Eur Arch Psychiatr Neurol Sci (1989) 239:9–16

European Archives of Psychiatry and Neurological Sciences

© Springer-Verlag 1989

Attention and Eye Movement Control: An Overview

Rudolf Groner and Marina T. Groner*

Psychology Department, University of Bern, Laupenstrasse 4, CH-3008 Bern, Switzerland

Summary. A review of recent experimental and theoretical findings is presented which relates the results of neurophysiological and psychological research on attention and eye movement to cognitive theorizing. With respect to the relation between shifts of attention and saccadic eye movements, several experiments have demonstrated that it is possible to dissociate the line of attention from the gaze direction. On the other hand, there is some indirect (although not yet conclusive) evidence that saccadic eye movements always produce a concomitant shift of attention. Another question is whether there is a moment-to-moment control of each consecutive saccade and latency or whether indirect control models (i.e. planning several saccades in advance) are more appropriate. The function of attentional processes which have to coordinate stimulus driven (bottom-up) and concept driven (top-down) mechanisms are discussed and related to some studies investigating local and global scanpaths.

Key words: Attention – Eye movements – Saccadic control – Scanpaths

Introduction

The functional significance of eye movements is closely related to the anatomy of the retina where, in the fovea, a small central region of approximately 2° of visual angle diameter, cone receptors are packed together very densely, allowing for a much higher resolution compared with the periphery of the visual field. It has also been shown (Spillmann 1971) that the size of the perceptive fields, measured by psychophysical methods, as well as the size of the receptive fields, assessed by single cell recordings, strongly increase from the centre to the periphery. The same holds for the size of the associated cortical areas (Rovamo and Virsu 1979). Therefore, the visual system can increase the resolution of the optical input by projecting it onto different retinal areas, through body locomotion and/or eye movements.

However, in addition to these arguments concerning the resolution or scale of image analysis, several researchers have proposed that there is also a qualitative difference between central and peripheral vision, involving two different visual systems: focal versus ambient vision (Trevarthen 1968), indentifying versus locating mode (Held et al. 1967; see also Ungerleider and Mishkin 1982), sustained versus transient mechanisms (Breitmeyer and Ganz 1976), feature extraction versus object identification (Treisman and Gelade 1980), or attentive versus preattentive vision (Julesz 1984). Despite the differences between these proposals, they all have in common that some kind of preprocessing is followed by a consecutive process of further elaboration, linked by some attentional mechanism.

Attention and Experimental Psychology

Earlier generations of experimental psychologists (e.g. Düker 1956) avoided the concept of attention because of its circularity between empirical phenomenon and theoretical construct. The term “attention“ became more popular in psychology with the change from the behaviouristic to the cognitivist paradigm emphasizing a more functionalist view on psychological processes. Furthermore, some experimental demonstrations became very well known (Posner et al 1980; Jonides, unpublished work) showing that the precueing of the location of a stimulus leads to an advantage in detection performance and reaction latency.

A first meaning of attention describes a general state of arousal or alertness in an organism and has

---

* Supported by the Swiss National Science Foundation, grants 1.187.85 and 3.940.84

Offprint requests to: R. Groner

This article was presented in part at the Symposium on Eye Movements and Psychopathology, Berlin, 23–24 June 1988

been well investigated (e.g. Magoun 1963; Duffy 1962) in connection with the study of the reticular activation system which serves as a regulatory control mechanism over the entire brain activity. Some studies have related saccadic activity to the arousal level (e.g. Hinton 1982); however, in the present context issues of selective attention are more important. Although no general definition exists, Posner's (1980) description of attention as an alignment of the sensory input is closest to the gist of most studies performed recently. There is a difference between research paradigms with divided attention, where information is presented simultaneously on competing channels, and orienting attention. Depending on what causes the orienting, one can distinguish between overt and covert orienting attention. Overt orienting refers to a change in the alignment of the sensory receptors. Jonides (1980) described covert attention as „the control of the mind's eye movements". A further distinction has been made between externally and internally controlled orienting. This distinction is very close to the characterization of data-driven (bottom-up) versus stimulus-driven or top-down processing (e.g. Kahneman 1973; Norman and Bobrow 1975). A final issue in attention is the notion of resource allocation or limited capacity (Shiffrin and Schneider 1977; Navon and Gopher 1979; Wickens 1984; Johnston and Dark 1986; Maylor 1985).

