Neuropsychologia, Vol. 25, No. 1A, pp. 73-83, 1987.
Printed in Great Britain.

0028-3932/87 $3.00+0.00
Pergamon Journals Ltd.

MECHANISMS OF VISUAL ATTENTION REVEALED BY SACCADIC EYE MOVEMENTS

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Abstract—This paper summarizes recent data on the initiation of saccadic eye movement in relation to the mechanisms of visual attention. In particular, the occurrence of express saccades, defined by their extremely short reaction times, is discussed on the basis of the observation that these saccades do not occur when the subjects (man or monkey) are attending to either a fixation point or to any other visual stimulus in the periphery of their field of view including the "future" saccade target location. It is concluded that the system of visual attention can be in two states: engaged or disengaged. In order to generate a saccade or to move attention from one point to another visual attention must be in the disengaged state. The disengagement takes some time which is or is not included in the saccadic reaction time depending on whether or not visual attention is engaged at the time of the onset of the saccade target. During engaged visual attention saccades are inhibited thereby providing steady central fixation or the absence of saccades during directed peripheral attention.

INTRODUCTION

SHIFTS OF the direction of attention are closely related to shifts of the direction of gaze. Yet we can shift attention without shifting gaze (POSNER [21]). But it is not clear whether or not we can shift gaze without shifting attention, at least when the gaze shift is a visually guided saccade.

Studies on attention have carefully tried to avoid eye movements in order not to confuse mechanisms of saccade preparation with mechanisms of attention.

This paper attempts to summarize recent experiments on the preparation of saccadic eye movements that give insight into certain aspects of visual attention. In particular we will analyse the time preceding a visually guided saccade, i.e. the saccadic reaction time (SRT), within which attentional mechanisms may come into play. The basic idea is that any change in the attentional system requires a certain time which is included in the saccadic reaction time, provided this change is necessary in order to execute the eye movement under specified conditions.

Whereas some of the data described in this paper have been published new observations will be reported as well. A general review of the neurobiology of attention is given by WURTZ *et al.* [30] and most recently by ROBINSON and PETERSEN [24] but the authors do not consider the contributions of studies on saccadic reaction times.

EXPRESS SACCADES

The classical value of a reaction time of a saccade in response to the onset of a peripheral target light is in the order of 200 msec. Only a relatively small fraction of this time is needed

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for afferent visual (about 30 msec) and efferent oculomotor (less than 25 msec) delays. What happens in the brain during the rest of the time?

SASLOW [26] reported in 1967 that the introduction of a temporal gap between the offset of a central fixation point and the onset of a peripheral target light decreased the human saccadic reaction time (SRT) to about 150 msec as compared to 250 msec when the fixation point remained visible (overlap). In 1983 FISCHER and BOCH [10], using the gap task in the monkey, reported goal directed saccadic eye movements that were characterized by their extremely short reaction times. The monkey had to fixate a fixation point which was turned off after a few seconds. After a temporal gap of 200 msec a peripheral target appeared, to which the animal was required to make a saccade, in order to detect a small dimming of the target's luminance. In the distribution of the SRT a separate peak occurred at about 70 msec besides a second peak at about 140 msec. Saccades contributing to the first peak were called express saccades, those forming the second peak were called fast regular saccades.

It was found later that the gap between fixation point offset and target onset was not a necessary condition for express saccades: even if the fixation point remained visible (overlap paradigm) the animals could make express saccades after some training [3]).

Using again the gap paradigm it was shown by FISCHER and RAMSPERGER [13] that human subjects can also execute express saccades. The corresponding peak in the SRT distribution occurs at about 100 msec or 120 msec depending on whether or not the target location is predictable [14]. As in the monkey it was not necessary to use the gap paradigm to obtain express saccades in man. They occurred also in the overlap task, in particular after some practice. However, with the instruction to fixate the fixation point attentively human observers rarely make express saccades in the overlap paradigm. Instead rather long reaction times in the order of 220 msec or more were obtained (slow regular saccades), in accordance with SASLOW [26].

