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Programming Saccades: The Role of Attention

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Many different lines of research have attempted to answer questions about how the brain produces a saccadic eye movement. Often visual attention is an important factor in the findings of eye movement research. For this reason, it should prove useful to review some basic issues in eye movement research and the role attention plays.

One point of controversy in the saccadic programming literature (also discussed in the chapters by Findlay and by Abrams, this volume), involves specifying exactly how a saccade is programmed. Many researchers have chosen to characterize a saccade in terms of the direction and amplitude of a new fixation position relative to the current position of gaze. That is, they define a saccade in terms of the direction in which the eyes move and the distance or amplitude through which they must move. Thus, programming a saccade involves the specification of values for these two parameters which together can unambiguously distinguish one saccade from all others (given a common starting point).

Much research has focused on questions about when or how these parameters are specified: (a) Are the parameters computed in a serial or a parallel fashion? (b) If they are computed serially, is this done in a fixed or variable order? (c) Are the computation times different for the two parameters (in particular, which one takes longer)? (d) In fact, are they even computed separately at all? The results of experiments dealing with these issues have been mixed. I will focus on two paradigms and some related attentional problems that caution against easy answers to these difficult issues.

One method for studying these questions uses a precuing paradigm. In this paradigm, subjects are first presented a precue that partially specifies the spatial location of the saccade target; next, they are presented a reaction signal that completely specifies the required movement; finally, they are required to make the appropriate saccade as quickly as possible (see Abrams's chapter in this volume). Such studies have examined the separate effects of advance knowledge about either direction or amplitude upon the latency of the following saccade. Some studies

suggest that advance information about amplitude results in reduced latencies (e.g., Viviani & Swensson, 1982). Others, however, report that saccade latencies are reduced by direction precuing, but are not affected by amplitude precuing (e.g., Megaw & Armstrong, 1973). Abrams and Jonides (1988) outlined several difficulties with the precuing paradigm. In particular, they questioned whether advance information about target location really helped the motor programming of the saccade or merely facilitated the detection of the stimulus. In other words, was the latency of the saccade reduced because of advance preparation of a component of the saccadic response or simply because advance information about target location led to faster detection of the target? Abrams and Jonides attempted to control for this possible confound by using a central cue both to precue and direct the saccade. They found that, under these conditions, saccade latencies were reduced, not only when subjects were provided with advance information about the direction, but also when they were provided with advance information about the amplitude of the upcoming saccade.

Another paradigm that has been used to investigate the question of whether or not direction and amplitude are separately programmed is the double-step paradigm (see, e.g., Komoda, Festinger, Phillips, Duckman, & Young, 1973; Lisberger, Fuchs, King, & Evinger, 1975; Wheelless, Boynton, & Cohen, 1966; for a review, see Findlay's chapter, this volume). In this paradigm, subjects are instructed to make an eye movement to the target as soon as it appears. However, on some trials the target moves to a second position—after the target's initial appearance but before the subject is able to make an eye movement. The subject must then try to modify or cancel the program for the first saccade in order to reach the final position of the target. Sometimes, subjects are able to suppress the saccade to the first target and move their eyes directly to the final position of the target. When that happens, the time required to reprogram a saccade (measured from the time of onset of the second step) depends on the type of displacement—that is, whether the displacement is one of direction or amplitude. When the second target position calls for a saccade in a different direction from the initial target position, some studies have shown that saccade latencies are elevated relative to the latency on a single-target trial (e.g., Hou & Fender, 1979; Komoda et al., 1973). However, when the second target position requires only a change in amplitude, some studies have shown that latencies are somewhat shorter (e.g., Becker & Jürgens, 1979; Komoda et al., 1973). Together, these studies suggest that modifying the direction of a saccade takes more time than programming the saccade from scratch, whereas modifying the amplitude of a saccade benefits from initial preparation for the first saccade. These results imply that direction and amplitude are computed separately and, in particular, that direction is specified before amplitude.

As Abrams and others (Abrams & Jonides, 1988; also see Abrams's chapter in this volume) have pointed out, however, there are attentional confounds in the double-step paradigm that limit hard-and-fast conclusions. Many researchers have shown that the onset of a peripheral stimulus automatically attracts attention to the region of the stimulus and, consequently, detection or discrimination is subsequently facilitated in this region (e.g., Jonides, 1981; Posner, Snyder, & Davidson, 1980). Such facilitation is often described in terms of a gradient in which facilitation falls off with distance from the location of the stimulus (Downing & Pinker, 1985; Erikson & Yeh, 1985; LaBerge, 1983). In addition, some researchers have noted an increased cost upon crossing the vertical meridian, so that when attention is drawn to one hemifield, the responses to stimuli appearing in the other hemifield are slower (Hughes & Zimba, 1985; Rizzolatti, Riggio, Dascola, & Ulmita, 1987).

