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Visual Attention and Eye Movement Control During Reading and Picture Viewing

JOHN M. HENDERSON

Experimental psychologists have known for some time that it is possible to allocate visual-spatial attention to one region of the visual field even as we maintain eye fixation on another region. As William James stated it, "... we may attend to an object on the periphery of the visual field and yet not accommodate the eye for it" (James, 1890/1950, p. 437). At the same time, experimental psychologists have also known that during the course of a complex visual task such as reading or picture viewing, our eyes move from one location to another at an average rate of 3 to 5 times per second (e.g., Rayner, 1978; Tinker, 1939; Yarbush, 1967). The question therefore arises how these covert and overt changes in processing focus are related. This is the question addressed in the present chapter.

As a rough first pass, there are at least three ways in which covert changes in the locus of visual attention and overt movements of the eyes might be related. First, it could be that when the eyes are free to move, attention is always directed toward the stimulus at the point of fixation. On this view, although it might be the case that attention can be allocated away from the point of fixation under appropriate experimental conditions, this finding would be explained away as of no functional significance in natural visual tasks. At the other extreme, it might be that covert shifts of visual attention and overt shifts of the eyes are completely decoupled in complex visual tasks, so that there is little relationship between the point of fixation and the focus of visual attention. Finally, in contrast to either of these two positions, it could be that during complex visual tasks there is a functional relationship between the allocation of visual attention and overt movements of the eyes. In this chapter, I will present a review of the evidence suggesting that this last position may well be correct.

Before moving on, a definition is in order. Throughout this chapter, I will define *visual attention* as the selective use of information from one region of the visual field at the expense of other regions of the visual field.

Relationship Between Eye Movements and Attention

In this section I will review the evidence supporting the position that covert shifts of attention and overt movements of the eyes are functionally related. This review will not be exhaustive; instead, I will concentrate on studies that have examined attentional processes under conditions where the eyes were free to move and eye movements were monitored. Most of these studies have employed the *contingent display change technique* (McConkie & Rayner, 1975), in which the stimulus is changed as a function of eye position. In the typical experimental setup for this type of study, the subject is seated before a computer monitor on which stimuli are presented. The subject's eye movements are recorded while he or she views the display. Because the display monitor and the eye tracker are both interfaced with the same computer, the display shown to the subject can be changed contingent on characteristics of the subject's eye movements.

Some of the earliest studies using the contingent display change technique involved presenting a reader with a line of text in which a window moved along with the subject's eyes. In this *moving window* paradigm, the text within the moving window is normal, whereas text beyond the window is mutilated in some way. For example, each letter space in the text beyond the window might be replaced by the letter x. The logic of the paradigm is that if text normally used during the course of a fixation is beyond the window region, then the reading process should be disrupted in some way. On the other hand, if some region of text is beyond the window, but reading is not disrupted, then that text is presumably not normally used.

One of the most robust effects to emerge from studies using the moving window paradigm in reading is that the *perceptual span*, or region from which useful information is acquired during an eye fixation, is asymmetric rather than symmetric around the point of fixation. The maximum perceptual span has been found to be about three to four character spaces to the left of the fixated character and up to 15 character spaces to the right of the fixated character (e.g., McConkie & Rayner, 1975, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985). Thus, the perceptual span generally encompasses the entire word under fixation, and one to two words to the right of the fixated word (Rayner & Pollatsek, 1987).

The fact that the perceptual span is asymmetric around the point of fixation strongly indicates that the perceptual span in reading is not determined by acuity factors alone. An obvious explanation for the asymmetry is that attentional factors contribute to the perceptual span, limiting information use from the left side and facilitating information use from the right. However, before accepting this explanation, several other possibilities must be ruled out.

One possible nonattentional explanation for the asymmetry of the perceptual span in reading is that it is due to lateralization of function in the cerebral hemispheres. Because language is left hemisphere dominant in about 80% of the population, and because the left hemisphere is more directly connected to retinal receptor cells receiving input from the right visual field, perhaps there is a cortical processing advantage for text in the right visual field. One study indicating that this explanation is incorrect was conducted by Pollatsek, Bolozky, Well, and Rayner (1981). In this study, bilinguals who could read both English and Hebrew were tested in the moving window paradigm. Hebrew is a language that, in contrast to English, is read from right to left. Pollatsek et al. found that when these bilinguals were reading English, their perceptual spans were asymmetric to the right, as found in the earlier studies. However, when these same subjects read Hebrew, then their perceptual spans reversed so that they were asymmetric to the left. This is exactly the result one would expect if the perceptual span is attentionally constrained. At the same time, this result is inconsistent with the view that the rightward asymmetry normally seen with English readers is due to hemispheric factors.

A second possible explanation for the asymmetry of the perceptual span is that it is intrinsic to the reading process rather than due to a dynamic allocation of visual attention. In other words, it could be that part of learning to become a fluent reader involves developing a perceptual module for reading in which the disposition to use information from a particular region of text is automatized or hard-wired. This explanation would suggest that the bilingual readers in the Pollatsek et al. (1981) study had developed two reading modules and were switching between them when they switched languages.