Figure 1 shows three distributions of SRTs obtained from a single human subject. In A the gap paradigm was used; and in B the overlap paradigm was used with the instruction to the subject that he direct his attention on the fixation point. One clearly sees two peaks in A and in B. The first peak in A, however, representing the express saccades is much larger than the first peak in B. Note that the second peak in A does not correspond to the second peak in B. In other words, the total spectrum of SRTs contains at least three distinct groups of reaction times.

It is this fact which led to the idea that the preparation of a saccade includes three time-consuming processes, one of which has to do with visual attention (the details of this idea, its anatomical and physiological bases are described in a review by FISCHER [6]).

Many more express saccades occurred in the overlap task if the subjects were asked to keep their gaze on the fixation point without paying attention to it [19]. Figure 1C shows this effect of changing only the instruction. The first peak is increased at the cost of the second peak.

It became clear that the presence or the absence of a fixation point could not account for the occurrence of express saccades. Control experiments have shown in adition that the phenomenon could not be explained by effects of anticipation or warning, because without warning signals and under randomized conditions express saccades occurred as well. (For more details and references see review by FISCHER [6]). Meanwhile the existence of express saccades has been confirmed in the monkey by SCHILLER *et al.* [27] and by ROHRER and SPARKS [25]. SCHILLER *et al.* [27] showed that the occurrence of express saccades—unlike regular saccades—needs an intact superior colliculus but not intact frontal eye fields.