These demonstrated attentional effects can complicate the findings obtained in the double-step paradigm. For example, when there is a change in direction, the second target position is often further from the original target position (and thus further from the attentional focus) than when there is a change in amplitude. This could explain reduced latencies following a change in amplitude. In addition, when the second target position differs in direction from the first position, it often falls in the opposite hemifield from the first position, incurring an additional attentional cost. Such is not the case when there is a change in amplitude because the second target position always occurs in the same visual hemifield as the original target position. This might explain longer latencies when there is a change in direction.

It is important to note that studies involving the double-step paradigm do not all contain an attentional confound of field (i.e., some have direction changes within the same hemifield) and they attempt in most instances to control for an attentional confound of distance (e.g., by maintaining an equal distance between the first and second step targets across conditions; see Aslin & Shea, 1987). However, as Abrams and Jonides (1988) point out, the possible effects of attention should be kept in mind when considering the results of eye movement experiments.

O'Regan's "optimal viewing position" phenomenon (see O'Regan's chapter in this volume) is another example of an attentional effect that may confound eye movement research. Although his aim is to investigate how this phenomenon is related to the behavior of the eye in normal reading, the phenomenon itself is likely to be an attentional effect due to the particular task used. When a set of words of a given length is presented at different initial positions relative to a fixation mark, a spatial expectancy about where the information will appear is generated. Specifically, there is certainty that some part of the word will appear in the vicinity of the fixation mark, with smaller probabilities that parts of the word will appear to the left or to the right of fixation. As many

have shown, the gradient of facilitation (or the size of the spotlight of attention) depends on the demands of the task (Erikson & Yeh, 1985; LaBerge, 1983; LaBerge & Brown, 1986; Treisman & Gelade, 1980). Thus, the longer latency obtained for fixations at the beginning or at the end of words may simply be the result of a less than optimal attentional facilitation due to the fact that a part of the word falls beyond the optimal region of attention created by task demands. One way to get around this problem would be to block trials so that the fixation always occurs in a given position of the word. Another method would be to provide a string of nonsense characters (e.g., asterisks) as a warning signal indicating where the word will appear relative to the fixation mark while the subject maintains fixation. Although both these suggestions seem good controls for removing attentional effects, it is clear that such an imposed task is not a good model for understanding how the eye behaves in normal reading, given that there are quite specific and robust attentional effects in reading (see Henderson's chapter, this volume). It is not surprising, then, that the optimal landing position effect is very small (as measured by refixation probability) and disappears completely (as measured by gaze duration) in a text-reading situation (Vitu, O'Regan, & Mittau, 1990).

Another area where attention has played a role in eye movement research is in the classification of saccadic eye movements. Saccadic eye movements are often categorized as either reflexive or voluntary. Reflexive saccades are target-elicited saccades, whereas voluntary saccades can be obtained, for example, by instructing a subject to look to the left or to the right. An extreme example of a voluntary saccade is demonstrated in the anti-saccade task, in which the subject is instructed to look to the visual hemifield opposite to the one in which a peripheral target appears. Fischer and colleagues (Fischer & Boch, 1983; Fischer & Breitmeyer, 1987; Fischer & Ramsperger, 1984, 1986) most recently have suggested that a separate category of saccades with a very short latency exists. These very short latency reflexive saccades, which they call "express" saccades, were first described by Saslow (1967) and Ross and Ross (1980, 1981); for reviews, see Klein, Kingstone, and Pontefract's and Findlay's chapters, this volume. These saccades are obtained in the so-called gap task—the fixation point is turned off and a temporal gap precedes the presentation of the peripheral target. Fischer claims that in order to make an eye movement, attention needs to be disengaged from its current focus in the visual field. In the gap paradigm, the removal of the fixation point disengages attention and thus allows a faster eye movement. In addition, Fischer and Breitmeyer (1987) have shown that attention directed to the target position provides no advantage over attention directed to the fixation point when a saccadic eye movement to a peripheral target is required. Other findings, however, suggest that attention to the target position does reduce saccadic latency. Shepherd, Findlay, and Hockey (1986) demonstrated that saccadic latencies were

shortened if a probe stimulus appeared at the target position. An important difference between the two paradigms might explain the apparent contradiction: in Fischer and Breitmeyer's experiment, attention was cued endogenously, whereas, in Shepherd et al.'s experiment, attention was cued exogenously (see Klein et al., this volume). More specifically, in Fischer and Breitmeyer's experiment, subjects were instructed to fixate the center of a screen while attending to a spot above the saccade target. In this overlap paradigm, the attention spot stayed on throughout the trial, requiring sustained or endogenous attention. However, in Shepherd et al.'s experiment, there was a sudden onset of a probe in the target position, resulting in transient or exogenous attention. To see how this difference could affect the results, it might help to use a classification of orienting that has been adapted from Klein et al. (this volume).

