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Visual Attention and Saccadic Eye Movements in Complex Visual Tasks

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even though the open-loop condition involves no extra randomization (in the sense that the target is locked to the eye). Nor were express saccades seen in an extension of the servo paradigm that randomized the appearance and direction of the target (large low contrast targets, Perron & Hallett 1991). As the consensus has always been that the eye is not under voluntary control in open-loop tracking (at least not initially in man, Hallett 1986), the necessary conclusion is that *automatic* tracking latencies are longer than conventionally measured express latencies (200–270 msec > 105 msec). The discrepancy is the relative advantage due to expectation, practice, and set-up under the conditions of the express saccade paradigm.¹

One direct estimate of the set-up time for express saccades is provided by the optimal value of the gap in the gap task (150–200 msec; F&W's Fig. 2; Kalesnykas & Hallett 1987). A second approximate estimate comes from an experiment with B. D. Adams in which the instructions "normal foveating task" or "anti task" were given as foveal visual cues at variable times in advance of the target displacement (Fig. 10.85 of Hallett 1986). An "advance" of less than 250 msec severely inflates latency; several hundred msec are required if the conventionally measured latency is not to be inflated at all. This approach overestimates set-up time because a control experiment using the same cues but only one instruction also required an appreciable advance (suggesting possible fixational or attentional "engagement" by the cues; F&W, sect. 10.2). However, either estimate supports appreciable set-up time. The effective latency of express saccades is therefore at least comparable to the intersaccadic interval of 200–270 msec in the classical open-loop experiments of Young and Stark (1963) and later workers (e.g., 200 msec set-up + 105 msec measured latency = 305 msec effective latency > 200–270 msec tracking latency).

Modes: The virtues of a finer look at latency. Perhaps the contribution of the Freiburg group that I most appreciate has been their repeatedly demonstrating the existence of distinct latency modes for saccades, for example, premature, anticipatory, express, fast regular, late, and so on, in their monkeys and many of their human subjects (Fischer & Ramsperger 1984; 1986; Weber & Fischer 1992). The corresponding concept of *varieties of saccadic planning* actually emerged from several laboratories prior to Fischer and Boch (1983), but it is considerably strengthened by repeated large samples in the Freiburg studies. Varieties of saccadic planning with cancellation and modification of saccades on a time scale of about 120 msec or even less are indicated by many studies: gap and overlap tasks (Saslow 1967a), two-step tracking (Becker & Jurgens 1979; Findlay & Harris 1984; Taumer et al. 1972), anti saccades (Hallett & Adams 1980), secondary or correction saccades (Becker 1976; Hallett 1978; Prablanc et al. 1978; Shebilke 1976), and predictive tracking (Smit & Van Gisbergen 1989). In a review of this topic I normalized and replotted latencies from 10 two-step tracking studies in the literature and found evidence for varieties of saccadic planning (Fig. 10.97 of Hallett 1986). Also discussed were two essentially visual modes in the latencies of secondary saccades to moderate amplitude target displacements (4–15 deg), with a possible division at about 150 (range 130–170) msec from the end of the primary saccade in about half of 11 subjects in this laboratory. Considerably prior to this, Becker (1972) had identified visual and nonvisual secondary saccadic modes for large target displacements. More recently, Kalesnykas and Hallett (1989) examined instructions, combined with different patterns of fixation point and target lightings, that should a priori lead to systematic increases in mean latency for the different conditions (because of increasing dependence on voluntary actions rather than stimulus initiated ones). Experimentally, the mean latencies progressed in steps of roughly 35–45 msec from one condition to the next. Finally, the Freiburg computational model shows latency modes with separations of 40 or 60 msec (F&W's Fig. 13).

The notion that various latency modes can arise from different

combinations of a set of neural processes or pathways would seem to be well worth pursuing (Fig. 13 of Fischer & Weber; Hallett 1986; Hallett & Adams 1980). Apart from several statistical issues, a potential difficulty for comparisons across different studies is the possible need to make allowances for the effects of expectation and strategy on the measured modes. In addition, one commonly neglected process or subprocess is the waiting time for sufficient photons (Barnes & Hallett 1992; Doma & Hallett 1988; 1989). Because this waiting time has varied between about 1–180 msec in our different conditions, it is important that it be controlled (Boch et al. 1984; Weber et al. 1991) or normalized so that theorists can usefully compare latencies across different lightings, adaptations, pupil sizes, or tasks.