A recent study by Inhoff, Pollatsek, Posner, and Rayner (1989) argues against the notion that the asymmetry is fixed within the reading system. In this study, native readers of English were asked to read text presented in several backward formats (e.g., words facing forward but ordered right-to-left; letters within words and words ordered right-to-left), so that the subjects were required to read right-to-left. Clearly, these subjects would have had very little, if any, experience reading in this manner, and therefore would not have had a chance to develop any automatized systems devoted to reading right-to-left. Yet, in this study the perceptual span was again found to be asymmetric in the direction that the text was being read.

In sum, the studies that have used the moving window paradigm to explore the acquisition and use of visual information from text during reading show that the perceptual span is asymmetric in the direction the eyes are generally moving. This effect is not due to having learned to read in a particular direction, but instead appears to be dynamically adapted to the reading situation encountered. These findings are consistent with the view that the perceptual span is determined by the allocation of visual

attention during each eye fixation. More particularly, it appears that visual attention is allocated to the region of the visual field toward which the eyes are moving. The finding that the perceptual span is not determined by acuity factors alone suggests that the term *perceptual span* is somewhat of a misnomer. Instead, the term *attentional span* would seem more appropriate.

The Sequential Attention Model

The studies reviewed in the previous section examining the attentional span in reading indicate that visual attention is generally allocated to that region of text toward which the eyes are moving. One interpretation of this finding is that there is a functional relationship between the covert allocation of visual attention and overt movements of the eyes. In this section I want to outline a particular model of this relationship. The model is based on both empirical evidence and on a consideration of recent theorizing in the cognitive control of eye movements during reading. Following presentation of the model, I will review further experimental work that bears on various aspects of the model.

Basic Assumptions

The sequential attention model contains five basic assumptions (Henderson, 1988; Henderson & Ferreira, 1990; Henderson, Pollatsek, & Rayner, 1989). First, at the beginning of each new eye fixation visual attention is allocated to the stimulus at the center of fixation. In reading, the attended stimulus is likely to be the word (McConkie & Zola, 1987), though in the case of longer words it may be just one part of the word. In scene perception, it would presumably be at the level of the object. Second, attention is reallocated to a new stimulus when the foveal stimulus is "understood." The simplest interpretation of "understood" here is that attention is reallocated when the foveal stimulus is identified (Rayner & Balota, 1989; Rayner & Pollatsek, 1987). However, attention could be reallocated when activation from the foveal stimulus reaches a critical threshold prior to recognition, or alternatively could be reallocated when a process following identification such as syntactic parsing (in reading) or semantic interpretation (in reading and scene perception) is imminent or completed. Third, the reallocation of attention is coincident with two aspects of eye movement programming: (a) when attention is reallocated, the system begins to program the motor movements necessary to bring the eyes to a new location, and (b) the new locus of attention is taken to be the location toward which the eyes should be moved. Fourth, the reallocation of attention to a new location gates higher level analysis at

that new location. Finally, the eyes follow the shift of attention to the attended location following the eye movement programming latency.

Secondary Assumptions

Several aspects of the sequential attention model require further elaboration. First, the model suggests a "rubber-band" view of the relationship between attention allocation and eye movement control. At a particular point in time attention is reallocated away from the fovea and to a new location; the eyes then catch up with attention after the eye movement motor commands have been programmed and executed. This aspect of the model would seem to offer a simple account of where the eyes go from one fixation to the next: they go to the location that is currently being attended. However, this begs the question of what region will be attended next. I will assume that the location to which attention is allocated is determined on the basis of relatively low-level stimulus attributes. In particular, I make the following assumptions: First, a preattentive map of likely stimulus locations is made available to the attention allocation system. Second, stimulus locations are weighted so that attention is allocated to the stimulus location with the largest weight. Koch and Ullman (1985) discuss a neurophysiologically plausible model of the allocation of attention based on a location weighting scheme similar to this. In reading, the largest weight can generally be assigned to the stimulus location immediately to the right of the point of fixation (except under conditions when higher level language processes require a regression back to a previously read region of text). In scene perception, the situation is less constrained, but a fairly simple process could assign weights on the basis of a salience measure automatically derived from low-level analysis (Mahoney & Ullman, 1988).

The motor programming aspect of the model derives from Morrison's earlier work on the cognitive control of eye movements in reading (Morrison, 1984; see also McConkie, 1979). In accordance with Morrison, I assume that it is possible to have several eye movement programs simultaneously active. This *parallel programming* occurs when a decision is made to abort a partially programmed movement and instead to make a different movement (Becker & Jurgens, 1979). The eye movement behavior observed following parallel programming of two saccades will depend on when programming of the second movement begins. For example, if the signal to begin a new program arrives when the first program is not too far along then the first program can simply be canceled, with a possible cost in saccade latency (Hogaboam, 1983; Pollatsek, Rayner, & Balota, 1986). In this case, the target of the original saccade would be skipped (but would have been parafoveally processed, Fisher & Shebilske, 1985). If the new signal arrives a bit later, then the two programs may overlap, and the eye movement will be determined by

a combination of the two programs. In this case, the eyes may land between the two target positions. Finally, if computation of the first program is well along when the signal arrives to construct a different program, then the first program may be executed. In this case, the eyes will land at the first target location, but the fixation may be brief because the program to move the eyes to the second location is already partially computed.