As illustrated in Figure 6.1, orienting is divided into four cells. Possible physiological underpinnings are listed underneath each type of orienting. It is suggested here that exogenous orienting may involve the superior colliculus and other related brain stem nuclei, whereas endogenous orienting may involve the prefrontal cortex, specifically the frontal eye fields (FEFs) and area 46 (the principal sulcus). The frontal eye fields project directly (Lynch & Graybiel, 1983) and indirectly to the superior colliculus. Recent work has suggested that an indirect projection from the frontal eye fields via the substantia nigra may be responsible for tonic inhibition of the superior colliculus (Fischer, 1987; Hikosaka & Wurtz, 1985a, 1985b). Such a finding would support the inhibition of exogenous processes by endogenous processes as shown in the diagram. Much behavioral work in frontal brain-damaged patients and lesion work in monkeys support the idea that the frontal eye fields play a controlling and often inhibitory role with respect to the superior colliculus (see, e.g., Guitton, Buchtel, & Douglas, 1982, 1985; Schiller, Sandell, & Maunsell, 1987). The diagram also makes explicit a mutual facilitation between covert (attentional) and overt (saccadic eye movement) mechanisms within the same structures.

Figure 6.2 illustrates the model in greater detail and incorporates several underlying assumptions. It is assumed that there are two general orienting systems—"exogenous" and "endogenous"—that operate in parallel in the sense that both systems receive visual inputs and both can produce a similar behavioral output. More than a century ago, Hughlings Jackson articulated the idea that the central nervous system is organized hierarchically with specific reference to the motor system. Critical to this formulation is the idea that higher centers act upon lower centers and that they merely represent in greater complexity the very same impressions and movements as the lower centers represent. Although perhaps not explicit in the diagram, a similar assumption of hierarchy is present: the cortical (endogenous) system acts upon and sometimes through the sub-cortical (exogenous) system. In the case of overt orienting, both outputs

ORIENTING

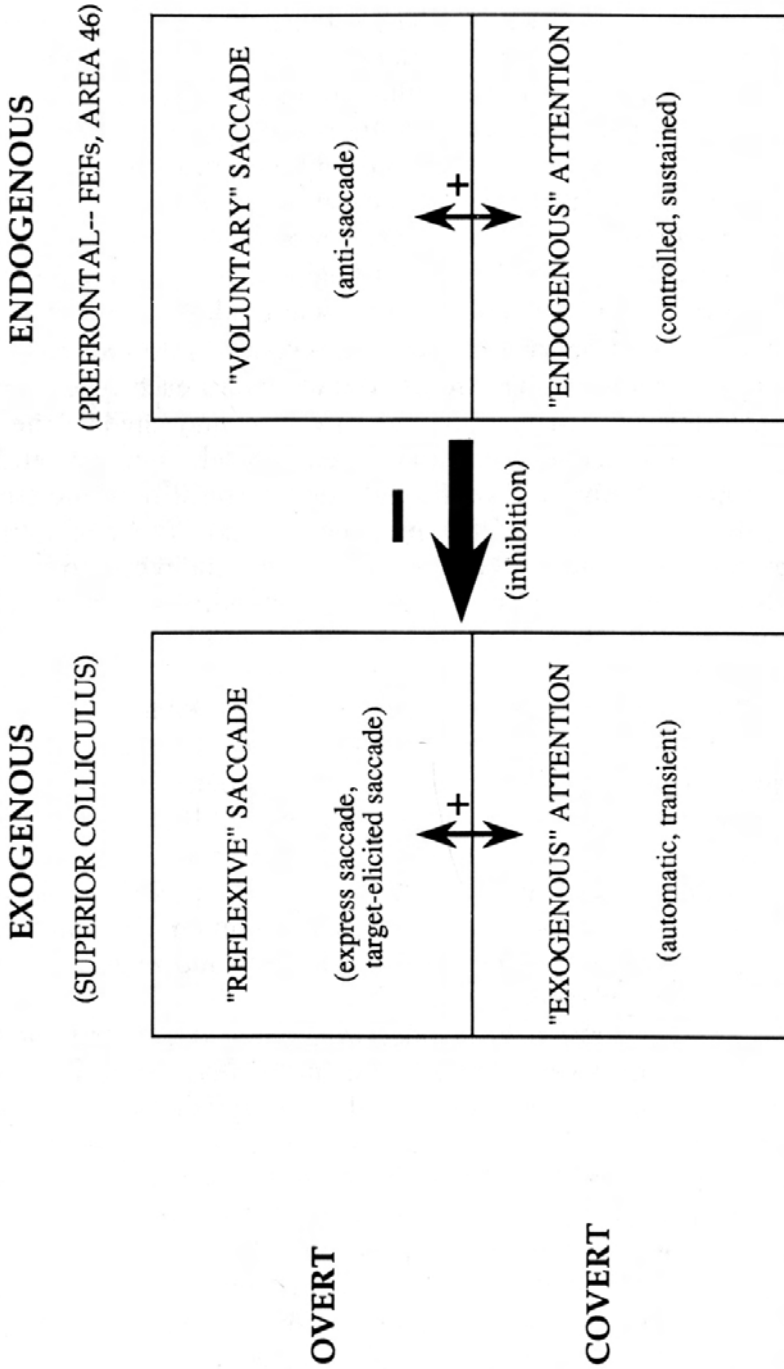


FIGURE 6.1. Classification of orienting, adapted from Klein, Kingstone, and Pontefract (this volume). FEFs, frontal eye fields; Area 46 = the principal sulcus.