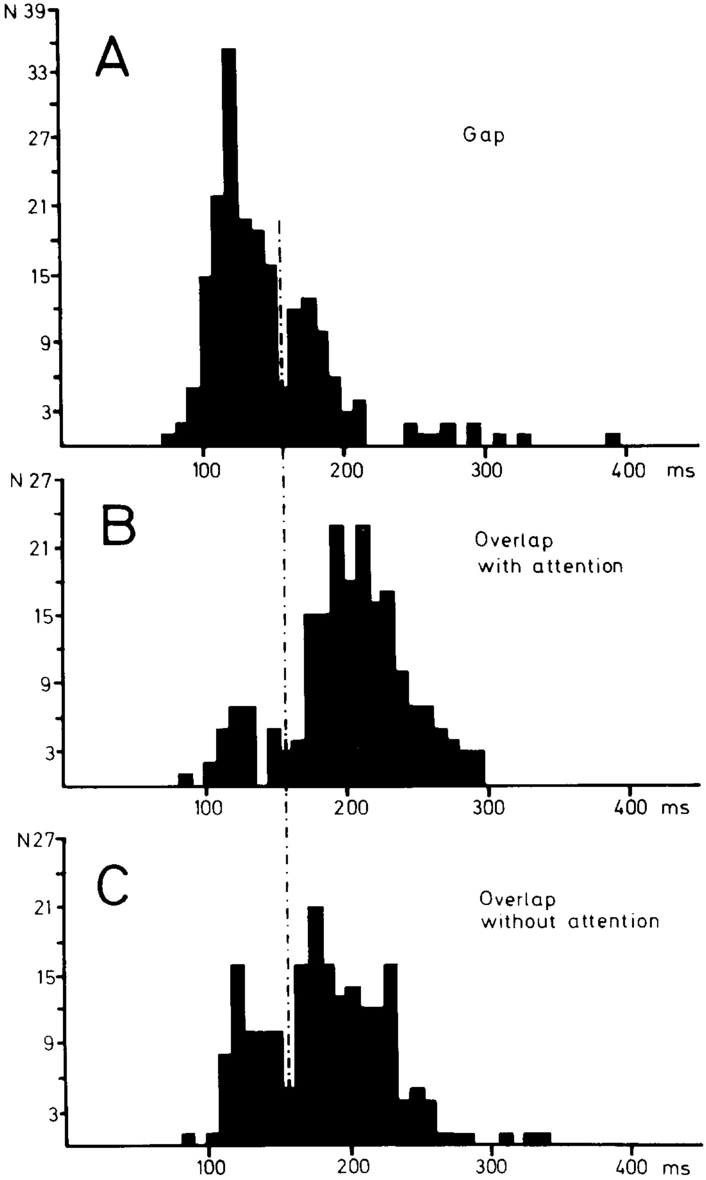

FIG. 1. Distributions of saccadic reaction times of a single human subject. In A the fixation point went off 200 msec (gap) before the saccade target was turned on. Saccadic reaction times (horizontal axis) are measured from target onset (bin width 10 msec). In B and C the fixation point remained visible (overlap). In B the subject was instructed to pay attention to the fixation point, in C the instruction was not to pay attention to it. The peaks of express saccades occur to the left of the vertical broken line.

ROHRER and SPARKS [25] showed that express saccades as well as other saccades are preceded by neural activity in the superior colliculus.

The question is what the actual conditions are under which saccadic reaction times could be reduced so drastically.

INHIBITION OF EXPRESS SACCADES BY DIRECTED VISUAL ATTENTION

Since the disappearance of the fixation point (in the gap paradigm) and the ignoring of the fixation point (in the overlap paradigm) seemed to facilitate the occurrence of express saccades, a number of experiments were conducted, in which the direction of gaze and the direction of attention were dissociated in space [19].

Subjects were instructed to direct their gaze straight ahead towards the center of a screen without providing them with a fixation point. They also were instructed to direct their attention to a small spot of light located in the periphery. When the saccade target appeared 4° to the right or left in a random order, they were to move their eyes from the center of the screen to the target. Two conditions were used again: (i) the attention target remained visible (overlap) when the saccade target appeared; (ii) the attention target disappeared (gap = 200 msec) before the saccade target appeared.

Figure 2A shows the SRT distribution in the overlap condition with the attention target located 5° above the center of the screen: express saccades are almost absent. The distribution of Fig. 2B was obtained in the gap condition: many express saccades are present. One conclusion from this result could be that attention directed to parts of the visual field other than the saccade target location prevents the occurrence of express saccades since a shift of attention might be necessary before the saccade can be initiated. In the overlap condition this attention shift requires extra time included in the total saccadic reaction time, whereas in the gap condition this shift can occur during the gap interval prior to saccade onset.

Given this interpretation, one would expect many express saccades in the overlap condition when the attention target is located at the saccade target location since attention already will have been shifted to that location. The result of this experiment is shown in Fig. 2C. Surprisingly enough, almost no express saccades occurred, even though the subjects' attention was constantly cued to the saccade target location. It was concluded that directed visual attention, no matter where in the visual field it is engaged, inhibits express saccades.

To show that the sensory effect of the offset of a peripheral target by itself (as in Fig. 2B) cannot explain the occurrence of express saccades, another control experiment was conducted. Subjects had to keep their gaze on a central fixation point in the presence of an additional peripheral stimulus at 4° to the left. The central fixation point remained visible when saccade target appeared (overlap), whereas the peripheral stimulus was turned off 200 msec (gap) before the saccade target appeared 4° to the right. In the first task subjects were asked to attend to the left (gap) peripheral stimulus. The result of one subject is shown in Fig. 3A. In the second task they were asked to attend to the central (overlap) fixation point. The result of the same subject is shown in Fig. 3B. Comparison of A and B shows that even though in both tasks the physical conditions were exactly the same, the results were clearly different: many express saccades occurred when attention was directed to the left. Here the offset of the attention target 200 msec prior to the onset of the saccade target enables a disengagement of attention such that the reaction to the saccade target could be an express saccade.

However, when the peripheral (left) stimulus was neglected and attention directed to the central (overlap) fixation point, the disengagement of attention was enabled only by the onset of the saccade target at the right. Again this supports the notion that engaged attention inhibits the saccade system.