When would parallel eye movement programs be active according to the sequential attention model? Recall that programming of an eye movement begins when attention shifts away from the fovea. Suppose that after some amount of time, attention shifts again to a second extrafoveal location prior to an eye movement to the first extrafoveal location. This could happen if, for example, the stimulus at the first extrafoveal location were easily recognized. Because a shift of attention initiates eye movement programming, and because the locus of attention is taken to be the target of the program, the shift of attention to a second extrafoveal location will cause a second program to be readied prior to execution of the first. The type of parallel programming, of the three types outlined above, that then occurred would depend on how soon after the first attentional shift the second shift occurred.

Tests of the Model

In this section I will review research that bears on various aspects of the sequential attention model as it was outlined above.

Generality

The sequential attention model is meant to provide an account of the relationship between the allocation of visual attention and movements of the eyes. This relationship is assumed to be a fundamental aspect of visual cognition. However, the studies reviewed above primarily dealt with eye movements and attention during reading. The first question to be addressed, therefore, is whether the sequential attention model generalizes beyond reading.

To explore how eye movements and the allocation of attention are related in a task other than reading, Henderson et al. (1989) had subjects view displays composed of four line drawings of objects positioned at the corners of an imaginary square surrounding the fixation point. The subject's task was to view each of the four objects in a prescribed sequence in order to prepare for an immediate probe memory test (e.g., "Was there a tree in the display?"). To determine which object or objects were being attended on each fixation, a variation of the moving window paradigm was employed. In the *full-display* condition, all four objects were continuously displayed throughout the trial. At the other extreme, in the

one-object condition, only the object currently being fixated was displayed; all other objects were replaced with a pattern mask. In the *one+next* condition, the object currently at the point of fixation and the object about to be fixated next in the prescribed sequence were displayed, and in the *one+last* condition, the object currently at the point of fixation and the object just fixated were displayed. Finally, in the *zoom* condition all objects were initially displayed, but once the subject moved his or her eyes to the first object, the trial proceeded as in the *one-object* condition.

The logic of this experiment was similar to that of the moving window studies in reading. If information that is normally used during picture viewing is outside of the window, then viewing behavior should be disrupted in comparison to the full-display condition. On the other hand, if information that is not normally used is beyond the window, then no disruption should be observed. The prediction of the sequential attention model is that eye movement behavior in the *one+next* condition should be similar to the full-display condition, because in both cases the information normally attended is available (the object at fixation and the object about to be fixated), and because information normally acquired preattentively (e.g., information about where potential objects are) is still available due to the location of the pattern masks. On the other hand, eye movement behavior should be disrupted in the *one-object*, *one+last*, and *zoom* conditions because the object about to be fixated is not available for processing.

These predictions were supported. The full and *one+next* conditions were statistically equivalent for both the first fixation and gaze duration measures. In addition, the *one*, *one+last*, and *zoom* conditions were disrupted in comparison to the full-display condition, and the former three did not differ among themselves. The finding that information is used primarily from the object currently fixated and the object about to be fixated suggests that the asymmetric attentional span is not unique to reading. The fact that the same result was found for the object at the second location, which was fixated following a vertical eye movement, suggests that the asymmetry of the attentional span is not unique to horizontal eye movements. Finally, even though eye movements were changing direction after each object was fixated, the object about to be fixated next was generally the only extrafoveal object processed during a given fixation. This strongly suggests that attention is allocated dynamically during each fixation to the location to be fixated next. Thus, it appears that the sequential attention model generalizes beyond reading to a situation involving the identification of pictures of objects.

Necessity of Attending to the Target Location

The question arises whether it is *necessary* that attention precede an eye movement to the target location of the movement. As Klein (1980)

pointed out, there are actually two independent sides to this question. First, in order to reorient attention, must an eye movement program to the attended location be initiated? Second, is an attentional shift necessary to initiate eye movement programming? Note that the sequential attention model is neutral about the first question. For the second question, the sequential attention model posits an affirmative answer. According to the model, if the eyes are going to move to a particular location, then attention must be oriented to that location in order to provide target-location parameters. Is there any evidence for this view? Shepard, Findlay, and Hockey (1986) conducted an experiment in which a target stimulus was more likely to appear at a location on one side of the fixation point, whereas the subject was required to make an eye movement to a location on the opposite side. Shepard et al. found that subjects could strategically allocate attention to the more likely location unless they were about to make an eye movement. When an eye movement was imminent, then attention was allocated only to the location that was the target of the saccade. Thus, it appears that prior to an eye movement, attention must be allocated to the location about to be fixated.