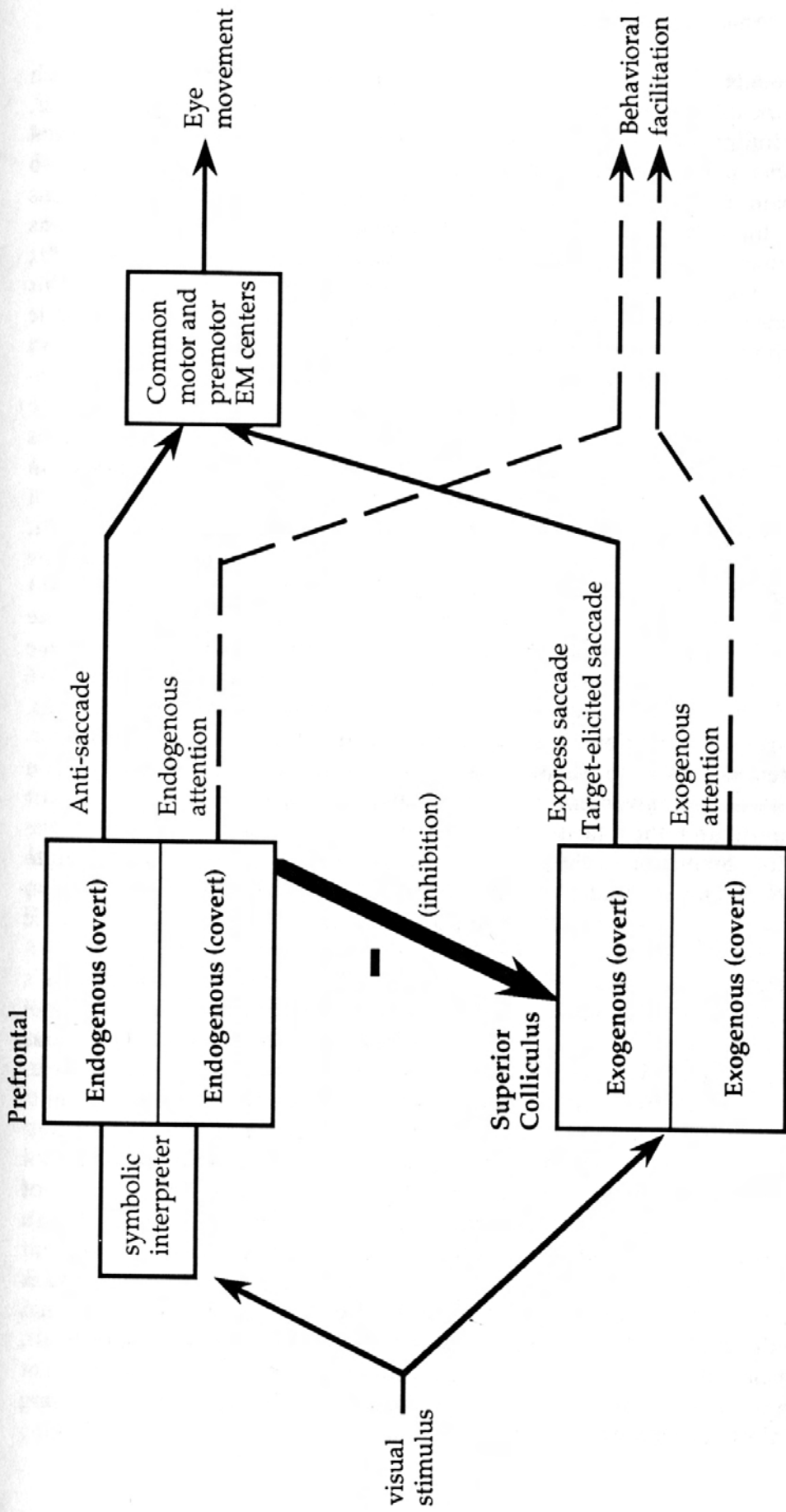


FIGURE 6.2. Proposed model of orienting.