Studies of Shifts of Covert Attention

An old question in psychology is whether it is possible to shift attention independent of eye movements. For instance, Helmholtz (1909) stated that "it is possible, simply by a conscious and voluntary effort, to focus the attention on some definite spot in a field". This was also argued by Wundt, who claimed that it is possible to separate the line of fixation from the line of attention. However, most experimental studies until the mid-1970s (e.g. Mowrer 1941; Mertens 1956; Grindley and Townsend 1968; Shiffrin and Gardner 1972) failed to demonstrate this claim on empirical grounds. After 1972, a number of studies appeared which seemed to demonstrate successfully shifts to attention in the absence of eye movements (Eriksen and Hoffman 1973; Jonides, unpublished work; Posner et al. 1972; Posner et al. 1980, etc.). The following example is typical of its genre.

A visual target appeared either on the right- or left-hand side of fixation. It was preceded by a cue which was either a plus sign or an arrow pointing to the right or left. If the plus sign was presented, the target was equally likely to occur to the left or right fixation. If an arrow was presented, the probability was 80% that the detection stimulus would occur on the indicated side (i.e. the cue was valid) and 20% that it would occur on the other side (invalid). Thus it was possible to examine both the benefits from knowing where in space the stimulus will occur, and the cost when it occurs at the position other than the expected position. Compared with the control condition (with the plus sign), Posner et al. (1978) were able to show a decrease of manual reaction time under the valid cue condition and an increase under the invalid condition. One might expect that this movement of attention should also correlate with retinal eccentricity. However, Posner (1978) found that costs and benefits from attention did not vary much with stimuli ranging from 0.5°–25° eccentricity, which is especially astonishing for the within-fovea condition, and in disagreement with Engel (1971). He required subjects to locate a simple form embedded in a complex visual field. He provided both a fixation point and a point away from fixation where attention was to be concentrated. He found the field of high acuity (what he termed "conspicuity") for the ability to identify the target included the fovea but was elongated in the direction of the subject's attention. The difference between Engel's and Posner's results might be due to the fact that Engel's task required high visual acuity and Posner's conditions are simple detection tasks well above threshold. According to Posner, although attentional orientation to the periphery allows detection to occur more quickly, it will not provide an increase in the retinal resolution and therefore does not produce any changes in acuity. According to Posner et al. (1980), attention represents a system for routing information and for control of priorities; it provides an alignment and not a sensitization. (For another perspective on this question, see Groner et al. 1986).

Posner's view of attention is compatible with Norman's (1968) metaphor referring to attention as a kind of spotlight with an adjustable beam. There is even some evidence that the beam can be split (Egly and Homa 1984; Lambert 1987; Müller and Findlay 1988). The spotlight metaphor was also extended to movements in space and time by Shulman et al. (1979) and Remington and Pierce (1984). In their experimental series, Remington and Pierce used as a precue an arrow that appeared above the fixation point, and targets occurred at a precueing validity of 80% either to the right or to the left along the horizontal meridian at eccentricities of 2° or 10°. These targets consisted of small dots to which the subjects had to respond as quickly as possible. The onset of the precue was separated from the target by stimulus onset asynchronies (= SOAs) ranging from 16 to 600 ms. In order to estimate the effect of retinal eccentricity on the shifting of attention, reaction times to the cued near location were subtracted from those to the cued for location separately for each SOA. Remington and Pierce concluded from their results that they were not compatible with a fixed velocity analogue model, but rather interpreted their data as showing that the attentional focus either moved at a speed proportional to the distance to be travelled, or – as an alternative interpretation – that the attentional focus moved in a discrete shift independent of the distance to be traversed.

With a similar experiment. Tsal (1983) arrived at quite different conclusions. The subjects were given a choice reaction time task in which they had to discriminate the letter X from the letter O at eccentricities of 4°, 8°, and 12°. As a precue, a small dot appeared close to the subsequent target location at an SOA between 50 and 183 ms. Inspecting the functions of the reaction times at different SOAs and target locations, and fitting a linear regression for the first parts of the functions up to the point where Tsal decided them to be asymptotic, Tsal came to the conclusion "that the SOA facilitated performance via movements of attention at a constant velocity" (p. 526), which he estimated to be approximately 8 ms per degree of visual angle. The conclusions of Tsal, Shulman et al. and Remington and Pierce have been questioned recently by Eriksen and Murphy (1987). They argued that in most of these studies at least five variables have been neglected that determine the shape and parameter of reaction time-SOA function: (1) the time required to perceive the cue and its location, (2) the latency of initiating the attentional relocation, (3) the time required for the relocation to occur, (4) individual differences and (5) general signal or warning effects (e.g. like those described by Ross and Ross 1985)

