts could explain the discrepancy between the observed modification times for direction and amplitude without positing differences in the mechanisms involved in programming those parameters for saccades.⁴

Other evidence from double-step studies has led also to the proposal that direction and amplitude computations are fundamentally different. Several researchers have observed that saccades directed to the position of the first target-step can sometimes be terminated in midflight on the basis of information contained in the second step (Becker & Jurgens, 1979; Hou & Fender, 1979). This implies that there is a point in the preparation or production of a saccade after which the amplitude of the saccade may be altered, but the direction may not. This finding has been used to argue that decisions about the direction of a saccade are completed before the amplitude has been programmed (e.g., Becker & Jurgens, 1979; Hou & Fender, 1979). But the evidence is equivocal. If a subject was able to issue a command to abort a saccade, but was unable to completely suppress eye movement, then a saccade that was terminated early would appear to have resulted from a change in amplitude rather than a change in direction. This interpretation predicts that subjects should be less likely to extend a saccade in response to a second step than they are to shorten one, a prediction that is amply supported (Becker & Jurgens, 1979; Hou & Fender, 1979; Levy-Schoen & Blanc-Garin, 1974). Thus, it appears that subjects are able to abort an incomplete saccade. This does not imply that computation of direction precedes that of amplitude.

Overview of Present Experiments

In response to the somewhat equivocal status of previous research, our main goal was to study the details of the motoric decision processes involved in programming saccades, as distinct from the visual/perceptual processes that give rise to these decisions. In particular, we focused on the specification of direction and amplitude parameters for an upcoming movement. One issue that was addressed was whether these parameters are computed and processed separately prior to a saccade or whether they are specified jointly in a unitary fashion. As discussed above, the evidence in support of separate treatment of direction and amplitude is not definitive. There is, in fact, reason to believe that saccades may be programmed more "holistically"—without any distinct computation of direction and amplitude values. For example, Mays and Sparks (1980) have shown that accurate saccades to briefly flashed targets can be produced despite unexpected (experimenter-induced) perturbations of the eye immediately prior to movement. This suggests that commands for saccades are encoded, at some level, in terms of the desired final position of the eyes in space, and not exclusively in terms of the direction and amplitude to be moved. Evidence consistent with this result has also been reported by Hallet and Lightstone (1976) and Zee, Optican, Cook, Robinson, and Engel (1976).

There is also some reason to believe that decisions about the direction and amplitude of saccades can be made separately. Robinson (1964) has shown that the force pulses produced in the ocular muscles move the eye through a prespecified distance, and not necessarily to a particular location. Becker and Jurgens (1979) argued that it would be beneficial to program the muscles to be used (i.e., direction) before specifying the force that must be produced in those muscles (i.e., amplitude). And evidence from studies of eye movements during reading suggests that decisions about saccade amplitude may be made after the decision has been made to move the eyes (Pollatsek, Rayner, & Balota, 1986). If direction and amplitude *are* computed separately, we are interested in the details of this programming process: Are the parameters specified serially or in parallel? Must one value be specified before another? Does each take the same amount of time to specify? These and related questions remain to be answered.

Movement Precuing Technique

In order to study questions about saccade preparation we used a reaction-time method that does not suffer from the problems discussed above. The method, called the *movement precuing technique*, was adapted from a procedure developed by Rosenbaum (1980), who initially applied it to the study of limb movements. The technique involves first presenting subjects with advance partial information (a precue) about spatial parameters of a saccade that must be executed. The subject presumably uses this information to partially program the saccade. Next, a reaction signal is presented that completely defines the required movement and thus includes whatever information that was not contained in the precue. The latency to begin moving the eye includes the time needed to prepare any parameters of the saccade that could not be prepared on the basis of information in the precue. With the appropriate selection of precues, this technique can be used to make inferences about the preparation of parameters for saccades.

This paradigm has several virtues when compared with past experimental techniques that have been applied to the problem of understanding saccadic planning. First, only one saccade is required on each trial. As a result, the latencies are more easily interpreted than in situations in which there may be multiple responses, as in double-step experiments. Second, the method that we employ uses a reaction signal that is independent of the parameter (direction or amplitude) that is not provided by the precue. Thus, properties of the stimulus are not confounded with the information it conveys. Finally, the stimuli need not involve a sudden displacement of a visual

⁴ Previous investigators using the double-step paradigm were, perhaps, interested in relatively global questions about the production of saccades in a rich visual environment. Thus, they implicitly adopted a broad definition of "saccade programming"—one that includes the processes involved in detecting important visual stimuli to which saccades should be directed. We chose to adopt a more limited definition of programming that includes only the motoric decision processes necessary to define a saccade to a particular location.

1977). The resulting velocity profiles were used to determine the occurrence of saccades. A saccade was defined to start at the first moment in time when the velocity of the eye exceeded $10^\circ/s$ (irrespective of sign), subject to the constraint that the velocity remained above that value and subsequently exceeded $50^\circ/s$ and remained above $50^\circ/s$ for at least 10 ms. Similarly, the end of a saccade was the first moment in time after the beginning of a saccade when the velocity of the eye fell below $10^\circ/s$. This algorithm results in values for saccade onsets and terminations that are in excellent agreement with judgments based on visual inspection of the trajectories.

Procedure. The events that occurred on a typical trial are illustrated in Figure 1. The subject first saw a display that included the fixation point, saccade targets, stimulus circles, and the precue for the trial. The precue was displayed by filling in the circle or circles corresponding to the saccade or saccades that might be required on that trial. In the example shown in the figure, the precue indicates that a saccade will be required to one of the targets to the right of fixation. Subjects understood that only those movements that were indicated in the precue could possibly be called for by the reaction signal.⁵ The precue remained visible for 3,000 ms, during which time the subjects were to prepare to make the saccade or saccades designated. It was emphasized to the subjects that the use of information in the precue could help to reduce saccade latencies. Next, the stimulus circles with the precue information disappeared, followed 500 ms later by the reappearance of the four open circles that served as a warning signal and marked the beginning of the foreperiod. The foreperiod varied randomly in duration from 500 to 700 ms. During this time the subjects were required to fixate the central position; any apparent departures from fixation greater than $\pm 1^\circ$ invoked the calibration routine, and the trial was repeated from the beginning. At the end of the foreperiod the reaction signal was presented. This consisted of filling in one of the stimulus circles that had been precued. The subject was to execute a saccade to the designated target as soon as possible after the appearance of this signal. In the example shown in Figure 1, the far

right target is indicated. As soon as the eye moved more than 1° (in either direction), the four dots that served as saccade targets disappeared.⁶

After each trial, subjects were shown feedback regarding their response. If the saccade latency was less than 100 ms or greater than 400 ms, an error message was displayed (STARTED TOO SOON or STARTED TOO LATE, respectively). Error messages were also shown if the saccade was in the wrong direction (WRONG DIRECTION) or if the eye landed more than 2° away from the target (MISSED TARGET). If no errors occurred, the message GOOD was displayed. Trials on which errors occurred were not repeated.