Specificity of the Attended Location

The sequential attention model clearly predicts that the focus of attention prior to an eye movement will be the *specific* location toward which the eyes will move. However, although the studies discussed above are consistent with this view, they are also consistent with the hypothesis that attention spreads out from the foveal location in the general direction of the next eye movement rather than to that specific location. For example, in the reading studies, the asymmetric perceptual span could be due to attention spreading from the fixated word to all words in the attended hemifield. This position receives some support from the suggestion that attention can only be allocated to a hemifield or at best a visual quadrant (Hughes & Zimba, 1985, 1987), though this view has recently come under attack (Henderson, 1991; Klein & McCormick, 1989). In the case of the Shepard et al. (1986) study, it could be that although subjects were unable to attend to a location in the hemifield opposite to that into which they were about to saccade, they still might be able to attend to different regions in the same hemifield. Similarly, in the Henderson et al. (1989) object study, there is no way to determine whether attention was directed to the specific location about to be fixated or more generally in the direction of the next eye movement.

I have recently conducted a study to test if attention is allocated to the specific location about to be fixated (Henderson, 1990). In this study, which is depicted in Figure 15.1, the subject began each trial looking at a fixation cross. Two preview letter strings were then presented to the right of the subject's point of fixation. In the *move* condition, the subject was

Experimental paradigm

1. Fixate:

+
.

2. Preview Appears:

near: + brand csboe
.

far: + csboe brand
.

control: + csboe csboe
.

3. Name Target Word:

move: + brand
 -----> .

no move: brand

FIGURE 15.1. An illustration of the experimental paradigm used by Henderson (1990) to examine the allocation of attention prior to a saccadic eye movement. The subject began each trial fixating a central cross. Two letter strings then appeared to the right of fixation, with a preview of the target word appearing close to the fixation point (near), far from the fixation point (far), or not at all (control). The subject then either executed an eye movement to the far letter string (move) and named the word that appeared there, or maintained fixation (no move) and named the word that appeared at that location.

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 contingent display change technique was employed 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. The subject's task was to name the target word as quickly as possible once the eyes had landed. In order to examine the location from which information was acquired prior to the eye movement, three *preview conditions* were employed. In the *near-preview* condition, the letter string closest to the initial point of fixation provided a preview of the target (i.e., was the same as the target word), and the letter string further from the point of fixation but at the location toward which the eyes were about to move did not provide a preview of the target (i.e., was an unpronounceable nonsense string). In the *far-preview* condition, the letter string positions were reversed so that the preview of the target word occupied the location toward which the eyes would be moving and the nonsense string occupied the closer location. In the *control* condition, the same nonsense

Preview Benefit

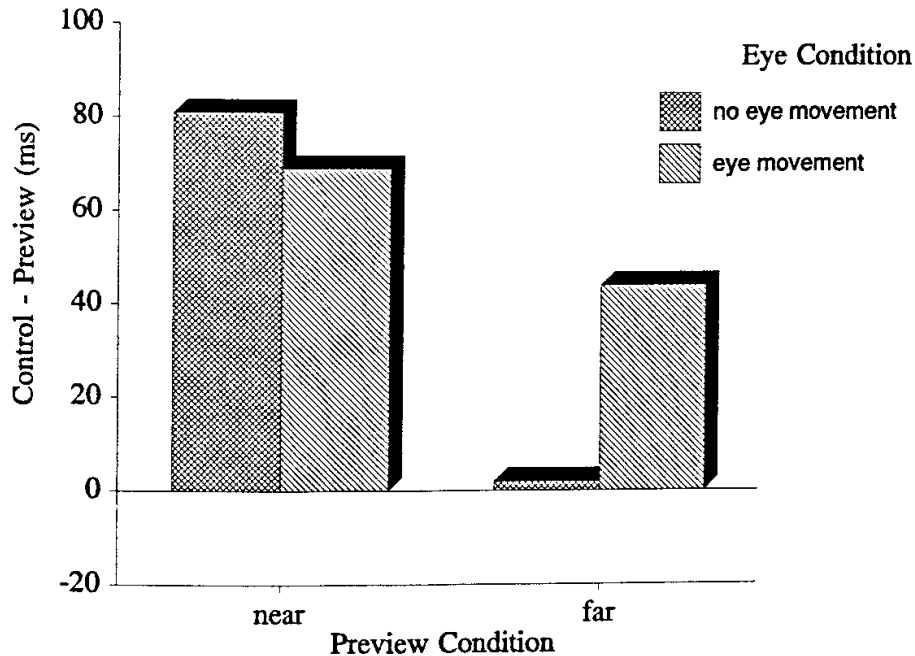


FIGURE 15.2. The results from Henderson (1990). When the preview appeared at the far location, more benefit was derived when the eyes were moving to that location compared with when the eyes remained stationary. In contrast, when the preview appeared at the near location, less preview benefit was derived when the eye moving to the far location compared with when the eyes remained stationary.

letter string occupied both locations. In the second eye behavior condition, termed the *no-move* condition, the subject was to maintain fixation on the central location throughout the trial. The same three preview conditions then occurred extrafoveally, but the target word appeared at the fixation location after a 200-ms presentation of the preview (the average saccade latency in the eye movement condition). Again, the subject was to name the target word as quickly as possible after it appeared foveally.