The Relation Between Attentional Processes and Eye Movements

There are some relevant results from single cell recording studies in monkeys. In the area of the superior colliculus, Goldberg and Wurtz (1972) showed an increase in the firing rate of single cells when the eyes began to move. Initially, Goldberg and Wurtz associated this system with a general attention mechanism. Later work by Wurtz and Mohler (1976) demonstrated that other methods of producing attention did not produce an increase of the firing rate of collicular cells. These and similar findings led Wurtz and Mohler to propose that the observed cell discharges were related to the readiness to make saccades rather than to the actual execution of the saccades.

The results already reported have shown that attentional processes could be elicited without any concomitant eye movements. However, it is quite unlikely that attentional pocesses and the elicitation of concomitant eye movements are two completely independent systems. For example, Gopher (1973) observed that during dichotic listening tasks subjects made large saccades followed by long fixations in the direction of the attended ear. This result was interpreted by Gopher as indicating that subjects were utilizing eye movements to emphasize the desired direction of attention. Besides these two logical extremes there are a variety of intermediate positions. One view already mentioned in connection with Wurtz and Mohler assumes that attention shifts are programs for the movement of the eyes. Klein (1980) performed two experiments which should determine (1) whether allocating attention to a position would facilitate making an eye movement to that position, and (2) whether making an eye movement would facilitate manual responses to stimuli at the target position for the eye movement. The subjects were given a cue as to where to shift attention and were then instructed either to move their eyes or to report a detection stimulus by pressing a key. Each trial began with a cue. There were two kinds of trial. In eye movement trials an asterisk appeared to the left or right of fixation; in detection trials the subject hat to respond to a luminance increment by pressing a key. Klein's results were negative with respect to both hypotheses. When the subjects had to move their eyes in the direction of attention, they were no faster than when they moved opposite to the direction of attention. Furthermore, the detection task was totally unaffected by the direction in which the subjects moved their eyes. These results show clearly that there are conditions under which one finds no relationship between spatial attention and eye movement latencies. However, these experiments involved a relatively unnatural discrimination, which resulted in very long saccade latencies and reaction times. It might be argued that under more normal conditions one would obtain different results, like those obtained by Remington (1980).

Shepherd et al. (1986) used an experimental technique avoiding peripheral stimulation unlike most earlier experiments. However, if attention is always "captured" by the peripheral stimulus, these experiments cannot distinguish between attention effects due to peripheral stimuli and those due to eye movements. The authors attempted to separate the effect of attention and eye movements through manipulating spatial attention by varying the probability that a peripheral probe stimulus would appear in different positions, while saccades were directed by a central arrow, thus avoiding peripheral stimulation. The probe stimuli had the following effect on saccade latencies. Probe stimuli appearing before the saccade shortened saccade latencies if they appeared at the saccade target, and they lengthened saccade latencies if they appeared at the opposite side of fixation. These facilitatory and inhibitory effects were shown to occur at different stages of saccade preparation and were interpreted as indicating that attention plays an important role in the generation of voluntary eye movements. With respect to the relation between the two entities, Shepherd et al. concluded "that while it is possible to make attention movements without making corresponding eye movements, it is not possible to make eye movements (in the absence of peripheral stimulation) without making a corresponding shift in the focus of attention".

Studies of Saccadic Latencies

Saccadic reaction time already presents a wealth of possibilities for studying the attentional mechanisms. Any change in the attentional system requires a certain time which is included in the saccadic time, provided this change is necessary in order to execute the eye movement and the process is serial and not parallel in nature (Fischer and Breitmeyer 1987). The underlying assumption of this approach is that mechanisms of attention regulate the preparation and execution of a saccade.