Design. There were 11 different possible precues, as shown in Table 1. The precues differed in terms of the number of alternative movements specified and the type of information provided. In the top panel, four precues are shown that completely specify the saccade to be made (one-alternative precues). In the middle panel are shown the six possible two-alternative precues. Two of these specify the direction of movement ("direction" precues), two define the amplitude ("amplitude" precues), and two specify neither direction nor amplitude completely but still designate only two possible alternative movements ("mixed" precues). Finally, in the bottom panel the four-alternative precue provides no information at all about the saccade that would be required on that trial.

For trials with two-alternative or four-alternative precues, each of the precued movements occurred as the saccade target equally often. Thus, there were 20 distinct trial types (combinations of precue and saccade target). Trials were run in blocks of 20, with each trial type occurring once in a random position. On Day 1, subjects completed two blocks of trials. These served as practice and were not included in the analyses. On subsequent days, subjects completed four or five blocks of trials. After each block, subjects were given a brief break, and their performance was discussed with them.

Results

Errors. The overall error rate was 21.1%. Proportions of each type of error in each condition are shown in Table 2. As can be seen, errors increased dramatically with the number of alternative locations specified in the precue. Overall error rates were similar for each type of two-alternative precue. Nevertheless, in order to determine whether subjects were sacrificing accuracy for reduced latencies in some conditions (speed-accuracy trade-off), we computed the correlation between errors and eye-movement latency. Overall, latency was positively correlated with errors, $r(3335) = .17$, $p < .0001$, suggesting the absence of such a trade-off. In addition, correlations performed separately within each condition were either positive or zero. Thus, there was no evidence that subjects were trading accuracy for speed, either between the various conditions or within each condition. Furthermore, the analyses reported below were conducted for correct trials only and

Table 1
Movement or Set of Movements Included in Each Precue in Experiment 1

Number of alternative movements	Parameter(s) specified	Precued responses	Parameter(s) not specified
1	Direction and amplitude	♀ ● + ● ●	None
		● ♀ + ● ●	
		● ● + ♀ ●	
		● ● + ● ♀	
2	Direction	♀ ♀ + ● ●	Amplitude
		● ● + ♀ ♀	
	Amplitude	♀ ● + ● ♀	Direction
		● ♀ + ♀ ●	
	None	● ♀ + ● ♀	Direction and amplitude
		♀ ● + ♀ ●	
4	None	♀ ♀ + ♀ ♀	Direction and amplitude

Note. Filled circles represent saccade targets. Arrows indicate the saccade or saccades included in the precue.

⁵ Verbal instructions to subjects were neutral with respect to regarding the precue as a list of values of parameters for saccades, as opposed to a list of possible saccadic responses. As Rosenbaum (1983) suggests, these two situations may be quite different psychologically, and subjects may adopt different strategies, depending on which of these biases is present. Experiment 5 addresses this issue.

⁶ We removed the targets when the eye began to move because pilot experimentation revealed that subjects would occasionally pause unintentionally at near-target locations as they attempted to look to the far targets. Target removal successfully eliminated that behavior.

Table 2
Mean Error Rates (%) for Each Precue Type in Experiment 1

Error type	Type of precue					Total
	1 alt.	Direction	Amp.	Mixed	4 alt.	
Missed target	3.4	23.1	19.5	20.4	34.3	20.1
Wrong direction	1.3	0.4	6.1	7.4	9.9	5.0
Latency error	2.2	0.9	2.1	2.5	6.1	2.8
Total	4.3	23.1	20.1	21.6	36.2	21.1

Note. "Missed target" means that the eye did not land within $\pm 2^\circ$ of designated target. "Wrong direction" means that the saccade was to the wrong side of fixation. "Latency error" means that saccade latency was less than 100 ms or greater than 400 ms. Column totals do not add exactly because some trials had more than one error. Alt. = alternative; amp. = amplitude.

were then repeated for all trials. Exclusion of the error trials did not change any of the major conclusions.

Saccade latencies. The results of most interest involve the latencies to initiate saccades in the various conditions. These are shown in Figure 2 separately for each type of precue and for each of the four saccade targets. As seen in the figure, latencies increased with the number of possible alternatives designated by the precue, $F(2, 22) = 76.18, p < .0001$. Considering only the two-alternative precues, there was a significant main effect of precue type, with direction- and amplitude-precue latencies an average of 13 ms faster than mixed-precue latencies, $F(2, 22) = 8.17, p < .005$. Latencies to outside targets were an average of 16 ms faster than those to inside targets, $F(3, 33) = 6.63, p < .005$. The effects of target and precue also interacted, $F(6, 66) = 2.51, p < .05$, as can be seen by comparing the shape of the cluster of four points for direction and amplitude precues with that for the mixed precues. Latencies with mixed precues were equal across the four saccade targets, but latencies were longer for inside targets (especially the 3° right target) with the amplitude and direction precues.

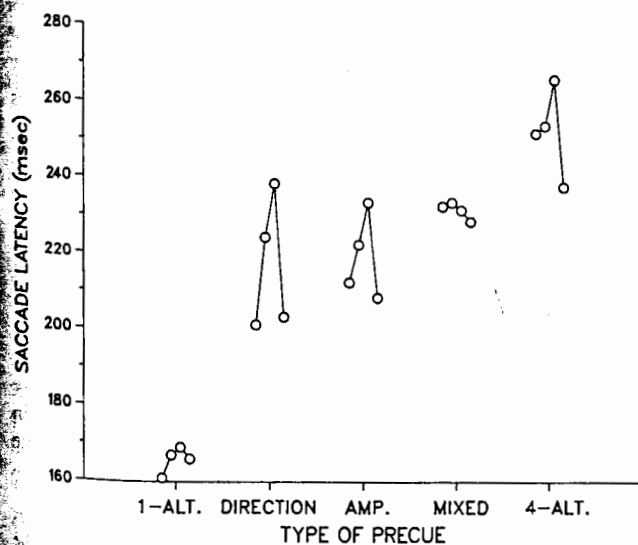


Figure 2. Mean saccade latencies from Experiment 1 as a function of the type of precue. (The four points in each cluster correspond to the four saccade targets, from left to right [6° left, 3° left, 3° right, and 6° right]). ALT. = alternative; AMP. = amplitude; msec = milliseconds.)

Saccade durations and distances. Mean saccade durations and distances are shown in Table 3 separately for each type of two-alternative precue. First, consider the durations. Saccades to outside targets (6° in amplitude) were, as expected, significantly longer in duration than saccades to inside (3°) targets, $F(3, 33) = 86.51, p < .0001$. The type of precue did not significantly influence saccade durations, $F(2, 22) = 3.25, p > .05$, but precue type did interact with the saccade target, $F(6, 66) = 3.59, p < .005$. The interaction is evident in somewhat longer movement durations to inside targets for direction precues, as compared with amplitude and mixed precues.