Two predictions can be made from the sequential attention model. First, in the move condition attention should shift to the location about to be fixated (the far location) and information at that specific location should be used to begin identifying the stimulus located there. Therefore, a greater *preview benefit* (control condition minus preview condition) should be observed for the far location (control minus far preview) in the move condition compared to the no-move condition. This prediction follows because in the no-move condition there is no reason for the subject to attend the far location over the near location. Second, a greater preview benefit should *not* be observed for the near location (control minus near preview) in the move condition compared to the no-

move condition, because attention is allocated specifically to the location toward which the eyes are about to move. If, on the other hand, attention is allocated generally in the direction that the eyes will move, then both the near- and far-preview conditions should show a greater preview benefit in the move condition compared to the no-move condition.

The results of the experiment are shown in Figure 15.2. First, consider the far-preview condition. When the eyes were not moving (no-move condition), no preview benefit was derived from a preview of the target word at the far location in comparison to the control condition. On the other hand, when the eyes were about to move to the far location (move condition), significant preview benefit was derived from a preview of the target at that location. These data are consistent with the view that attention precedes an eye movement to the location toward which the eyes are about to move. Consider now the near-preview condition. The amount of preview benefit derived when the eyes were moving to the far location was statistically *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 to the no-move condition is clearly inconsistent with the view that attention spreads out from the fixation location in the direction that the eyes are about to move. Instead, these data suggest that attention moves away from the fixation point prior to the saccade. Because the near word is closer to the fixation point, when attention is directed away in the move condition, the preview benefit derived from the near location is reduced.

In sum, the results of this experiment strongly suggest that attention is allocated to the specific location toward which the eyes are about to move, and not in the general direction that the eyes are about to move. Thus, these results support the sequential attention model.

Foveal Load and the Perceptual Span

A third prediction of the sequential attention model is that variations in the difficulty of the foveal stimulus should not affect the amount of preview benefit derived from the extrafoveal stimulus about to be fixated next. This prediction follows because attention does not shift away from the foveal stimulus until foveal processing reaches a criterion level of completion. The eyes then follow the reallocation of attention to an extrafoveal location by a constant amount of time. Therefore, if the foveal stimulus is more difficult, attention should remain on that stimulus for a greater amount of time. This predicts longer fixation durations on more difficult stimuli, a ubiquitous finding (see Just & Carpenter, 1987; Rayner & Pollatsek, 1989). However, because the preview benefit derived from an extrafoveal location is a function of the programming latency (the amount of time attention is focused on the extrafoveal stimulus before the eyes get there), and because this latency does not

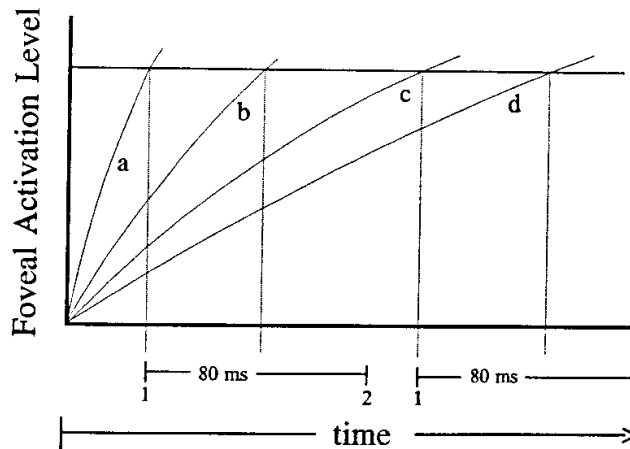


FIGURE 15.3. An illustration of the sequential attention model. The activation of the foveal stimulus is plotted against time since the beginning of the fixation. Curves (a) through (d) illustrate activation functions for progressively more difficult foveal stimuli. The horizontal line indicates the attention-shift criterion; the point in time when an activation crosses this criterion indicates when attention will shift to a new location. Along the time axis, point (1) indicates when attention shifts and point (2) indicates when the eyes begin moving, given the saccadic programming requires 80 ms (an arbitrarily chosen value). Note that for both an easy stimulus (function a) and a more difficult stimulus (function c), the latency between the shift of attention and movement of the eyes is a constant 80 ms.

change as a function of foveal load, there should be no effect of foveal load on the obtained preview benefit. Figure 15.3 illustrates this aspect of the model graphically.

READING

Although the sequential attention model clearly predicts that foveal load should not affect extrafoveal information acquisition, there are several studies that seem to indicate that foveal load may affect the perceptual span in reading. Using the moving window paradigm, Rayner (1986) found that the perceptual span for beginning readers was considerably smaller than for skilled readers. In addition, he also found that the perceptual span was smaller for skilled readers when they were reading more difficult text. One explanation for these results is that in the cases of beginning readers and skilled readers with difficult text, the reader was allocating more attention to the foveal word and therefore had less attention left over to devote to the extrafoveal words. Similarly, in the backward-reading study described above, Inhoff et al. (1989) found that the perceptual span was smaller when readers were forced to read words that were printed right to left. Here again, it could be that because the right-to-left words required more capacity to identify, there was less attention available for acquiring information from extrafoveal words.