The modal value of the reaction time of a saccade in response to the onset of a peripheral target is in the order of 200 ms. However, only a minor part of this time is needed for afferent neural transmission (about 30 ms) and for efferent oculomotor delay (approximately 25 ms). What goes on in the brain during the rest of the time? Saslow (1967) reported that the introduction of a temporal gap between the offset of a central fixation point and the onset of a peripheral target light reduced the human saccadic reaction time to about 150 ms as compared with 250 ms when the fixation point remained visible (called overlap condition). Using the gap task with monkeys, Fischer and Boch (1983) reported goal-directed saccadic eye movement characterized by their extremely short reaction times in the order of about 70 ms. The task of the monkey was to fixate a fixation point which then was turned off, and after a temporal gap of 200 ms a peripheral target appeared to which the animal was required to make a saccade in order to detect a small reduction in the target's luminance. In the frequency distribution of the saccadic reaction times a separate peak occurred at about 70 ms in addition to a second peak at about 140 ms. Saccades being centred around the first peak were called by Fischer (1987) "express saccades", those around the second peak "fast regular saccades". Using the gap paradigm with human subjects, Fischer and Ramsperger (1984) again demonstrated the occurrence of express saccades. Humans were somewhat slower than monkeys; their corresponding peak in the saccadic reaction time distribution occurred at 100–200 ms. It was demonstrated that the disappearance of the fixation point (gap condition) or ignoring of the fixation point (in the overlap paradigm) facilitates the occurrence of express saccades. As a logical consequence, the direction of gaze and the direction of attention were to be dissociated in space in the next experiments (Mayfrank et al. 1986; Fischer and Breitmeyer 1987). Their subjects were instructed to direct gaze straight ahead towards the centre of a screen, however without providing them with a fixation point. In addition, they were instructed to direct their attention to a light source located in the periphery, and when the target appeared 4° to the right or left, they had to move their eyes from the centre of the screen to the target. Surprisingly, even when under the overlap condition attention was directed to the target location, hardly any express saccades could be observed; but unter the gap condition, although the peripheral attention target was on a different location, a great number of express saccades were recorded. One hypothesis compatible with this result is that a disengagement of attention is necessary before the saccade can be initiated. In the overlap condition, this disengagement of attention needs some extra time, whereas in the gap condition this shift can occur during the gap interval prior to saccade onset. This can be related to Klein's (1980) finding, discussed earlier, that shifting attention to a target location does not facilitate saccadic reaction time. Under this hypothesis, one could expect a large number of express saccades in the overlap condition when the attention target is located at the saccade's target location, since attention does not have to be shifted on that occasion. Surprisingly, under this condition only a very small percentage of express saccades occurred, although the subject's attention was constantly directed toward the target location. This finding suggests that directed visual attention, wherever in the visual field it might be engaged, inhibits express saccades. The result of these and similar experiments led Fischer and Breitmeyer (1987) to the conclusion that "(1) directed visual attention largely reduces the occurrence of express saccades; (2) the attentional system has two states (a) disengaged and (b) engaged. 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 time, thus adding to the saccadic latency". An important aspect of this model is that – unlike the earlier hypotheses about the relation between attention and saccade production – it focuses on an aspect which is at least as important as the eye movement, that is the eye fixation. From a functional point of view it is important that the visual system has sufficient time for processing the available information.

Towards Cognitive Models of Gaze Control

How can the so-called higher functions be brought into neurophysiological models of saccadic control? There seems to be hardly any other than the attentional system with which it is possible to incorporate the effects of cognitive functions like memory and motivation. It becomes apparent that the concept of attention in information processing terms is something like an interface between the higher processes and elementary visual information processing. Attention also serves the function of a multiplexing device which coordinates simultaneous or competing demands from different centres into one executable process. It is difficult to measure attention in a direct way. In the experiments reported earlier, attention was manipulated as an independent variable by one of the three following characteristics: (1) by means of expectations (typically by varying the probability of stimulus occurrence in different positions); (2) by instruction; or (3) by stimulus saliency. In information processing terms, (1) and (2) can be characterized as top-down processes, whereas (3) constitutes a bottom-up process (Norman 1968; Groner 1978; Groner and Groner 1982, 1987). With respect to the attentional processes, one has to expect a mutual interaction between bottom-up and top-down processes, since it is most likely that the control modes operate at the same time or at least in rapid succession.

With complex pictures, there was one feature which attracted most fixations according to Berlyne (1958), Yarbus (1967) and Mackworth and Morandi (1967): informativeness. In Yarbus' complex paintings, the informative parts were the persons depicted (as opposed to furniture), the eyes, mouth and nose of faces, etc., but explicitly not the very darkest or the very brightest regions of the picture, nor regions with the greatest details nor the contours. However, Mackworth and Morandi (1967), using the same term "informativeness" independently of Yarbus, reported contours as regions of a high information content in contrast to regions composed largely of unbounded textures (with a supposedly low information content). Although the term "informativeness" is possibly the lowest common denominator one can find between the widely different stimulus aspects, it is not only a very fuzzy term, but it is also highly circular in the sense that it is just a word rather than an explanation. Even though Mackworth and Morandi assessed ratings of informativeness of different regions of the picture by other subjects, one could argue that the subjects rated as informative just what captured their eyes. This, of course, could be called attention, but in its tautological sense, as criticized by Düker (1956). Thus, in this context the word "attention" had better be avoided and replaced by the notion of "control".