The saccade distances reveal patterns that closely parallel those for the durations: There was a strong effect of target, $F(3, 33) = 1,703, p < .0001$; type of precue had no influence, $F(2, 22) < 1$; and precue interacted with target, $F(6, 66) = 4.47, p < .001$. The interaction is revealed by longer saccades to inside (3°) targets for direction precues, as compared with amplitude and mixed precues.

Discussion

The most salient feature of the results from Experiment 1 is that saccade latencies decreased dramatically as the information provided by the precue increased and, correspondingly, as the stimulus-response uncertainty decreased. This result shows that subjects were attending to the information in the precues, but it is not definitive regarding the details of the saccade programming because the advantage could have arisen from reduced uncertainty about the stimulus, the response, or both.

The results most relevant to programming saccades involve the conditions with two-alternative precues. Subjects were faster to initiate saccades when they knew the direction or amplitude of the saccade to be made in advance. When neither parameter was known in advance, subjects were on the average 13 ms slower to begin moving the eye. Our interpretation of this result is that subjects were able to program the known parameter in advance of the reaction signal on direction- and amplitude-precue trials. On mixed-precue trials, however, knowledge of either direction or amplitude was not completely available until the reaction signal appeared, thus precluding any advance preparation of either parameter. As a result, mixed-precue latencies were longer.⁷

⁷ Advance knowledge of direction or amplitude reduced saccade

Table 3
Mean Durations (in Milliseconds) and Distances (in Degrees) of Saccades From Experiments 1, 5, and 6

Target location	Type of precue					
	Direction		Amplitude		Mixed	
	Dur.	Dist.	Dur.	Dist.	Dur.	Dist.
Experiment 1						
6° left	39.4	5.5	40.7	5.9	40.5	5.6
3° left	34.8	3.5	32.7	3.1	31.8	3.1
3° right	34.4	3.5	32.5	3.2	32.5	3.0
6° right	39.7	5.6	38.7	5.7	39.9	5.8
Experiment 5						
6° left	36.9	5.2	38.2	5.7	37.3	5.6
3° left	31.7	3.2	32.2	3.2	30.2	2.9
3° right	31.5	3.1	31.6	3.2	32.6	3.2
6° right	37.2	5.4	38.4	5.8	38.6	5.7
Experiment 6						
10° left	52.8	9.6	54.5	10.0	54.7	9.8
5° left	39.5	4.5	39.5	5.1	36.9	4.6
5° right	36.9	4.8	37.6	5.4	36.2	5.0
10° right	48.7	9.6	49.9	10.1	50.4	9.9

Note. Dur. = duration; Dist. = distance.

We also found that saccades to the 3° targets on direction-precue trials were slightly longer in both duration and distance than saccades to the same targets on amplitude- and mixed-precue trials. Such a pattern is similar to the "range" effect (Fitts, 1951; Kapoula, 1985; Kapoula & Robinson, 1986) in which the shortest movements within a set of movement amplitudes are lengthened. The relative overshooting of the short targets could also be due to a "global" effect (Findlay, 1982). This refers to the tendency for saccades to land toward the center of a configuration of visual stimuli.⁸ Nevertheless, it should be emphasized that the differential precue effect that we obtained was most pronounced for those movements that exhibited equivalent durations and amplitudes across conditions.

The present results have several important implications for the processes involved in programming saccadic eye movements. First, the fact that any partial advance preparation occurred suggests that saccades need not be specified holistically—that is, with decisions about direction and amplitude made simultaneously. Rather, it seems that the specification of direction and of amplitude for a saccade can be performed serially. Second, the observation that advance knowledge of either direction or amplitude was useful without knowledge of the other parameter suggests that the two parameters need not be programmed in a fixed order. Subjects appear to have

latencies for three of the four targets studied. However, there was no apparent benefit (nor cost) of such advance knowledge for the 3° right target. One possible reason that these movements were different is that they are most similar to the saccades that occur during reading. It is possible that different mechanisms may underlie the production of those highly practiced movements.

been able to program the amplitude (or direction) for a saccade before knowing in which direction (or how far) the eye was to move. This contrasts with claims by others that direction must be specified before computations about amplitude can be performed. Finally, advance knowledge of either direction or amplitude reduced saccade latencies by equal amounts relative to mixed-precue trials. This suggests that the times needed to specify direction and amplitude are equivalent.

There are at least two possible alternative explanations of our results that would attribute the differential precue effect to processes other than those involved in preparing individual parameters for saccades. According to the first, our pattern of latencies could arise from differences in the time needed to perceive the stimuli in the different precue conditions. Such a situation might have occurred if the direction and amplitude precues were easier for the subjects to encode and remember. The mixed precue might then have been less effective in reducing stimulus uncertainty, resulting in longer latencies on mixed-precue trials. If this actually occurred, then it would severely limit the implications of our results for saccadic preparatory processes. Experiments 2, 3, 4, and 6 address this issue.

A second alternative explanation would attribute our results to motoric preparation processes, but processes other than those that we propose. In particular, rather than specifying the individual parameter provided by the precue and then awaiting the reaction signal, subjects may have completely prepared all possible saccades and then simply selected the appropriate movement from the prepared set when the reaction signal appeared (cf. Rosenbaum, 1980). If the time needed to select and initiate the designated saccade depended on the relations between the prepared saccades (i.e., the type of precue), then this could account for our results. Experiment 5 addresses this question.

Experiment 2

Experiment 2 was designed to rule out possible differences in the time needed to perceive the stimuli under the various precue conditions in Experiment 1. Exactly the same stimuli were used as in Experiment 1. However, instead of requiring one of four possible saccades on each trial, we had subjects press a single response key when the reaction signal appeared. Only one response was ever required, regardless of the location of the signal. Thus the perceptual demands of the two experiments were equivalent, and only the motoric response processes differed. If the pattern of results we obtained in Experiment 1 was due to differences in the time needed to perceive the stimuli, then the same pattern should also be obtained in the present experiment. However, if the differential precue

⁸ It is interesting to note that the range effect or global effect was strongest in the direction precue condition—when subjects knew the direction of movement in advance. This suggests that these phenomena are not only due to physical features of the movement situation but also may depend on subjects' expectations.

effects from Experiment 1 reflect properties of the saccadic programming mechanism, then the latencies obtained here should not depend on the type of precue.

Method

Subjects. Seven subjects served in the present experiment. They were drawn from the same pool as in Experiment 1, although none had served in that experiment. Subjects were paid \$3.50 for each of four 50-min sessions, plus bonuses based on performance.