eventually pass through the same motor and premotor centers (which may include the superior colliculus itself). In the case of covert orienting, both outputs produce a facilitation of response due to an attentional enhancement. Temporal characteristics are important, but difficult to indicate in the figure. There is much evidence suggesting that exogenous orienting is fast, transient, and relatively automatic, whereas endogenous orienting is slow, sustained, and under voluntary control (Jonides, 1981; Nakayama & Mackeben, 1989; see also Klein et al.'s chapter, this volume). Endogenous orienting often requires an extra stage of symbolic interpretation. The symbolic interpreter merely represents the extra processing steps required to interpret an endogenous cue or the instruction "look to the field opposite to the target," in the case of the anti-saccade task. Note that, although endogenous covert orienting is slower, the model permits situations where endogenous instructions can eliminate benefits of an exogenous cue by increasing the inhibitory role of the endogenous system. Such a situation may explain why Warner, Juola, and Koshino (1990) come to their conclusion that attentional capture by abrupt-onset stimuli is not strongly automatic.

The present model may account for apparent contradictions in the literature, for example, whether attention facilitates or inhibits an eye movement (see discussion above with reference to Shepherd et al., 1986 and Fischer & Breitmeyer, 1987). In Fischer and Breitmeyer's experiment, endogenous attention inhibits exogenous mechanisms, including target-elicited saccades. In Shepherd et al.'s experiment, exogenous attention facilitates eye movement production (within common motor or premotor centers), and thus facilitates endogenous or voluntary saccades. One possible prediction of the model is that endogenous attention can facilitate an endogenous saccadic eye movement. A simple test of such a prediction would be to show whether or not an endogenous cue facilitates saccadic response time in an anti-saccade task.

Such a model can also explain difficulties arising in Henderson's sequential attention model (this volume). Specifically, the present model of orienting would argue that each particular type of attention (exogenous or endogenous) is automatically coincident with its respective eye movement preparation because, within a system, attention and eye movements may share the same structures (or at least activate similar neural networks). However, eye movement preparation, like attention, does not necessarily lead to an eye movement. Explaining how the difficulty of foveal processing can affect extrafoveal processing (see Henderson's chapter, this volume) does not require one to assume that eye movement programming begins prior to a shift of attention. If foveal processing is easy, then attention can precede the final eye movement programming, and the preview benefit will be maximal. If foveal processing is difficult, then the attention shift will coincide with the beginning of eye movement programming, reducing the amount of extrafoveal attentive processing and thus the preview benefit.

Much evidence agrees with the proposed orienting model (Figure 6.2). Patients with frontal lesions are often unable to make voluntary saccades; they also exhibit more short latency saccades (Guitton et al., 1982, 1985). Inhibition of return is an inhibitory effect occurring about 300 ms after a visual event as long as attention is not maintained at the location of the event (Posner & Cohen, 1984). Rafal, Calabresi, Brennan, and Sciolto (1989) have shown that inhibition of return is intimately connected to exogenous orienting but not to endogenous orienting. In agreement with the tentative physiology of the model, it has been demonstrated that patients with peritectal degeneration show inhibition of return only for the same directions in which their eye movements are intact (Posner, Rafal, Choate, & Vaughn, 1985). Schiller et al. (1987) have reported supporting evidence for overt orienting in the monkey. Monkeys with frontal eye field lesions make more express saccades, whereas monkeys with superior colliculus lesions are unable to generate express saccades.

This model is the underlying framework for some work I am currently doing on attention and oculomotor function with schizophrenic patients (Sereno, 1991). Holzman and colleagues have previously established that although 60 to 80% of schizophrenic patients have disturbed smooth pursuit eye movements, less than 10% of normal subjects show similar abnormalities (Holzman & Levy, 1977; Holzman, Proctor, & Hughes, 1973; Holzman et al., 1974). A frequent interruption that occurs in the abnormal smooth pursuit trackings of schizophrenic patients is a saccadic intrusion. Saccadic intrusion is a generic term that has been used to describe several classes of saccadic events occurring during smooth pursuit tracking or fixation which are disruptive rather than corrective. In addition to this disinhibition of the saccadic system, schizophrenic patients often have low gain during smooth pursuit (Levin et al., 1988). The deficit in schizophrenic patients probably involves both the saccadic and smooth pursuit systems.

The most often cited behavioral deficit in schizophrenia has been an attentional disorder. The hypothesis that an attentional dysfunction is a central aspect of schizophrenic psychopathology is as old as the recognition of schizophrenia as a psychiatric disorder (Kraepelin, 1919). Taken together, the pattern of deficits in eye movements and attention in schizophrenic patients might help elucidate how the brain programs an eye movement.