There are two main classes of models. The first one postulates a direct moment-to-moment control. It is assumed that the decision as to how long the eye is to remain at a fixation and where to move it next is controlled by the information extracted from the current fixation (Rayner and McConkie 1976; Rayner 1977; O'Regan 1979; Levy-Schoen and O'Regan 1979; Just and Carpenter 1980; O'Regan 1983; Carpenter and Just (1983). Probably the most radical formulation of a direct moment-to-moment control model has been advanced by Just and Carpenter. Their assumptions are (1) the immediacy assumption, where it is assumed that the reader tries to interpret each word immediately upon encountering it, and (2) the eye-mind assumption, where the reader continues to fixate a word until all cognitive processes initiated by that word have been completed. According to Carpenter and Just (1983; see also Fisher and Shebilske 1985), these assumptions are supported by evidence that the time spent looking at a word (1) is strongly influenced by the characteristics of that word (the word n-effect) and (2) the time spent looking at the word is not influenced by the length or frequency of the preceding word [the word (n-1-null result)]. They suggested that encoding and lexical access "begin on the word that enables them, as immediacy posits, and that they tend to be completed before the next word is fixated, as the eye-mind assumption posits" (Carpenter and Just 1983; p. 280). However, it should also be made clear that Carpenter and Just's assumption does not relate to single fixations and saccades, but to "gazes", i.e. dwelling times within certain areas. The second class of models assumes a more delayed or indirect control of several saccades and fixation times by cognitive processes like a memory buffer (Bouma and de Voogd 1974; Shebilske 1975) or by means of pre-programming of eye movements (Buswell 1935; Vaughan and Graefe 1977; Vaughan 1979; Zingale and Kowler 1987).

The Analysis of Scanpaths and Models of their Regulation

Buswell (1935) and Yarbus (1967) noted that under certain conditions the sequence of successive fixations appeared as a relatively regular pattern. This observation was followed up and formulated as a strong hypothesis by Noton and Stark (1971) as the so-called scanpath hypothesis. They suggested that subjects confronted with a particular stimulus will exhibit a specific sequence of fixations, called scanpath, which will recur with the same stimulus during recognition. Some tendency towards scanpath-like patterns was also found by other authors. [For a review see Stark and Ellis (1981) and a report study by Ellis and Smith (1985)].

In some of our own studies, the fixation data of several subjects in a facial recognition task were analysed with respect to scanpaths (Groner et al. 1984). The within-subject correlation between the learning and recognition of the faces was compared with the between-subject correlations. For four of six subjects, there was a statistically significant correlation between their own scanpaths in learning and recognition and this correlation was in most cases also higher than the corresponding between-subjects correlation. It was concluded that, with these subjects, elements of individual scanpaths could be found. Subsequently these idiosyncratic fixation patterns were called "local scanpaths", local in the sense that the fixations follow each other in immediate local succession. In addition to those, interesting statistical patterns on a larger time scale were found, called "global scanpaths". Global scanpaths can be defined in the following way. First divide the total inspection period into different parts (e.g. start, middle, and end). Next compare the frequency distributions at different inspection periods. Thus, local scanpaths reflect the spatiotemporal organization of eye fixations on a local scale of successive events, while global scanpaths reflect the distribution of eye fixations when taking into account the entire inspection process. It is proposed that local scanpaths are controlled by the momentary fixation in combination with the peripheral information in a moment-to-moment control mode, and that global scanpaths are regulated by some top-down processes like search plans or cognitive strategies. Some evidence in this direction was found in an experiment in which European subjects had to learn a set of Japanese Kanji symbols which were previously completely unknown to them (Koga and Groner 1988). While the initial scanpaths of the subjects were rather irregular and hardly displayed any local scanpaths, the learning process can be described as a large-scale global scanpath.