Apparatus and stimuli. The equipment and stimuli were the same as those used in Experiment 1, with the exception that eye movements were not monitored in the present experiment. Instead, subjects responded to the reaction signal by simply pressing a single response key on a keyboard in front of them. The computer recorded the latency with which the subjects responded.

Procedure and design. The sequence of events on each trial, with the exception of the response required, was identical to that in the previous experiment (see Figure 1). Summarizing briefly, a precue was displayed for 3,000 ms, followed by a brief pause. A warning signal then appeared, followed after a variable foreperiod by the reaction signal. Subjects were instructed to press a response key as quickly as possible after the occurrence of the reaction signal. Subjects were strongly urged to attend to the precue, because it would reliably indicate the possible positions in which the reaction signal would appear. Further, subjects were informed that "previous experience" had shown that the use of information in the precue would help them reduce their latencies and thus increase the bonus that they could earn.

After each trial, subjects received feedback regarding their responses. If the latency was less than 100 ms or greater than 600 ms, an error message was presented (PREMATURE RESPONSE OR TOO SLOW, respectively). Otherwise, the message GOOD was displayed.

Each of the precues included in the previous experiment was also used here (see Table 1). However, in the context of the present experiment, the precues served to reduce uncertainty only about the stimulus and had no bearing on the possible response required. Trials were presented in blocks of 20, as in Experiment 1. Subjects performed 12 blocks of trials in the first session. These served as practice, and data from these trials are not reported. Seventeen blocks of trials were performed in each of the remaining three sessions.

Results

The overall error rate was 6.6%. Most of the errors (71%) were anticipations (latency < 100 ms). Errors occurred on 7.8%, 7.3%, 6.6%, 6.3%, and 4.7% of the one-alternative, direction, amplitude, mixed, and four-alternative trials, respectively. Errors decreased slightly as the number of possible alternative movements increased, reflecting a reduced tendency to anticipate the stimulus as stimulus uncertainty increased. Reaction time was positively correlated with errors overall ($r = .031$, $p < .01$) and separately within each condition. Thus, there was no evidence of a speed-accuracy trade-off.

The mean reaction times for each condition are shown in Table 4. As can be seen, latency increased with the number of alternatives specified by the precue, $F(2, 12) = 9.17$, $p < .01$, but there were no differences in reaction times among the three types of two-alternative precues, $F(2, 12) = 3.67$, p

Table 4
Mean Reaction Times (in Milliseconds) for Manual Responses in Experiments 2, 3, and 4

Experiment	Type of precue				
	1 alt.	Direction	Amp.	Mixed	4 alt.
2	206.4	209.9	211.4	211.8	216.0
3	252.1	365.4	351.6	354.7	427.5
4		296.3 ^a	285.4 ^b	284.4 ^c	

Note. Alt. = alternative; amp. = amplitude.

^a Shared: hand condition. ^b Shared: finger condition. ^c Shared: neither condition.

< .10. There were also no differences in the latencies as a function of the location of the reaction signal, $F(3, 18) = 1.66$, $p < .25$. No interaction attained significance.

Discussion

The main finding of the present experiment is that manual reaction times were equal among the different two-alternative precues. This suggests that the time needed to detect the stimulus did not depend on the relation between the possible locations at which the stimulus could appear (i.e., the type of precue). Because the stimuli here were identical to those used in Experiment 1, we may attribute the differences in latencies in the earlier experiment to response factors, namely the programming of direction and amplitude parameters for saccades, rather than to processes involved in perceiving the stimuli.

Although there were no differences among the various two-alternative precues, we did obtain a significant effect of stimulus uncertainty: Latency increased with the number of possible alternative locations of the reaction signal. This demonstrates that subjects were attending to the precue and that our experiment was sufficiently powerful to detect small latency differences (< 10 ms) between conditions, further bolstering our earlier conclusion.

Nevertheless, there is reason to question the adequacy of the present experiment as a control for stimulus perception in Experiment 1. The difficulty lies in differences in the meaning of the precue and of the reaction signal between the two experiments. In each experiment, the precue reduced uncertainty about where the stimulus might appear; however, in Experiment 1 the precue also served to designate the possible response that might be required. Thus, subjects needed to *detect* the reaction signal before responding in both experiments; however, in Experiment 1 subjects were required also to *identify* the stimulus (i.e., discriminate the reaction signal from other possible reaction signals) before responding. It might be that stimulus identification and discrimination depend on the relations between the precued movements but that simple detection does not. If so, then the pattern of latencies obtained in Experiment 1 may actually reflect perceptual/stimulus factors, not saccade programming operations, and Experiment 2 would not be sensitive to these effects. Experiments 3 and 4 pursue this possibility.

Experiment 3

In Experiment 3, subjects were presented with precues and reaction signals in the same manner as in Experiments 1 and 2. As in Experiment 1, subjects produced one of four possible responses on each trial. Thus, they were required to both detect and identify the reaction signal. Instead of producing saccades (as in Experiment 1), subjects in the present experiment responded by pressing one of four response keys (using the index and middle fingers of each hand). If the pattern of results obtained in Experiment 1 was due to perception and identification of the stimulus, then the same pattern should be observed here. However, if the differential precue effects of Experiment 1 reflected the preparation of individual parameters for saccadic eye movements, then the pattern of latencies here should be different.

Method

Subjects. Eight subjects participated in four 45-min sessions on separate days and were paid \$3.75 per session, plus bonuses based on performance. None had served previously.

Apparatus, procedure, and design. All aspects of this experiment were identical to Experiment 1 (see Table 1), with only one exception: Instead of producing saccades, subjects responded by pressing one of four response keys (using index and middle fingers of each hand) on a keyboard in front of them. The mapping between the stimuli and the response keys was the same as in Experiment 1: The far left circle corresponded to the far right response key, the near left circle signaled the near right response key, and so forth. (Response keys were assigned to fingers in a natural manner: E.g., the middle finger of the right hand was assigned to the rightmost key.) Even though saccades were not necessary in this experiment, we monitored eye position and required subjects to fixate at the center of the display during the foreperiod, as in Experiment 1. Any departures from fixation invoked the eye-monitor calibration routine, as described previously (see Experiment 1).

Because manual responses were required, the two-alternative precues took on somewhat different meanings in the present experiment. Direction precues informed the subject of the hand (left or right) that would be used for the response, but not the finger; the amplitude precues designated the finger (index or middle) to be used, but not the hand; and mixed precues defined neither the finger nor the hand completely. For convenience, we will continue to refer to these as direction, amplitude, and mixed precues. The feedback presented after each trial was that which was most appropriate for manual responses (see Experiment 2). One additional error message was included if the subject pressed the wrong key (INCORRECT). Subjects completed six or seven blocks of trials per session.