Although the above studies are suggestive, they both suffer from a potential confound that makes them difficult to interpret. Specifically, in both studies foveal and extrafoveal difficulty covaried. For example, the relatively undeveloped word decoding skills of the beginning readers in the Rayner (1986) study would make both foveal and extrafoveal word processing more difficult. Similarly, in the Inhoff et al. (1989) study both the foveal and the extrafoveal words were printed right to left and were therefore more difficult. There is evidence that extrafoveal difficulty directly affects the perceptual span during reading (e.g., Balota, Pollatsek, & Rayner, 1985; Inhoff & Rayner, 1986). Therefore, it is difficult to know whether the reduction in the perceptual span found in the Rayner (1986) and Inhoff et al. (1989) studies was due to increased foveal load or instead was caused by increased extrafoveal difficulty.

In order to test more directly the effect of foveal load on the perceptual span in reading, Henderson and Ferreira (1990) conducted a study in which foveal load and extrafoveal preview information were independently manipulated. While their eye movements were recorded, subjects read simple sentences such as

(1a) Mary bought a chest despite the high price.

(1b) Mary bought a trunk despite the high price.

These experiments employed the *boundary technique* (Rayner, 1975), a variant of the contingent display change technique in which only a single letter string changes as a function of eye position. For example, consider the sentence "Mary bought a chest despite the high price." In this example, the boundary was placed between the penultimate and final letters of the word *chest*, designated word n . Either a *same preview* ("despite") or a *different preview* ("zqdloyv") of word $n+1$ ("despite") was displayed as long as the eye position was to the left of the boundary.¹ When the eyes crossed the boundary, the preview was replaced by the target word ("despite"). Because the boundary was generally crossed during a saccade from word n to word $n+1$, vision was suppressed and the subjects were not consciously aware that display changes were taking place. The preview benefit derived from word $n+1$ could be assessed by comparing fixation times once the eyes landed on $n+1$ as a function of preview condition (preview benefit equals fixation time on word $n+1$ following a different preview minus fixation time following a same preview).

¹ One other preview condition was also employed, in which the first three letters of the preview were the same as the target word, but the final letters were different. The results from this condition were virtually identical to those in the same preview condition.

In addition to manipulating the type of preview available for word $n+1$, we also manipulated the difficulty of word n . In the *lexical difficulty* manipulation, word n was either easy or difficult depending on the frequency of the word, as assessed by the Kucera and Francis (1967) norms. The words were matched in length and roughly similar in meaning. For example, in sentences (1a) and (1b) above, "chest" and "trunk" were the high- and low-frequency versions of word n . Previous studies have shown that low-frequency words are more difficult to process (Becker & Killion, 1977; Morton, 1969) and therefore receive longer fixations during reading (Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986). If foveal load affects the amount of information acquired from an extrafoveal word, then the preview benefit observed for word $n+1$ should be reduced when word n is lower in frequency.

If it were found that lexical frequency did affect the preview benefit derived from an extrafoveal word, then we would have some evidence that foveal load affects the perceptual span. However, it could be the case that foveal lexical frequency would affect preview benefit because both lexical frequency and preview benefit are lexical phenomena. We would thus not have evidence that foveal load in general affects the perceptual span, but only that foveal load at the lexical level decreases lexical processing of the extrafoveal word. To determine if foveal load at a non-lexical level would affect preview benefit, we also employed a *syntactic difficulty* manipulation, as shown in the following sentences:

- (2a) She warned that Harry bought small gifts.
- (2b) She warned Harry bought small gifts.

The preview of word $n+1$ ("small" in sentence 2) was again manipulated by showing either a same or different preview, as described above. The difficulty of word n , however, depended on the syntactic structure of the sentence. In both the easy (2a) and difficult (2b) conditions, the sentences contained an embedded sentential complement. In the easy condition, the overt complementizer "that" was included in the sentence. In the difficult condition, the complementizer was absent. It has been shown that in such sentences, there is a bias on the part of the reader to take the first noun of the embedded complement as the direct object of the verb when the complementizer is absent (Ferreira & Henderson, 1990; Frazier & Rayner, 1982; Rayner & Frazier, 1987). When the verb of the embedded complement is then encountered, the sentence must be reanalyzed so that the analysis is consistent with the complement reading. Thus, processing difficulty (and reading times) are increased on the embedded verb when the complementizer is absent. If foveal load induced by syntactic difficulty affects the perceptual span, then the preview benefit observed for word $n+1$ should be reduced when word n is syntactically more difficult. Note that with the syntactic difficulty manipulation word n does not change as a

function of difficulty; in the example in sentence (2), "bought" is word n in both the easy and difficult conditions.