A more systematic attempt towards the identification of local and global scanpaths was undertaken by Groner and Menz (1985). Using a complete factorial design, the relative contribution of the stimulus, task and subject as well as their mutual interactions were investigated with respect to local and global scanpaths. Since the experiment involved two stimuli, three tasks and 12 subjects, and each of these combinations was to be replicated within the same individual five times, a problem arises with respect to habituation effects. This problem was solved by using random dot patterns in which the gross characteristics could be kept constant but the small details or fine-grain structure changed. The factorial design allowed the test of all possible interactions between the factors, and many of them reached statistical significance. With respect to both local and global scanpaths, it was shown that they are subject specific. It was also demonstrated that different tasks (free inspection, a search and a concept identification task) produce specific global scanpaths patterns. This is in accordance with the hypothesis that global scanpaths reflect a top-down mode of information processing. However, this experiment also demonstrated the limits of experimental control in complex tasks where individual differences come in. This situation apparently allows the subjects to make up for their own strategies. This is in accordance with Putz-Osterloh and Lüer (1979), who demonstrated that different information processing strategies occur in high- and low-ability subjects in spatial ability tests which were measured by means of an eye movement analysis.

Concluding Remarks

While it seems possible to direct visual attention to parts of the visual field without associated eye movements, it has been argued that saccadic eye movements always elicit an attentional response. The attentional and the saccadic system seem to be regulated by different, although closely interrelated, control systems, which serve as some kind of interface and multiplexer between motivational states, memorized events and expectations, interconnected with a system that monitors new incoming stimuli. The way in which such top-down and bottom-up processes interact with each other is still an open question which should be approached experimentally and with explicit information-processing models.

References

Berlyne DE (1958) The influence of complexity and novelty in visual figures on orienting responses. J Exp Psychol 55: 289–296

Bouma H, Voogd AH de (1974) On the control of eye saccades in reading. Vision Res 14:273–284

Breitmeyer BG, Ganz L (1976) Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression and information processing. Psychol Rev 83:1–36

Buswell GT (1935) How people look at pictures. University of Chicago Press, Chicago

Carpenter PA, Just MA (1983) What your eyes do while your mind is reading. In: Rayner K (ed) Eye movements in reading: perceptual and language processes. Academic Press, New York, pp 275–305

Duffy E (1962) Activation and behavior. Wiley, New York

Düker H (1956) Untersuchungen über die sogenannte Aufmerksamkeit. Bericht 20. Kongress der Deutschen Gesellschaft für Psychologie, Berlin 1955. Hogrefe, Göttingen

Egly R, Homa D (1984) Sensitization of the visual field. J Exp Psychol [Hum Percept] 10:778–793

Ellis SR, Smith JD (1985) Patterns of statistical dependency in visual scanning. In: Groner R, McConkie GW, Menz C (eds) Eye movement and human information processing. North Holland, Amsterdam, pp 219–238

Engel RL (1971) Visual conspicuity, directed attention and retinal locus. Vision Res 11:563–576

Eriksen CW, Hoffman J (1973) The extent of processing of noise elements during selective encoding from visual displays. Percept Psychophys 14:155–160

Eriksen WW, Murphy TD (1987) Movements of attentional focus across the visual field: a critical look at the evidence. Percept Psychophys 42:299–305

Fischer B (1987) The preparation of visual guided saccades. Rev Physiol Biochem Pharmacol 106:1–35

Fischer B, Boch R (1983) Saccadic eye movements after extremely short reaction times in the monkey. Brain Res 260: 21–26

Fischer B, Breitmeyer B (1987) Mechanisms of visual attention revealed by saccadic eye movements. Neuropsychologia 25: 73–83

Fischer B, Ramsperger E (1984) Human express-saccades: extremly short reaction times of goal directed eye movements. Exp Brain Res 57:191–195

Fisher DF, Shebilske WL (1985) There is more that meets the eye than the eyemind assumption. In: Groner R, McConkie GW, Menz C (eds) Eye movements and human information processing. North Holland, Amsterdam, pp 149–157

Goldberg MH, Wurtz RH (1972) Activity of superior colliculus in behaving monkey. II. Effect of attention on neuronal responses. J Neurophysiol 35:560–574

Gopher D (1973) Eye movement patterns in selective listening tasks of focussed attention. Percept Psychophys 14:259–264

Grindley DG, Townsend V (1968) Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. Q J Exp Psychol 20:11–19

Groner R (1978) Hypothesen im Denkprozess. Grundlagen einer verallgemeinerten Theorie auf der Basis elementarer Informationsverarbeitung. Huber, Bern

Groner R, Groner M (1982) Towards a hypothetico-deductive theory of cognitive activity. In: Groner R, Fraisse P (eds) Cognition and eye movements. North Holland, Amsterdam, pp 100–122