Results

The mean overall error rate was 7.1%. The majority of errors (77%) were due to subjects' pressing an incorrect key. Error rates were 1.6%, 8.6%, 5.8%, 6.5%, and 13.1% for the one-alternative, direction, amplitude, mixed, and four-alternative trials, respectively. Errors increased with stimulus uncertainty but were similar for each two-alternative precue. Reaction times and errors were positively correlated overall, $r(3078) = .15$, $p < .01$, and correlations were either positive or zero separately for each type of precue.

Mean reaction times for each type of trial are shown in Table 4. As can be seen, there was a very strong effect of uncertainty, because latencies increased with the number of alternative possible responses, $F(2, 14) = 253.4$, $p < .0001$. For the two-alternative trials, direction precues resulted in latencies that were 12.3 ms slower than with amplitude or mixed precues, $F(2, 14) = 3.87$, $p < .05$. There were also some latency differences between the different fingers, $F(3, 21) = 5.11$, $p < .01$: The right hand was 11.3 ms faster than the left, and middle fingers were 14.1 ms faster than index fingers. The effects of finger did not interact with those of the type of precue, $F(6, 42) = 1.48$, $p < .25$.

Discussion

The finding of primary interest is that the pattern of latencies from the two-alternative precue trials was different from the pattern obtained in Experiment 1, although the same stimuli were used. If the differences obtained in Experiment 1 were due to perception and identification of the reaction signal, then the same differences should have emerged here. However, in the present experiment, latencies to stimuli on direction-precue trials were significantly slower than those on amplitude- or mixed-precue trials, and the latter two conditions exhibited equivalent reaction times. Thus, the data support the hypothesis that the latencies in Experiment 1 reflect the time needed to prepare parameters of saccadic eye movements.

There is a problem in accepting this conclusion, however. Suppose that underlying the pattern of responses to two-alternative precues there actually is a pattern similar to that found in Experiment 1, with mixed precues taking longest to stimulate a response. The requirement to execute a manual response in the present experiment may have masked this pattern by adding to it an idiosyncratic pattern of latencies that reflects manual motoric processes. This could have happened, for example, if it takes more time to choose a response between two fingers on the same hand (direction precues in this experiment) than to choose between two fingers on different hands (amplitude and mixed precues). In fact, this was the pattern that we observed, and the same pattern has been reported by others (Kornblum, 1965; Rosenbaum & Kornblum, 1982; Zelaznik & Hahn, 1985). To be sure that we hadn't simply obscured one pattern of latencies with another, we conducted an additional experiment.

Experiment 4

Experiment 4 was designed to assess the time needed to initiate manual responses as a function of the relations between the possible alternative responses that might be required. Subjects produced the same responses as in Experiment 3. The stimuli were presented in such a way as to ensure that the time needed to detect and identify the stimuli did not depend on the relation between the possible responses. If stimulus identification times in the previous experiment did not depend on the precue condition, then the results from the

monitored.

Stimuli. There were two possible stimuli on each trial: A star (*) would appear either just above a horizontal line at the center of the CRT ("star above"), indicating one response, or below the line ("star below"), signaling the other response. The line was 0.87° long. The star was approximately 0.36° in diameter, and appeared 0.57° above or below the center of the line.

Design. Each trial of the experiment involved a two-alternative forced-choice response. Within each block of trials subjects chose between the same two alternative responses. In different blocks, the relation between the two possible responses was manipulated. This relation could take one of three forms: (a) *shared:hand*, in which the two alternative responses involved the middle or index finger of one hand; (b) *shared:finger*, in which the two responses used homologous fingers on different hands (e.g., both index fingers); or (c) *shared:neither*, in which the two responses shared neither the same hand nor finger (e.g., right index and left middle).

There were two instances of each of the three types of trials, for a total of six distinct types of blocks. Subjects performed three consecutive sets of the six blocks, in a counterbalanced order, on each day. The first six blocks, which included 10 trials per block, served as practice and are not reported below. There were 64 trials in each of the remaining 12 blocks. Within each block, the two responses were required equally often.

Procedure. At the beginning of each block subjects were shown a display that indicated which two fingers and response keys would be used in that block. Also shown on the display was a reminder of which stimulus would signal each response. For one half of the subjects, a star above the line always indicated the rightmost of the two possible responses in each block and a star below the line signaled the leftmost of the two responses. This arrangement was reversed for the other subjects. After studying this display, subjects pressed a button to proceed to the test trials.

Each trial began with the presentation of a warning signal, a small horizontal line at the center of the display. After a 500-ms foreperiod, a star appeared either above or below the line. The appearance of the star indicated the required response and marked the beginning of the latency interval. The display blanked after the subject responded. One of three errors could occur on a trial: TOO SLOW, if the subject did not respond within 1 s of the reaction signal; PREMATURE RESPONSE, if the latency was less than 100 ms; and INCORRECT, if the subject pressed the wrong keys. When appropriate, an error message was displayed for 1 s. No message appeared if there were no errors. After 1 s, the next trial began.

4.37, $p < .05$. The magnitude of this effect is not reliably different from that for the two-alternative precues of Experiment 3, $t(12) = .13$, $p > .5$.

Discussion

The results of primary interest from this experiment involve the latencies to produce manual keypress responses to one of two alternative stimuli as a function of the relation between the responses to be produced. When the two fingers to be used shared the same hand, latencies were longer than when they were on different hands. These results conform closely to those from Experiment 3, as well as to those of other investigators (Kornblum, 1965; Rosenbaum & Kornblum, 1982; Zelaznik & Hahn, 1985). Because the stimuli we used did not depend on the relation between the responses, we feel confident that the pattern of latencies reflects properties of the mechanisms involved in the production of manual responses.

How do these results bear on questions about saccade programming? The close correspondence between the results of this and the previous experiment permits the inference that the latency results in Experiment 3 were due to the nature of the response-selection process. Furthermore, to the extent that the present results were not contaminated by differential stimulus-identification factors, then neither were those of Experiment 3. Because Experiment 3 employed exactly the same stimuli as did our saccade experiment (Experiment 1), then we may infer that the saccade latencies are also not contaminated by stimulus factors. Thus, our initial conclusion, that the differences in saccade latencies reflect motoric rather than perceptual factors, is upheld.

This conclusion is further bolstered by the results of Experiment 2. In that experiment, only one response was used throughout, precluding any possible differences in motor preparation times. Latencies in that task did not depend at all on the nature of the two-alternative precue, confirming again that the contributions of differential stimulus identification times to our saccade experiment are minimal.

Experiment 5

Given that the pattern of results in Experiment 1 appears to reflect motoric preparation times for saccadic eye movements, we now return to issues regarding the details of the preparatory process. We hypothesized that the pattern of latencies reveals a process in which subjects individually specify values for direction and amplitude parameters of an upcoming saccade. Recall, however, that there is an alternative interpretation of the results of Experiment 1. This is that the benefit of advance knowledge of direction or amplitude (relative to a mixed precue without such knowledge) does not lie in the fact that subjects need to prepare only one additional parameter after the reaction signal. Rather, according to this interpretation, the benefit is instead due to the relative ease with which subjects can select from memory one of two completely prepared saccades when the saccades share either the same direction or amplitude. When they share neither parameter, it is more difficult (and, hence, takes longer) to choose between them.