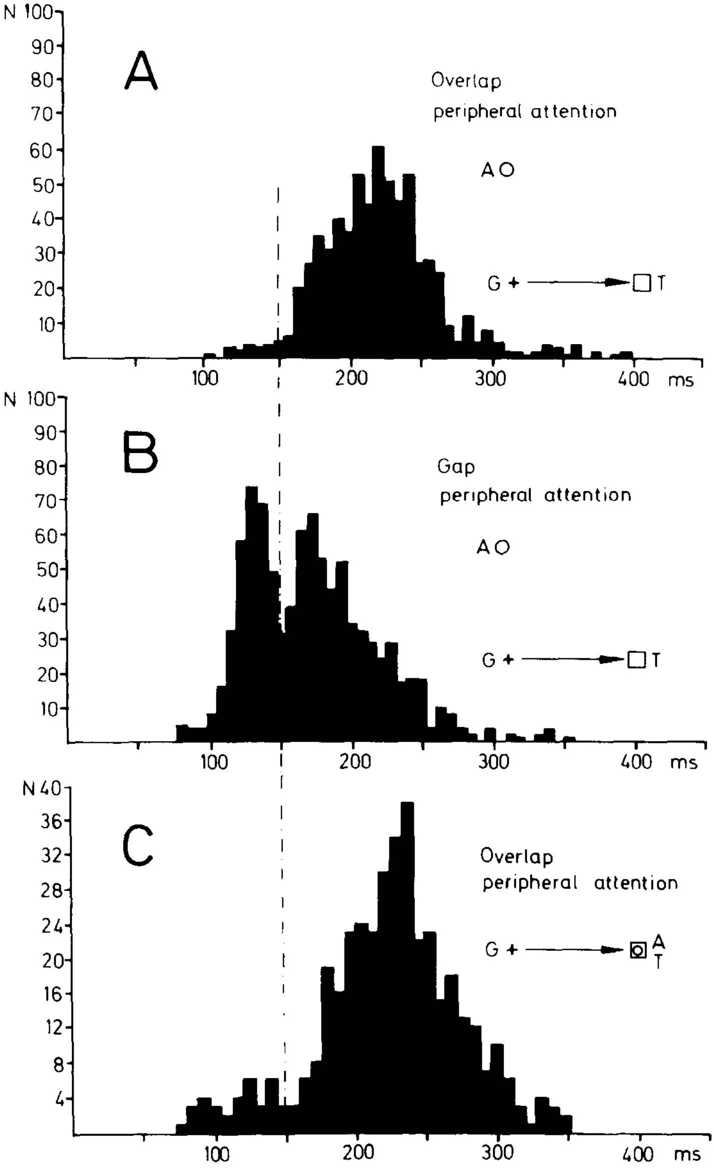

FIG. 2. Effect of peripheral attention on the occurrence of express saccades. In A the overlap paradigm was used with the instruction to pay attention to a peripherally located stimulus (A). Express saccades are virtually absent. In B the peripheral attention target (A) was turned off before the saccade target (T) occurred randomly at the right or left. In C the peripheral attention target was located just above the saccade target and remained visible (overlap). In all three conditions the subjects were required to keep their direction of gaze (G) in the middle of the screen without providing them with a fixation point.