Groner R, Groner M (1987) Hypothesis theory – a review. In: Meer E van der, Hoffmann J (eds) Knowledge aided information processing in human beings. North Holland, Amsterdam, pp 193–219

Groner R, Menz C (1985) The effects of stimulus characteristics, task requirements and individual differences on scanning patterns. In: Groner R, McConkie GW, Menz C (eds) Eye Movements and human information processing. North Holland, Amsterdam, pp 239–250

Groner R, Walder F, Groner M (1984) Looking at faces: Local and global aspects of scanpaths. In: Gale AG, Johnson F (eds) Theoretical and applied aspects of eye movement research. North Holland, Amsterdam, pp 523–533

Groner R, Groner M, Hofer D (1986) The role of anticipiation in the encoding of motion signals – sensitization or bias. In: Klix F, Hagendorf H (eds) Human memory and cognitive capabilities. Mechanism and performances. North Holland, Amsterdam, pp 275–285

Held R, Ingle D, Schneider GE, Trevarthen CB (1967) Locating and identifying: two modes of visual processing. Psychol Forsch 31:44–62, 299–348

Helmholtz H von (1909) Handbuch der physiologischen Optik, 3rd edn. Voss, Hamburg

Hinton JW (1982) Ocular responses to meaningful visual stimuli and their psychological significance. In: Groner R, Fraisse P (eds) Cognition and eye movements. North Holland, Amsterdam, pp 204–212

Johnston WA, Dark VJ (1986) Selective attention. Annu Rev Psychol 37:43–75

Jonides J (1981) Voluntary versus automatic control over the mind's eye's movement. In: Long J, Baddeley A (eds) Attention and performance IX. Laurence Erlbaum, Hillsdale, pp 187–203

Julesz B (1984) Toward an "axiomatic" theory of preattentive vision. In: Edelmann GM, Gall WE, Cowan WM (eds) Dynamic aspects of neocortical function. Wiley, New York

Just MA, Carpenter PA (1980) A theory of reading: from eye fixation to comprehension. Psychol Rev 87:329–354

Kahnemann F (1973) Attention and effort. Prentice-Hall, Englewood Cliffs

Klein F (1980) Does oculomotor readiness mediate cognitive control of visual attention? In: Nickerson R (ed) Attention and performance. VIII. Lawrence Erlbaum, Hillsdale, pp 259–276

Koga K, Groner R (1988) Intercultural experiments as a research tool in the study of cognitive skill acquisition: Japanese character recognition and eye movements in non-Japanese subjects. In: Mandl H, Levin J (eds) Knowledge acquisition from texts and pictures. North Holland, Amsterdam, pp 279–291

Lambert AJ (1987) Expecting different categories at different location and selective attention. Q J Exp Psychol 39A:61–76

Lévy-Schoen A, O'Regan JK (1979) The control of eye movements in reading. In: Kolers PA, Wrolstad ME, Bouma H (eds) Processing of visible language, vol 1. Plenum Press, New York, pp 7–36

Mackworth NH, Morandi A (1967) The gaze selects informative details within pictures. Percept Psychophys 2:547–552

Magoun HW (1963) The waking brain. Thomas, Springfield

Mayfrank L, Mobashery M, Kimmig H, Fischer B (1986) The role of fixation and visual attention on the occurence of express saccades in man. Eur Psychiatry Neurol Sci 235:269–275

Maylor EA (1985) Facilitatory and inhibitory components of orienting in visual space. In: Posner MI, Marin OSM (eds) Attention and performance. XI. Lawrence Erlbaum, Hillsdale

Mertens JJ (1956) Influence of knowledge of target location upon the probability of observation of peripherally observable test flashes. Opt Soc Am 46:1069–1070

Mowrer OH (1941) Preparatory set (expectancy). Further evidence of its central locus. J Exp Psychol 28:116–133

Müller HJ, Findlay JM (1987) Sensitivity and criterion effects in the spatial cueing of visual attention. Percept Psychophys 42:383–399

Navon D, Gopher D (1979) On the economy of the human processing system. Psychol Rev 86:114–255

Norman DA (1968) Towards a theory of memory and attention. Psychol Rev 75:522–536

Norman DA, Bobrow DG (1975) On data-limited and resource-limited processes. Cognitive Psychol 7:44–64

Noton D, Stark L (1971) Scanpaths in saccadic eye movements while viewing and recognizing patterns. Vis Res 11:929–942