In order to test this hypothesis, we had subjects produce one of two saccades that either did or did not share a parameter. Individual preparation of direction and amplitude parameters was discouraged by using arbitrary signaling stimuli and by having subjects choose between the same two alternative saccades throughout each block of trials.

Method

Subjects. Four subjects who had not served previously participated. They were paid \$3.75 for each of five 50-min sessions, plus bonuses for good performance.

Apparatus. The computer, video display, and eye-movement monitor were the same as in Experiment 1.

Procedure. This experiment essentially combined the saccade production task of Experiment 1 with the design and stimuli (star above or below the horizontal line on the CRT) of Experiment 4.

On each trial within a block of trials, subjects were to produce one of two possible saccades. At the beginning of each block, subjects saw a display showing the two alternative saccades that would be possible on each trial within that block. There were six types of blocks, corresponding to the six possible sets of two alternatives from the four saccade targets (see Table 1, two-alternative precues).

The sequence of events for each trial is illustrated in Figure 3. Each trial began with a display that consisted of a small horizontal line at

the center of the CRT and four small dots indicating the saccade targets in the periphery. The targets were 3° and 6° to the left and right of fixation, as in Experiment 1. After 2.5 s had elapsed, a dot appeared in the middle of the horizontal line. The dot served as a fixation point and marked the beginning of the foreperiod. The foreperiod varied from 1,000 to 1,260 ms in duration. During this time, the computer verified that subjects were fixating within $\pm 1^\circ$ of the fixation dot; if they were not, then the eye-monitor calibration routine was invoked, as in Experiment 1. At the end of the foreperiod, a reaction signal appeared. The signal consisted of a star (*) presented either directly above or directly below the horizontal line, as in Experiment 4. For one half of the subjects, a star above the line always indicated the rightmost of the two possible responses in each block and a star below the line signaled the leftmost of the two responses. This arrangement was reversed for the other subjects. When the eye moved 1° in either direction, the four saccade targets disappeared. Possible errors and error messages were as in Experiment 1.

Design. Six blocks of trials were presented in each session (one for each type of block), in a counterbalanced order. On Day 1, there were 10 trials in each block; on the remaining days 18 trials were included in each block. The first two sessions were considered practice and are not reported.

Results

The overall error rate was 24.4%. Most of these (94.4% of the total) were trials on which the saccade was not to the correct target. Error rates were 30.8%, 20.6%, and 21.8% for the direction, amplitude, and mixed precue conditions, respectively. The correlation between latency and errors was not different from zero overall ($p > .05$) and was either zero or positive separately for each condition. Thus there was no evidence of a speed-accuracy trade-off.

Latencies of saccades are shown in Figure 4 separately for each target and condition. There was no main effect of either the saccade target, $F(3, 9) = 2.99, p > .05$, or precue type, $F(2, 6) < 1$. Target and precue, however, did interact, $F(6, 18) = 2.75, p < .05$. The interaction can be attributed to latencies in the direction precue condition, which were slower to 3° targets and faster to 6° targets compared with amplitude- and mixed-precue conditions.

Mean saccade durations and distances are presented in Table 3. Durations were longer for outside targets $F(3, 9) = 27.3, p < .0005$, but did not depend on the precue condition, $F < 1$. The effects of target and precue did not interact, $F(6, 18) = 1.46, p < .25$.

The distances of the saccades also were not influenced by precue condition ($F < 1$), but saccades to 6° targets were significantly longer in extent than saccades to 3° targets, $F(3, 9) = 403.5, p < .0001$. As with the latencies, target and precue interacted, as evidenced by shorter saccades to the outside (6°) targets in the direction precue condition as compared with amplitude or mixed precues, $F(6, 18) = 3.16, p < .05$.

Discussion

The main finding of the present experiment is that latencies to initiate one of two saccades did not depend on the spatial relation between the saccades. Latencies were equivalent

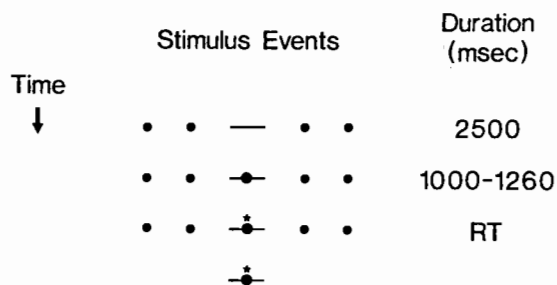


Figure 3. Sequence of events on a typical trial in Experiment 5. (RT = reaction time.)

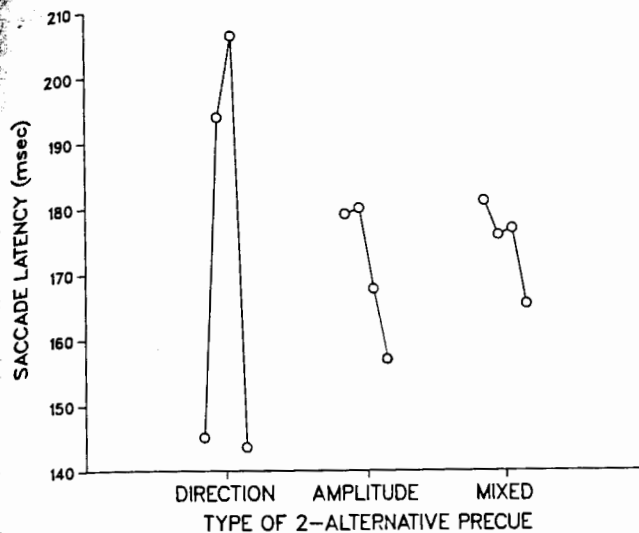


Figure 4. Mean saccade latencies from Experiment 5 as a function of the type of precue. (Msec = milliseconds.)

whether the two possible responses shared the same direction, the same amplitude, or neither direction nor amplitude. This result contrasts with the pattern obtained in Experiment 1, in which subjects appear to have programmed any common features of the two possible responses (i.e., direction or amplitude) in advance of the reaction signal, thus reducing their latencies when common features did exist. However, in the present experiment subjects were encouraged to regard the two possible saccades on each trial as two distinct, complete responses, as opposed to two lists of parameters that either shared or did not share a common parameter (cf. Rosenbaum, 1983). Apparently this manipulation was successful.

This finding helps to discredit the alternative movement-selection hypothesis discussed earlier. Contrary to that hypothesis, when subjects are encouraged to completely prepare the two possible responses in advance, the selection or activation of the appropriate response does not depend on the spatial relation between them.