In schizophrenic patients who exhibit smooth pursuit eye movement deficits, several studies have shown that the generation of slow eye movements (i.e., smooth pursuit-like eye movements) in these patients is normal and free of intrusive saccades when their eye movements are based on vestibular signals or full-field visual signals (Latham, Holzman, Manschreck, & Tole, 1981; Levy, Holzman, & Proctor, 1978; Levin, Jones, Stark, Merrin, & Holzman, 1982). These results argue against the presence of a deficit or lesion in motor or premotor eye movement centers, where the separate neural pathways generating the various types

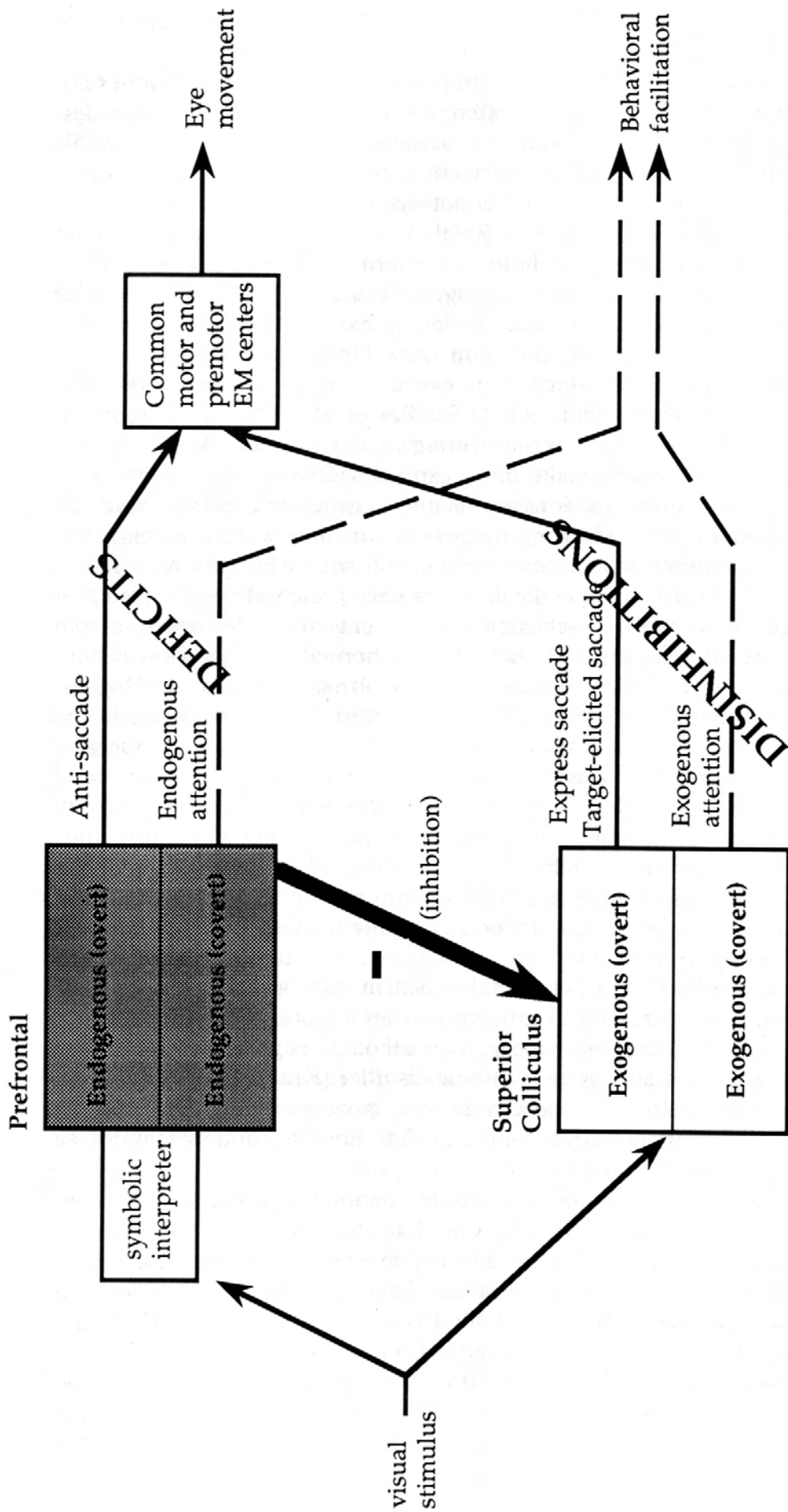


FIGURE 6.3. Proposed model of schizophrenic orienting. It is suggested that a prefrontal dysfunction in schizophrenic patients leads to deficits in their endogenous orienting system and disinhibitions in their exogenous orienting system.

Thirteen schizophrenic patients, 13 patients with affective disorder, and 14 normal controls were tested on a series of tasks examining attention, saccadic eye movements, and smooth pursuit eye movements. There was no significant difference between groups with regard to age, gender, years of education, and handedness. In addition, patient groups did not differ on age of onset or duration of illness.