NOTE

1. The discrepancy should be reduced if human or primate subjects are inhibiting and delaying tracking in the open-loop case. However, the only grounds for this speculation (the tendency for latencies to often be somewhat less than 200 msec when practised subjects saccade to targets in single moderately randomized trials) is also a situation where expectation, set-up, and practice must help.

Visual attention and saccadic eye movements in complex visual tasks

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Fischer & Weber (F&W) provide an interesting summary of the evidence concerning the phenomenon of express saccades and propose a model of saccadic eye movement programming in which attentional disengagement is a prerequisite for saccadic programming. The question I want to address here is whether visual attention is normally disengaged from all visual stimuli prior to a saccadic eye movement during complex, real-world visual tasks such as scene viewing and reading. There is in fact a large body of evidence suggesting that prior to a saccadic eye movement in complex tasks, visual attention is disengaged from the foveal stimulus and *reengaged* at the extrafoveal stimulus that is the target for the saccade prior to that saccade (Henderson 1992b).

Most of the evidence concerning the allocation of visual attention during complex visual tasks derives from the "eye-contingent display change technique" (McConkie & Rayner 1975), in which the visual stimulus presented to the viewer is changed as a function of eye position. Initial experiments using this technique involved the use of the moving window paradigm in reading: Subjects read text in which a window or region of normal text was surrounded by regions of uninformative visual information. As the reader moved through the text, the window moved along with the eyes. Results from these studies indicate that visual information is acquired from an asymmetric region around the current point of fixation. This is shown by the finding that reading rates (and comprehension) are identical when the reader is given an asymmetric window with 4 character spaces to the left and 15 character spaces to the right of the current fixation point and when the entire line is visible (McConkie & Rayner 1975, 1976; Rayner et al. 1980; Underwood & McConkie 1985). These findings are not simply due to left-hemisphere (right hemifield) language dominance: Pollatsek et al. (1981) showed that when English-Hebrew bilinguals were reading English, they acquired information asymmetrically to the right, but when these same subjects read Hebrew, which is read from right to left, they acquired more information from the left side of the fixation point. Similarly, Inhoff et al. (1989) showed that when native readers of English were asked to read from right to left text that was presented in several backward formats (e.g.,

words facing forward but ordered right-to-left; letters within words and words ordered right-to-left), their perceptual spans were found to be asymmetric to the left, in the direction that the text was being read.

These results are not specific to reading: Henderson et al. (1989) had viewers engage in an object identification task. The viewers examined displays composed of four line drawings of objects positioned at the corners of an imaginary square. To determine which object or objects were being attended on each fixation, a two-dimensional variation of the moving window paradigm was used. The main finding was that parafoveal information concerning object identity was acquired only from the object currently fixated and the object about to be fixated next. Even though eye movements were changing direction after each object was fixated, the object about to be fixated next was the only one in addition to the object currently fixated that was processed during a given eye fixation. This indicates that attention is allocated dynamically during each fixation to the location to be fixated next. Together, these results strongly suggest that the allocation of visual attention to the location about to be fixated next prior to a saccadic eye movement is a general aspect of complex visual-cognitive functioning.

There is also evidence suggesting that prior to a saccade, attention *must* be allocated to the target location of that saccade. Shepherd et al. (1986) had subjects press a button whenever they detected a simple light flash. At the same time, they were to execute an eye movement to a predetermined target location. In one condition, the light flash was most likely to appear at the same location as the target for the saccade. In another condition, the light flash was most likely to appear at a location that was different from the location toward which they were to execute the eye movement. Shepherd et al. found that subjects could strategically direct attention to the more likely location *unless* the eye movement was imminent. When an eye movement was imminent, however, subjects could only direct attention to the location that was the target of the saccade. Thus, these results indicate that before an eye movement, attention must be allocated to the location about to be fixated.