We did observe an interaction between precue condition and saccade target that was evident in both the saccade latencies and distances. When subjects knew the direction of the saccade in advance, they appear to have prepared to move to the outside target (as evidenced by shorter latencies). This bias may reflect the relative ease with which saccades can be shortened as opposed to lengthened (as discussed earlier). We also found that the saccades to outside targets were slightly shorter in extent in the direction-precue condition. This may indicate the presence of a global effect, or range effect, as discussed earlier (see *Discussion* section of Experiment 1). Nevertheless, the interactions do not bear on the hypothesis being tested in the present experiment. That hypothesis makes the prediction that latencies for saccades to a given target on mixed-precue trials should be longer than those to the same location on direction- or amplitude-precue trials. That pattern was not observed for any of the saccade targets studied.

Experiment 6

Experiments 2-4 were designed to test the possibility that nonmotoric factors may have produced the pattern of saccade latencies observed in Experiment 1. A number of potential influences were considered; any of these influences should have been revealed in the control experiments involving manual responses if they had been present in Experiment 1, but no such effects were observed. Nevertheless, it is possible, in theory, to conduct a more direct test of the potential effect of nonmotoric factors on the saccade latencies of Experiment 1. This would involve having subjects produce saccades in a situation similar to that used in Experiment 1—except with different stimuli. If the latency differences observed in Experiment 1 were due to motoric processes involved in the programming of saccades, then those differences should appear whenever subjects have to prepare one out of a number of possible saccades regardless of the stimuli that elicit the saccades. Such a test is even more desirable in light of the results of Experiment 5. There it was seen that subjects may be able to completely prepare a set of saccades in advance when a limited number of saccades are repeatedly required.

In the present experiment the stimulus display used was one in which the stimulus for a particular saccade was on the same side of fixation as the saccade target itself. We chose not to use such an arrangement in Experiment 1 because of concern for the possibility that the sudden onset of a light might automatically facilitate the production of a saccade in the direction of the onset (Todd & Van Gelder, 1979). If such an effect were to occur, our experiment would be open to some of the same objections that we raised about previous work, namely, that attentional factors may complicate the interpretation of saccade latencies. Nevertheless, there may be some value in conducting such an experiment in light of the results of Experiment 1.

Method

Subjects. Four subjects who had not served previously participated. They were paid \$3.75 for each of four 50-min sessions, plus bonuses for good performance.

Apparatus and stimuli. The computer, video display, and eye-movement monitor were the same as in the previous experiments. The method of signaling saccades was the same as that used in Experiment 1; however, the assignment of stimuli to responses was different. In the present experiment, the four stimulus circles were assigned to the four possible saccade targets in a compatible manner. That is, the far left circle designated the far left saccade target, the near left circle indicated the near left saccade target, and so on. Furthermore, in order to assess possible differences between short and long saccades, the saccade targets were 5° and 10° away from fixation.

Procedure. The procedure was essentially the same as that used in Experiment 1, with a few exceptions designed to expedite data acquisition. First, the subjects always received a two-alternative precue. Thus, on each trial of the experiment they had to produce one of two possible responses (the two possible responses varied from trial to trial). Next, the warning signal (four open circles) appeared immediately after the offset of the precue. Finally, the foreperiod varied randomly from 400 to 600 ms.

Design. There were six different two-alternative precues and thus 12 distinct combinations of precue and saccade target. Each of the 12 trial types was presented twice, in a randomly determined position, within a block of 24 trials. Subjects completed 5–7 such blocks of trials on the first day. These served as practice and are not reported. On subsequent days subjects completed six or seven blocks of trials.

Results

The overall error rate was 19.0%. Most of these (98.1% of the total) were trials on which the saccade was not to the correct target. Error rates were 18.9%, 16.0%, and 22.0% for the direction-, amplitude-, and mixed-precue conditions, respectively. The correlation between latency and errors was not different from zero, $r(1963) = .06$, $p > .05$. Thus there was no evidence of a speed-accuracy trade-off.

Latencies for each condition are shown in Figure 5 separately for each saccade target. Latencies were not influenced by the type of precue, $F(2, 6) = 1.68$, $p < .30$, or the location of the target, $F(3, 9) = 1.02$, $p < .50$. The interaction between the type of precue and the location of the target did not reach significance, $F(6, 18) = 2.50$, $p < .10$, although a pattern similar to that found in Experiment 5 is evident in Figure 5: Latencies of movements to outside targets tended to be shorter than those to inside targets in the direction-precue condition.

The saccade durations and distances are shown in Table 3. As would be expected, saccades to the 10° targets were longer in both duration, $F(3, 9) = 99.43$, $p < .0001$, and distance, $F(3, 9) = 955.3$, $p < .0001$. The type of precue had no influence on the saccades: duration, $F(2, 6) = 3.76$, $p < .10$; distance, $F(2, 6) < 1$. The effects of precue type also did not interact with those of the saccade target for the movement durations, $F(6, 18) = 2.36$, $p < .10$, but an interaction was observed in the saccade distances, $F(6, 18) = 5.74$, $p < .005$. Subjects produced slightly longer saccades (i.e., less under-

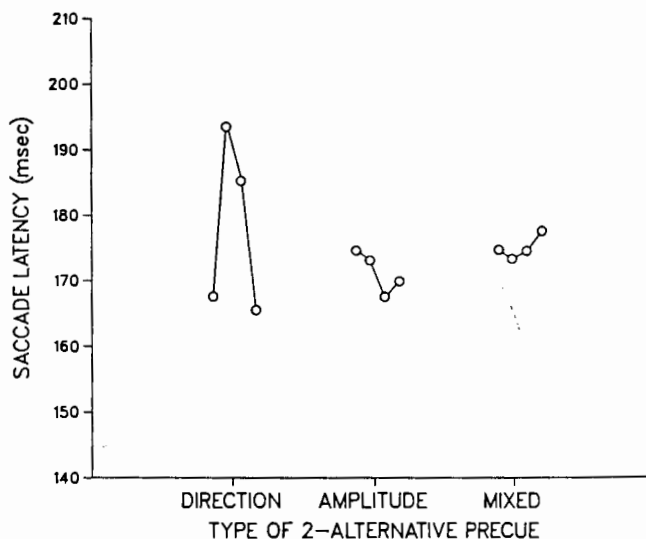


Figure 5. Mean saccade latencies from Experiment 6 as a function of the type of precue. (The four points in each cluster correspond to the four saccade targets, from left to right [10° left, 5° left, 5° right, 10° right]). Msec = milliseconds.)

shooting was observed) when they knew the amplitude of the saccade in advance.