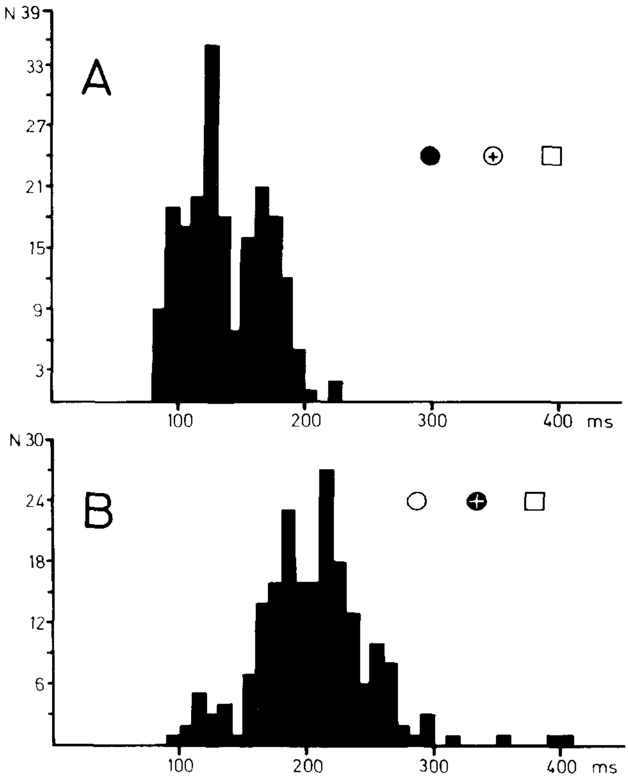

FIG. 3. Effect of peripheral attention in the presence of a central fixation point. In A attention was directed to a peripheral stimulus (indicated by the solid black circle) located 4° to the left of a central fixation point (indicated by the cross in the open circle). The saccade target (indicated by the outlined square) appeared 4° to the right, after the attention target had disappeared 200 msec before (gap). In B, exactly the same arrangement was used, but attention was directed to the fixation point (indicated by the solid black circle containing the white cross) while the peripheral stimulus at the left was ignored. One clearly sees the difference in the SRT distribution: many express saccades in A, few express saccades in B.

The logical consequence of this conclusion is that the attentional system can be in two states: "engaged", which is equivalent to "directed", or else "disengaged". In other words, if visual attention is disengaged express saccades are allowed. In contrast, in cases where the command to make the saccade is given when visual attention happens to be engaged, the change from engaged to disengaged attention takes a time thus adding to the saccadic latency.

LEARNING OF EXPRESS SACCADES

We noticed earlier that when the fixation point temporally overlaps the target onset the instruction not to pay attention to the fixation point leads to some but not to many express saccades. In light of the previous section one could argue that subjects might have difficulties in following the instruction "do not pay attention to the fixation point", because it is an unnatural and inconvenient situation not to pay attention to the only visible object in the visual field while keeping the gaze on it. However a reasonable possibility is that with some practice one can learn to disengage one's attention from the fixation point, thereby increasing the chances of producing express saccades.

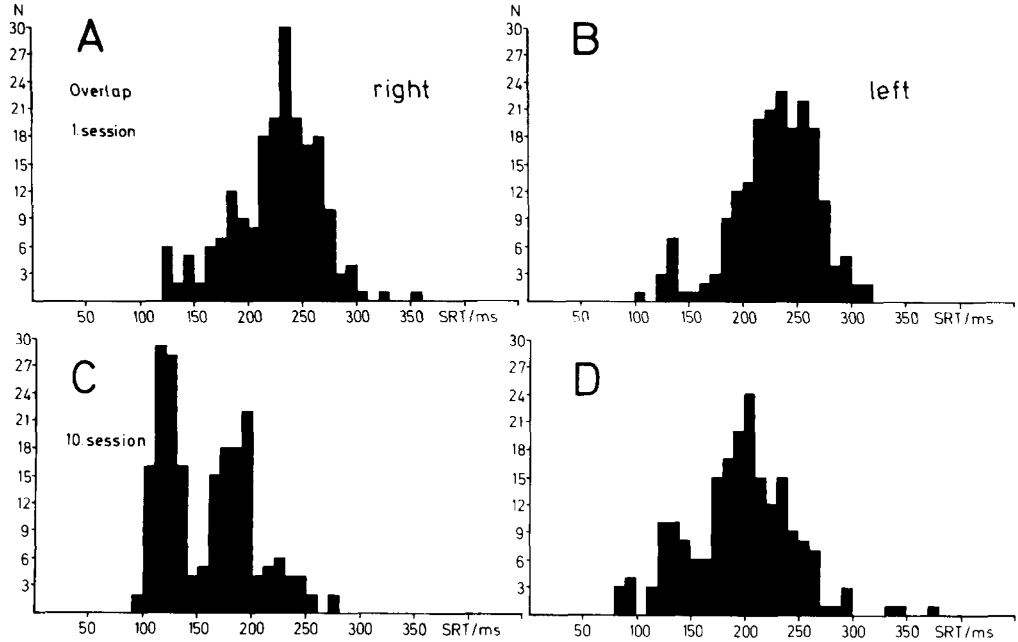

FIG. 4. Effect of daily practice on saccadic reaction times obtained in the overlap paradigm. A and B show the distributions for saccades to the right and to the left, respectively, before the training period. C and D show the same after the subject was trained for saccades to the right only. Comparison of A and C shows the effect of practice. Comparison of B and D shows that there was little transfer of the training effect to the untrained side. During all sessions (200 saccades each) the instruction was not to attend to the fixation point.