There were two main results of this study. First, there was a clear effect of foveal load on word n for both the lexical and syntactic difficulty manipulations, as expected. Second, when word n was easy, there was a clear preview benefit: fixation times were shorter when the preview of word $n+1$ was the same compared to when it was different from the target word. On the other hand, when word n was difficult, the preview benefit disappeared. This was found even though in the difficult condition, fixation time on word n was longer, thus potentially affording more time for acquiring information from word $n+1$. Thus these data support the hypothesis that foveal load affects the amount of information acquired from an extrafoveal location prior to an eye movement to that location. The finding that foveal load decreased extrafoveal information acquisition in the syntactic case as well as the lexical case suggests that the reduced use of extrafoveal information is not simply due to interference within the lexicon.

PICTURE VIEWING

Similar results to those just described have also been observed in a picture-viewing study (Henderson, 1988). In that study, subjects viewed arrays of pictures of four objects as described above. Foveal difficulty was manipulated via the semantic similarity of the foveal object (object n) to the object viewed at the immediately prior location. We have found in previous experiments that encoding difficulty and therefore fixation time is affected by this manipulation (Henderson, 1992; Henderson, Pollatsek, & Rayner, 1987). In addition, availability of preview information from the next object ($n+1$) was manipulated: either the *same* object or a *blob* control consisting of meaningless line segments were presented as the extrafoveal preview. The difference in fixation times on object $n+1$ as a function of preview condition was again taken as the measure of preview benefit. Gaze durations on object n were 367 ms in the easy (semantically related) condition and 404 ms in the difficult (semantically unrelated) condition. Most important were the data from object $n+1$. Encoding time (as assessed by first fixation durations) for object $n+1$ was less facilitated by a preview of that object when object n was difficult (23 ms) compared with when object n was relatively easy (80 ms). Thus, these data mirror with objects the essential results of the Henderson and Ferreira (1990) study.

The finding that foveal processing difficulty affects the benefit derived from the extrafoveal stimulus about to be fixated clearly presents a problem for the sequential attention model as originally proposed. In the next section, I will explore several ways in which the model might be modified to account for these results.

Revisions to the Sequential Attention Model

The finding that foveal difficulty affects the preview benefit derived from the extrafoveal stimulus about to be fixated is clearly at odds with the sequential attention model. The model specifies that attention does not shift to the extrafoveal stimulus until the criterion level of processing is reached; as was shown in Figure 15.3, delaying when the criterion is reached affects fixation time on the foveal stimulus but should not decrease the time that attention is focused on the extrafoveal stimulus prior to the eye movement.

At this point, one possible solution would be to abandon the sequential attention model. However, given that the model is able to offer a simple account of many aspects of both the cognitive control of eye movements in complex tasks (Morrison, 1984; Rayner & Pollatsek, 1989) and the acquisition of extrafoveal information during eye fixations (Henderson et al., 1989; Henderson & Ferreira, 1990), it would seem reasonable to attempt to revise it in order to accommodate the foveal load effect.

Revision 1: Parallel Allocation of Attention

One intuitively appealing way to account for the effect of foveal load on the acquisition of extrafoveal information would be to hypothesize that attention is allocated in parallel to both the foveal stimulus and the stimulus about to be fixated next. There are several ways that this might work. The simplest version would suggest that attention be thought of as an elongated spotlight asymmetrically stretching from the foveal stimulus to the stimulus about to be fixated. However, this version would predict that a spatially intermediate stimulus between the currently fixated stimulus and the stimulus about to be fixated next should be attended. This did not happen in the Henderson (1990) study described above. A slightly more sophisticated view would suggest that attention is discretely split between the fixated stimulus and the stimulus about to be fixated. This view could account for the finding that spatially intermediate stimuli were not attended. To account for the effect of foveal load, the hypothesis would be that attention is shared between the foveal and extrafoveal stimuli, so that when one stimulus is more difficult, attention must be diverted from the other.

There are at least three potential problems with this parallel attention hypothesis. First, abandoning the sequential assumption loses much of the explanatory power of the model in accounting for eye movement control. In the original Morrison (1984) conception, the decision of when to move the eyes was based on a simple monitoring of processing success at the attended foveal location. The programming decision would be far more difficult if two locations were being attended simultaneously. In

fact, abandoning the sequential assumption undermines the basic reason that the sequential attention model is able to parsimoniously account for eye movement control, because it is the signal to shift attention away from the fovea that initiates eye movement programming. Second, most theorists studying visual attention have concluded that attention cannot easily be split between two spatially noncontiguous locations (e.g., Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980). Therefore, proposing such a split would require the assumption that the visual attention system operates differently when it is linked with the eye movement system.