To test covert orienting, a spatially directed visual attention task was used. A horizontal bar was briefly (33 ms) presented as a cue to indicate the position of the following target. After a brief interval, the target appeared for 150 ms with an 80% probability of occurring in the position opposite to the position of the cue (valid trial) and a 20% probability of occurring in the position of the cue (invalid trial). The interstimulus interval (ISI) between the cue and target was either 67 or 500 ms, as illustrated in Figure 6.4. Subjects were balanced so that half of them first performed the short then long ISI version of the task and vice versa. It was expected in the short ISI version that normal subjects would show facilitation of response times when the target appeared in the same position as the preceding cue, despite the fact that subjects knew this was not where the target was most likely to appear. This expectation was based on the well-documented finding that a peripheral cue automatically captures attention (see, e.g., Jonides, 1981; Nakayama & Mackeben, 1989). With the long ISI version, normal subjects were expected to be faster when the target appeared in its most likely position (opposite the cue). This expectation was based on the finding that a symbolic cue, which indicates where the target is to appear, summons an attentional effect beginning about 200 ms after the onset of the cue and peaking around 350 ms (see, e.g., Posner, 1980; Shulman, Remington, & McLean, 1979). In addition to these tests of covert orienting, there were three saccadic eye movement tasks: (a) a saccade task where there was simultaneous onset of the target and offset of the fixation point, (b) a gap task where the offset of the fixation point preceded the onset of the target by 150 ms, and (c) an antisaccade task where the fixation overlapped the presentation of the target and subjects were required to look to the field opposite to the target as quickly as possible. Finally, subjects were instructed to track a horizontally moving target while their smooth pursuit eye movements were recorded.

Preliminary results on the covert orienting tasks indicate that no group (normal, schizophrenic, or affective disorder) showed facilitation on invalid trials at the short ISI. This agrees with the recent findings of Warner et al. (1990) who demonstrate in a similar paradigm that the exogenous component of attention can be reduced by task demands. However, only schizophrenic patients showed a significant difference in the effect of validity across the two different ISI intervals. It appeared that some factor reduced the validity effect at the short ISI interval in schizophrenic patients. These results agree with the idea that schizophrenic

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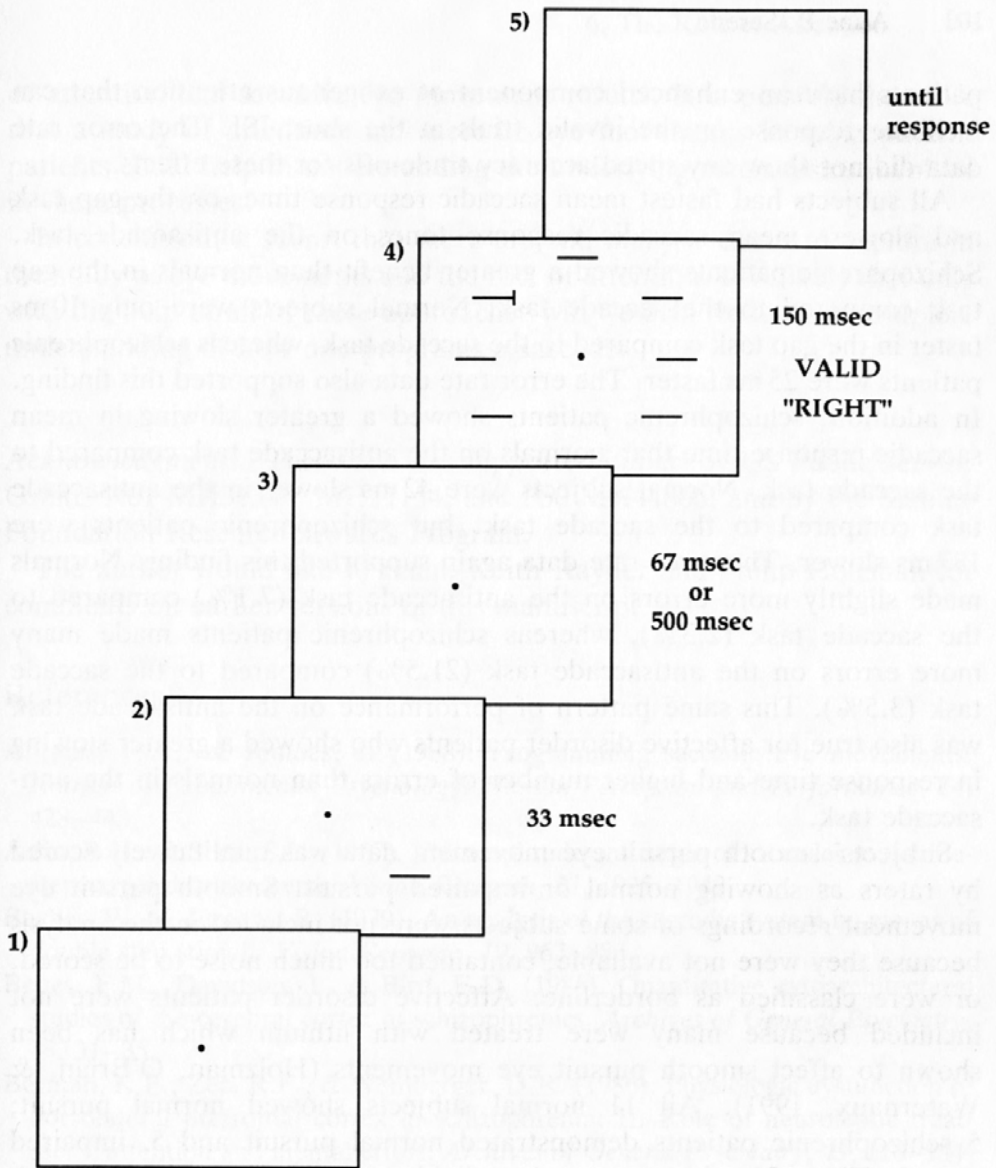