Figure 4 summarizes the results of a subject before and after 10 days of practice. In the 1st session the subject made 200 saccades to the right and 200 saccades to the left in the overlap condition. The resulting distributions are shown in Fig. 4 A and B. During the following days 200 saccades per day were made to the right only. After 10 sessions the results of the lower two panels (C, D) were obtained again for 200 saccades to the right and to the left. One clearly sees the effect of practice for saccades to the right (trained) side and—in this particular subject—only a slide generalization of the effect for the saccades to the left (untrained) side. The effect of training was not so much a uniform shift of a unimodal SRT distribution to lower values but rather a differential development of the three different peaks in a trimodal distribution. In Fig. 4 A, prior to training, one can identify a small peak below 150 msec, a somewhat larger one just below 200 msec and a large one around 250 msec. After training (Fig. 4 C) the first and second peak increase and shift a little to lower values. The third peak decreases and may also shift a little to lower values. This subject was tested again 6 months later. The asymmetry between the right and the left side was still evident. Other subjects showed different degrees of transfer of the training effects to the untrained side.

The conclusion from this result is not only that one can learn to voluntarily disengage one's attention but also that the attentional system is constructed in a retinotopic way. This could already be assumed from observations in the monkey by FISCHER *et al.* [12]. Their monkeys learned to make express saccades to one particular location. After the training the animals made mostly regular saccades to untrained locations but express saccades to the trained location and to its close neighbourhood even though the target positions were unpredictably distributed trial by trial over the whole visual field.

COORDINATION OF VISION AND EYE MOVEMENTS BY ATTENTION

The data summarized above have shown that: (i) directed visual attention largely reduces the occurrence of express saccades; (ii) the attentional system has two states (a) disengaged and (b) engaged; (ii) it takes time to change from the engaged into the disengaged state.

The question arises, how the visual system (as a sensory system), the saccadic system (as a motor system), and the attentional system (neither sensory nor motor) work together under natural viewing conditions.

Let us assume that the express saccade is a reflex eye movement mediated by the superior colliculus [27] and possibly including striate cortex [3], but not the frontal eye fields [27]. Then the results described above imply that this reflex is directly or indirectly inhibited by directed visual attention. Since during attentive fixation all saccades must be prevented by definition, let us assume further that directed visual attention in general inhibits any saccade, not only express saccades.

This view leads to the following statements. (i) Fixation is more than the absence of saccades, because during fixation saccades are actively suppressed not just absent. Electrical stimulation of parietal cortex [28], the frontal eye fields [15], and the superior colliculus supports this view, because from any of these structures saccades are more difficult to elicit electrically during fixation than during periods characterized by a passive absence of eye movements. Active fixation is a state in which the direction of gaze and the direction of attention are identical in space. Eccentric "fixation" is achieved by visual attention engaged (or directed) to a peripheral part of the visual field. (ii) For any goal directed saccade to be generated it is necessary to disengage attention from wherever it has been engaged before.

This means that during natural vision with moving eyes there is not only a sequence of saccades but also a sequence of disengaging and engaging visual attention. Figure 5 illustrates this idea schematically. As long as the attentional system is in the engaged state (black circle at the left) the direction of gaze is fixed and saccades are actively suppressed. After going into the disengaged state (open circle) the saccade generating system (square) is enabled but does not necessarily initiate a saccade. This happens only if a peripheral stimulus is presented which—by instruction or other behavioural disposition—is a target for an eye movement. If the target happens to appear when attention is already disengaged the saccade can be an express saccade. It is as if the attentional system being disengaged releases a reflex pathway from inhibition. If no saccade occurs, attention may be moved and engaged again at a new position. In this newly engaged state of peripheral attention saccades are also suppressed. In order for the next saccade to occur attention must be disengaged again. It should be noted that disengaged attention does not mean "no attention" or "inattentive".