Finally, there is evidence that prior to a saccade, attention is disengaged from the fovea and reengaged at the specific target location of the impending saccade. Henderson (1992b) had subjects participate in a transsaccadic word identification task. The subject began each trial fixating a central cross presented on a computer monitor. Two preview letter strings were then presented, one just to the right of the subject's point of fixation and the other several degrees to the right. In the *move* condition, the subject was asked to execute an eye movement to the location of the letter string furthest to the right as soon as the letter strings appeared. The eye-contingent display change technique was used so that during the saccade the two letter strings could be replaced by a single target word positioned at the location of the letter string toward which the eyes were moving. Because the change was accomplished during the saccade, the subjects never saw the change itself. The task was to name the target word aloud as quickly as possible once the eyes had landed. Naming latency was taken as a measure of word identification time.

The results indicated that when the subject was maintaining fixation on the central cross (no-move condition), preview of the target word at the far location provided no preview benefit. In contrast, when the subject was about to execute an eye movement (move condition), a preview of the target word at that far location led to significant preview benefit. These data indicate that attention precedes an eye movement to the location toward which the eyes are about to move. In contrast, the amount of preview benefit derived from the near location when the eyes were moving to the far location was *less* than the amount derived when the eyes remained stationary. The finding that the preview benefit at the near location was reduced in the move

compared with the no-move condition suggests that attention moves away from the fixation point prior to the saccade.

Taken together, the above results, along with similar findings (see Henderson 1992b for a review), strongly suggest that during complex visual tasks involving multiple eye fixations, visual attention is disengaged from the foveal stimulus and reengaged on the extrafoveal target of an upcoming saccade prior to that saccade. These results are difficult to reconcile with the view that attention must be in a disengaged state in order to permit (disinhibit) a saccade, as proposed by Fischer & Weber.

Visual attention may not control the occurrence of express saccades

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Is there a distinct population of express saccades, as argued by Fischer & Weber (F&W)? The experimental data are persuasive. Furthermore, express saccades appear to fit into a comprehensive model of saccade control that considers evidence from several sources. These include behavioral data from different species, neuroanatomical findings, data from cognitive-attention studies, and results of mathematical modelling. Although I am intrigued by the scope of this work, I am hesitant to endorse the use of attention as the central explanatory construct.

Several findings suggest that a relatively abstract cognitive process such as attention is implicated in the occurrence/absence of express saccades. For example, express saccades disappear when the subject is *instructed* to "attend" to the periphery, irrespective of whether overlap or gap tasks are used. Auditorily provided information can trigger express saccades to visually presented lateral targets, suggesting the use of abstract-amodal control processes. Furthermore, neuroanatomical as well as behavioral studies (e.g., Klein 1980; Posner 1980) reveal a functional relationship between saccade programming and visuo-spatial attention.

Other aspects of the described data argue against the use of attention, however. First, express saccades do not occur when the eyes are moved across less than 2 degrees of visual angle in the gap and overlap tasks. Disengagement of attention, as it is expected to occur in a standard gap task, should be unaffected by the eccentricity of the *subsequently* presented target.

Second, none of the studies provides an independent measure of attention; and at least one consideration suggests that disengagement of attention *per se* may not account for the gap effect. According to F&W, the disengagement of attention should require approximately 40 to 50 msec, roughly corresponding to the difference between the modal values of express (110 msec) and fast regular (150 msec) saccades. It is unclear, however, whether a short gap duration of approximately 40 msec will yield express saccades. A distinct distribution of express saccades emerges when gaps of 100 msec or more are used. The distinct express mode is also evident at considerably longer gap intervals of up to 500 msec. In these conditions, considerable time elapses between the disengagement of attention and the occurrence of the peripheral target. What occurs in this interval? Does the system enter an attentional void state? Do express saccades occur when the system has entered the attentional void state? Can the system remain for a considerable time within an attentional void state, knowing that a visual target is to be presented?

Since no independent measure of attention is provided, the attention hypothesis could be turned on its head and still