FIGURE 6.4. A sample trial from the attention tasks. Each trial was composed of 5 events: 1) A fixation point screen that was present before the initiation of the trial until 550 ms after the initiation of the trial. 2) A cue that appeared briefly (33 ms) indicating where the target was most likely to appear. 3) The interstimulus interval (ISI), which consisted of a fixation point screen having a duration of either 67 ms in the “exogenous” attention task or 500 ms in the “endogenous” attention task. 4) A target screen, which was presented for 150 ms and consisted of the target and seven distractors. 5) A blank screen, which was presented until the subject responded by pressing a key. Eye position was monitored throughout the trial, and the trial was automatically aborted and rerun later if the subject moved his/her eyes away from the fixation point during the cue, ISI, or target screens. Valid trials were trials in which the target appeared in the position opposite to the cued position; 80% of the trials were valid trials. Invalid trials were trials in which the target appeared in the same position as the cue; 20% of the trials were invalid trials. The correct response for the valid trial pictured was “right” (versus “left”).

patients have an enhanced component of exogenous attention that can facilitate response on the invalid trials at the short ISI. The error rate data did not show any speed-accuracy trade-offs for these effects.

All subjects had fastest mean saccadic response times on the gap task and slowest mean saccadic response times on the antisaccade task. Schizophrenic patients showed a greater benefit than normals in the gap task compared to the saccade task. Normal subjects were only 10 ms faster in the gap task compared to the saccade task, whereas schizophrenic patients were 25 ms faster. The error rate data also supported this finding. In addition, schizophrenic patients showed a greater slowing in mean saccadic response time than normals on the antisaccade task compared to the saccade task. Normal subjects were 42 ms slower in the antisaccade task compared to the saccade task, but schizophrenic patients were 187 ms slower. The error rate data again supported this finding. Normals made slightly more errors on the antisaccade task (7.1%) compared to the saccade task (2.3%), whereas schizophrenic patients made many more errors on the antisaccade task (21.5%) compared to the saccade task (3.5%). This same pattern of performance on the antisaccade task was also true for affective disorder patients who showed a greater slowing in response time and higher number of errors than normals in the antisaccade task.

Subjects' smooth pursuit eye movement data was qualitatively scored by raters as showing normal or impaired pursuit. Smooth pursuit eye movement recordings of some subjects were not included in the analysis because they were not available, contained too much noise to be scored, or were classified as borderline. Affective disorder patients were not included because many were treated with lithium which has been shown to affect smooth pursuit eye movements (Holzman, O'Brian, & Waternaux, 1991). All 11 normal subjects showed normal pursuit; 5 schizophrenic patients demonstrated normal pursuit and 5, impaired pursuit. These 21 subjects were then divided into two groups: those with normal pursuit ($N = 16$) and those with impaired pursuit ($N = 5$).

There was a trend toward an interaction between smooth pursuit eye movement performance and the attention tasks in response latency, such that subjects with impaired pursuit showed a larger difference in the validity effect at the two different intervals and subjects with normal pursuit showed less difference in the validity effect at the two different intervals. Subjects with impaired pursuit showed larger benefits in mean saccadic response times on the gap task compared to the saccade task than did subjects with normal pursuit. Subjects with impaired pursuit made significantly more errors on the antisaccade task compared to the saccade task than did subjects with normal pursuit. There was also some indication that subjects with impaired pursuit had slower saccadic response times on the antisaccade task compared to the saccade task than did subjects with normal pursuit. Preliminary analysis thus suggests that impaired smooth pursuit eye movements are related to a specific pattern

of attention and saccadic eye movement results. It is possible therefore that a study of attention and saccadic eye movements in schizophrenic patients could help in understanding the underlying mechanisms involved in these processes.

In conclusion, it seems that there are still many avenues to explore in the study of eye movements and the role of attention. It is likely that only with the help of all of these approaches will we achieve a more complete understanding of how one programs a saccade.

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