DISCUSSION

In this section we discuss the possible integration of other data into the concept of attention as revealed by observations on saccadic eye movements.

Most importantly there is the work of POSNER *et al.* [22] on patients with parietal lobe lesions. These patients had difficulties in using a central cue to move their attention to the periphery. The conclusion of POSNER *et al.* [22] is similar to the concept developed in this

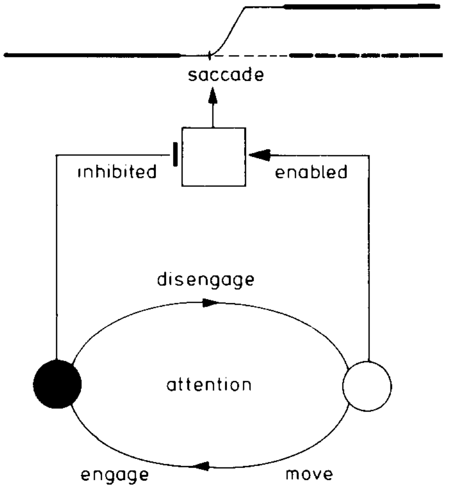

FIG. 5. Schematic diagram of the mechanisms in visual attention and their coordinating relationship to the generation of saccades. The upper trace shows eye position during engaged attention (heavy line) and during disengaged attention (thin line). If no saccade occurs (broken line) attention may be moved and engaged again resulting in a situation of directed peripheral attention. Engaging attention (solid circle) inhibits saccades; disengaging attention (open circle) enables saccades.

paper, namely that attention in order to be moved must be disengaged. (In fact we have adopted the terms "engagement" and "disengagement" from POSNER *et al.* [22].) The neglect syndrome observed so often after parietal injuries occurs as a consequence of being unable to disengage attention in a directional specific way.

Neural activity prior to saccades has been recorded in a number of brain structures such as the superior colliculus [29], the frontal eye fields [4], the posterior parietal cortex [5], and more recently in the prelunate gyrus of the visual cortex of the rhesus monkey [7,8]. A feature that neurons in these areas have in common is that their responses to the onset of a receptive field stimulus is enhanced if that stimulus (not others) is a target for a saccade. Subsequently it was shown that cells in the prelunate gyrus are activated also by the fixation point's offset in absence of the eye movement [11]. It was argued that this activity reflects the animal's attention being directed to the stimulus.

This view was substantiated by MORAN and DESIMONE [20] who noticed that selective attention to a stimulus within the receptive field of prelunate cells enhanced their responses. Similarly, cells in the inferotemporal cortex are more responsive to light if during an interval of no eye movements the monkey is left without a fixation point to actively fixate [23].

Any structure which receives input from cells whose activity is modulated by visual attention will also be influenced. Signals which represent the disengagement of attention will in particular impinge on structures closely related to the initiation of saccades, i.e. the frontal eye fields, the superior colliculus (intermediate and deep layers), and the brain stem. Even if activity in the latter structures occurs only prior to saccades one of its sources may be the attentional system cooperating with the saccade system as shown in Fig. 5.

The pathways and the exact mechanism through which the signals of disengagement disinhibit the saccade system are not yet clear. The inhibitory GABA mediated action of the substantia nigra pars reticulata onto the superior colliculus may play a role [17,18].

Interestingly the saccade suppression by fixation seems to require an intact frontal cortex, because patients with frontal lobe lesions have difficulties in suppressing reflexive glances [16].

Further neurophysiological studies are required to possibly demonstrate the differential effects of disengagement, movement and engagement of visual attention at a neural level.

Acknowledgement—This work was supported by the Deutsche Forschungsgemeinschaft, Sonderforschungsbereich "Modulation und Lernvorgänge in Neuronensystemen" (SFB 325, Tp C5).

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