O'Regan JK (1979) Eye guidance in reading: evidance for the linguistic control hypothesis. Percept Psychophys 25:501–509

O'Regan JK (1983) Elementary perceptual and eye movement control processes in reading. In: Rayner K (ed) Eye movements in reading: perceptual and language processes. Academic Press, New York, pp 121–139

Posner MI (1978) Chronometric explorations of mind. Lawrence Erlbaum, Hillsdale

Posner MI, Nissen MJ, Ogden WC (1978) Attended and unattended processing modes: the role of set for spatial location. In: Pick HL, Saltzman EJ (eds) Modes of perceiving and processing information. Lawrence Erlbaum, Hillsdale, pp 137–157

Posner MI, Snyder CRR, Davidson BJ (1980) Attention and the detection of signals. J Exp Psychol 109:160–174

Putz-Osterloh B, Lüer G (1979) Wann produzieren Probanden räumliche Vorstellungen beim Lösen von Raumvorstellungsaufgaben? Z Exp Angew Psychol 26:138–156

Rayner K (1977) Visual attention in reading: eye movements reflect cognitive processes. Memory Cognition 4:443–448

Rayner K, McConkie GW (1976) What guides a reader's eye movements? Vision Res 16:829–837

Remington RW (1980) Attention and saccadic eye movements. J Exp Psychol [Hum Percept] 6:726–744

Remington R, Pierce L (1984) Moving attention: evidence for time-invariant shifts of visual selective attention. Percept Psychophys 35:393–399

Ross E, Ross S (1985) Target information and eye movement latency. In: Groner R, McConkie GW, Menz C (eds) Eye movements and human information processing. North-Holland, Amsterdam New York Oxford, pp 41–57

Rovamo J, Virsu V (1979) An estimation and application of the human cortical magnification factor. Exp Brain Res 37:495–510

Saslow MG (1967) Effects of components of displacement-step stimuli upon latency of saccadic eye movement. J Opt Soc Am 57:1024–1031

Shebilske W (1975) Reading eye movements from an information processing point of view. IN: Massaro D (ed) Understanding language. Academic Press, New York

Shepherd M, Findlay JM, Hockey RJ (1986) The relationship between eye movements and spatial attention. Q J Exp Psychol 38A:475–491

Shiffrin RM, Gardner GT (1972) Visual processing capacity and attentional control. J Exp Psychol 93:72–82

Shiffrin RM, Schneider W (1977) Controlled and automatic human information processing. II. Perceptual learning, automatic attending – a general theory. Psychol Rev 84:127–190

Shulman GL, Remington RW, McLean JP (1979) Moving attention through visual space. J Exp Psychol [Hum Percept] 5: 522–526

Spillmann L (1971) Foveal perceptive fields in the human visual system measured with simultaneous contrast in grids and bars. Pflügers Arch 326:281–299

Stark L, Ellis SR (1981) Scanpaths revisited: cognitive models direct active looking. In: Fisher DF, Monty RA, Senders JW (eds) Eye movements: cognition and visual perception. Lawrence Erlbaum, Hillsdale, pp 193–226

Treisman A, Gelade G (1980) A feature-integration theory of attention. Cognitive Psychol 12:97–136

Trevarthen CB (1968) Two mechanisms of vision in primates. Psychol Forsch 31:299–337

Tsal Y (1983) Movements of attention across the visual field. J Exp Psychol [Hum Percept] 9:523–530

Ungerleider LG, Mishkin M (1982) Two cortical visual systems. In: Ingle DJ, Goodale MA, Mansfield RJW (eds) Two cortical visual systems. MIT Press, Cambridge, Mass.

Vaughan J (1979) Control of visual fixation duration in search. In: Senders JW, Fisher DF, Monty RA (eds) Eye movements and the higher psychological functions. Lawrence Erlbaum, Hillsdale, pp 135–140

Vaughan J, Graefe TM (1977) Delay of stimulus presentation after the saccade in visual search. Percept Psychophys 22:201–205

Wickens CD (1984) Processing resources in attention. In: Parasuraman R, Davis EA (eds) Varieties of attention. Academic Press, Orlando, Florida, pp 63–102

Wurtz RH, Mohler CW (1976) Enhancement of visual responses in monkey striate cortex and frontal eye fields. J Neurophysiol 39:766–772

Yarbus AL (1967) Eye movements and vision. Plenum Press, New York

Zingale CH, Kowler E (1987) Planning sequences of saccades. Vision Res 27:1327–1341

Received October 27, 1988