Discussion

The main finding from Experiment 6 is that latencies to initiate saccades did not depend on the nature of the advance information available about the potential saccade targets. This suggests that subjects were not individually preparing direction and amplitude parameters during the latency interval, as they apparently had in Experiment 1. Rather, subjects appear to have prepared saccades in the present experiment more holistically. A procedural difference between Experiment 1 and the present experiment may account for the different pattern of results obtained. In the present situation, the stimuli that signaled the saccades were sudden onsets of light in a display that was spatially compatible with the configuration of saccade targets. That was not true in Experiment 1.

Why might the two different procedures lead to different conclusions about the programming of saccades? It is possible that subjects in the present experiment did not need to specify individual parameters in advance of the reaction signal. Rather, people may be able to "automatically" move their eyes in the direction of a sudden onset. This possibility is supported by the finding that saccades to sudden onsets of light can be produced with latencies that are independent of the eccentricity of stimulation and of the number of possible stimulus locations (Saslow, 1967; Todd & Van Gelder, 1979; White, Eason, & Bartlett, 1962). The results of the present experiment help to extend those previous findings to a situation in which the sudden onset does not serve as the target for the saccade, but rather is merely in the same direction as the saccade target. This conclusion fits well with models of saccade programming proposed by others (e.g., Becker & Jurgens, 1979; Findlay, 1983). In those formulations, the sudden appearance of a stimulus is believed to serve as a "trigger" for preparation of a saccade in the direction of the stimulus. Computation of the amplitude of the saccade is thought to occur after the trigger signal has been received. As we discuss below, these results may provide important insights into the distinction between reflexive and voluntary eye movements.⁹

General Discussion

In this article we have presented evidence that shows that the preparation of saccadic eye movements can sometimes be characterized as consisting of separate decisions regarding the direction of movement and the amplitude of movement. In Experiment 1 we showed that advance information about

⁹ Of course, it is possible that subjects did prepare the precued parameter in advance of the reaction signal in this experiment but that the sudden onset caused the subjects to abandon their partial saccade program in order to switch to a more reflexive preparatory strategy (cf. Inhoff, 1986). The existence of such a strategy would not rule out the individual preparation of direction and amplitude parameters after the reaction signal: Subjects may have prepared both parameters after the reaction signal in all conditions.

either direction alone or amplitude alone could be used to minimize subsequent saccadic latencies, suggesting that decisions about direction and amplitude are made in series and in a variable order. Experiments 2-4 showed that these findings were not due to processes involved in perceiving and encoding the stimuli, but rather reflected saccadic programming operations. Experiment 5 demonstrated that our initial findings were not simply due to the selection or activation of one response from among a set of completely prepared saccades. Experiments 5 and 6 showed that there are some situations where saccades appear to be programmed in a different manner.

Reflexive Versus Voluntary Control of Saccades

One important question that remains unanswered involves the extent to which our results can be generalized across different eye-movement situations. Although we have provided evidence that people can separately prepare the direction and the amplitude of a saccade in advance, we have also shown that there are some situations in which saccades may be prepared differently. The most obvious difference between these situations involves the extent to which the saccades can be characterized as reflexive or voluntary. Such a distinction has been made by others (e.g., Findlay, 1981, 1983; Klein, 1978).

Under what circumstances would people be expected to individually prepare spatial parameters for saccades? Our results suggest that such preparation may occur any time there are more than just a few (i.e., two) potential saccade targets in the environment and when the "stimulus" to move is not a sudden transient in the direction of the eye-movement goal. These requirements would be satisfied in most situations in which humans are scanning a relatively stable visual environment—where an almost unlimited number of locations could serve as the target for a saccade. In other words, we would expect people to prepare parameters individually for saccades whenever the saccades are centrally (voluntarily) produced.

A complementary issue is, of course, under what circumstances would people be expected to prepare saccades by using some alternative strategy, and what alternative strategies might they use? Clearly, one strategy seems to be used when the saccades are reflexively directed toward an abrupt stimulus onset. This finding fits in well with current research on eye movements and visual attention. It is known that an abrupt stimulus onset may automatically attract attention to the location of the onset (Yantis & Jonides, 1984), and attention directed to one hemifield may facilitate detection of stimuli throughout the entire hemifield (Hughes & Zimba, 1985). Similarly, Todd and Van Gelder (1979) have shown that a sudden onset may automatically "attract" a saccadic eye movement to the onset, whereas we have presented evidence that suggests that an onset may also facilitate other saccades within the same hemifield. Thus, our results suggest a close link between the processes underlying covert movements of attention and overt movements of the eyes—a suggestion also made by others (e.g., Klein, 1980; Remington, 1980; Shepherd et al., 1986).

Another alternative strategy used to program saccades without specifying values for individual spatial parameters involves the complete preparation in advance of a number of different saccades, followed by the selection of the appropriate response. Subjects appear to have been doing this (as intended) in Experiment 5. Such advance preparation has also been shown to occur in other motor systems (Rosenbaum, 1980). Presumably such a strategy would be useful only when there are a limited number of potential movements to be produced.

Relation to Previous Eye Movement Research

The present results and conclusions also fit well with other proposals regarding properties of the saccadic system. Most notably, our findings bear on the distinction between retinocentric and spatiotopic coding of a desired eye position. Evidence from several sources suggests that a saccade may be internally specified not only in terms of the direction and amplitude of movement but also in terms of the final absolute position desired (Hallet & Lightstone, 1976; Robinson, 1975; Sparks & Mays, 1983; Sparks & Porter, 1983; Zee et al., 1976). As we have shown, in some situations saccade programming seems to consist of specification of direction and amplitude parameters, whereas in others, the saccades appear to be organized more holistically—perhaps solely in terms of the desired final location.

Our results are also relevant to a number of more formal models of saccade programming that emphasize a distinction between direction and amplitude parameters (e.g., Becker & Jurgens, 1979; Findlay, 1983). As we have shown, under some circumstances the spatial dimensions of an upcoming saccade can be processed separately. Nevertheless, our results do differ in some respects from those of others. We found that direction and amplitude computation may be performed in any order, whereas others have suggested that the specification of direction must precede that of amplitude (Becker & Jurgens, 1979; Hou & Fender, 1979; Komoda et al., 1973). Also, we found no evidence that saccade latencies are more dependent on either directional uncertainty (cf. Megaw & Armstrong, 1973) or amplitude uncertainty (cf. Viviani & Swensson, 1982).

Conclusion

A number of researchers have suggested that partial information about spatial dimensions of an upcoming saccade might be beneficial—either to expedite the programming of the saccade (Becker, 1972; Henson, 1978) or to release limited mental resources for use in other tasks (Just & Carpenter, 1980; Rayner, Slowiaczek, Clifton, & Bertera, 1983). The results reported here show just how advance information about new fixation targets may be used in preparing saccades. In addition, our findings may help in understanding differences in the preparation of voluntary and reflexive saccades and may also lead to insights regarding the relation between movements of the eye and movements of attention.

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