Finally, and perhaps most problematically, the parallel allocation assumption predicts that an increase in *extrafoveal* difficulty should decrease *foveal* information acquisition. However, an examination of previous experiments provides no support for this prediction. I will present here a few illustrative examples. Consider again the Henderson (1988) study described above, in which four objects were viewed successively in two preview conditions. Subjects began each trial fixated in the center of the array of objects. They then made a saccade to the first object, and subsequently to each object in turn. When the first object was fixated, either that object and an extrafoveal blob, or that object and the next object became visible on the screen. If it were the case that attention is shared between the foveal and extrafoveal objects, then processing time (and therefore fixation durations) on the foveal object should be increased when two objects were displayed. Contrary to this prediction, first fixation durations were 232 and 236 ms in the blob and two-object conditions. The equivalent gaze durations were 579 and 584 ms. Thus, there was no difference in processing time on the foveal object as a function of the availability of the extrafoveal object. Similar examples come from reading studies. For example, consider again the Henderson and Ferreira (1990) foveal load study. In this study, the parafoveal preview was either a word or a nonsense letter string. If more attention were being expended on the preview when it was a word, then foveal processing on word n should have been increased when word $n+1$ was a word. This did not happen. Mean first fixation durations were 230 and 232 ms when the preview was a word and a nonsense letter string; respectively, in the lexical difficulty experiment, and 215 and 214 ms in the syntactic difficulty experiment. The equivalent gaze durations were 257 and 262 ms in the lexical difficulty experiment and 236 and 243 ms in the syntactic difficulty experiment. Finally, Blanchard, Pollatsek, and Rayner (1989) alternated the size of the window from fixation to fixation in a moving window study. Thus, on some fixations the foveal word and the next word were displayed, and on some fixations only the foveal word was displayed. They found that the availability of parafoveal word information had no effect on the duration of the current fixation. Again, if attention were shared between the foveal and parafoveal words in reading, then the

availability of the parafoveal word should have increased processing time for the foveal word.

In sum, it would appear that a model of the relation between visual attention and eye movements based on the parallel allocation of attention is not viable.

Revision 2: Fixation Cutoff Assumption

Henderson (1988; Henderson & Ferreira, 1990) proposed a modification to the sequential attention model that enables it to account for the effects of foveal load on the acquisition of extrafoveal information while expanding the model's ability to account for eye movement behavior observed in reading and picture viewing. The general notion is that the eye movement control system has a predisposition to keeping the eyes moving. Presumably, it is adaptive to continuously sample new areas of the visual field. It would be maladaptive to fixate a stimulus indefinitely, even if processing were still continuing (e.g., in attempting to identify a camouflaged animal). Therefore, although I assume that the eye movement system is usually driven by successful completion (or impending completion) of foveal processing, if success is not achieved in a certain amount of time, fixation of that stimulus will be terminated.

Evidence for the notion of a fixation cutoff derives from studies varying foveal stimulus onset during reading (Morrison, 1984; Rayner & Pollatsek, 1981). In these studies, subjects read a line of text while their eye movements were recorded. At the beginning of a new fixation, the onset of the stimulus was delayed. For example, the stimulus might not be displayed until 50 ms after the eyes had landed at a new position. The main results were that for relatively short onset delays, fixation duration on a stimulus increased by an amount of time roughly equal to the duration of the delay. These results suggest that the duration of a fixation is controlled by visual characteristics of the stimulus during that fixation. More importantly for our purposes here, however, was the finding that as the onset delay increased, the probability that the eyes would move off of a word location prior to the word's appearance increased. For example, in the Morrison (1984) study the eyes left the word prior to its onset 70% of the time when the onset delay was 350 ms. These anticipatory saccades occurred even when the duration of the onset delay was blocked. Presumably, in the blocked conditions the subject knew that the best strategy would be to wait out the delay. Thus, it appears that the eye movement system keeps the eyes moving even when comprehension would be better served by waiting.

An illustration of the sequential attention model including the fixation cutoff assumption is shown in Figure 15.4. The fixation cutoff occurs at some point in time following the beginning of a fixation. In order for the system to generate an eye movement by the fixation cutoff, a *program-*

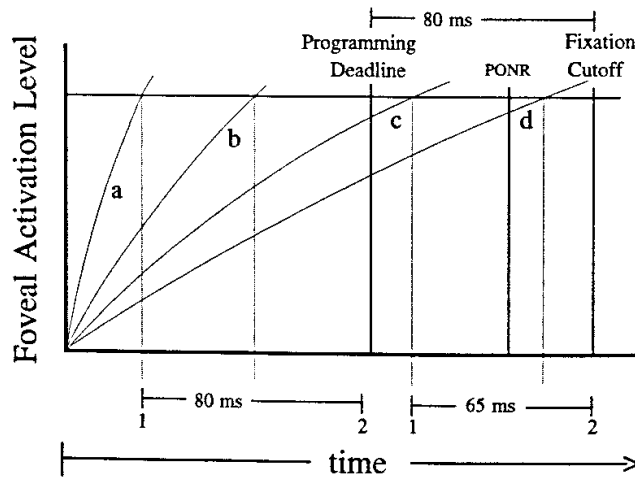


FIGURE 15.4. An illustration of the sequential attention model modified to include a fixation cutoff. This figure is to be interpreted in the same way as Figure 15.3. The fixation cutoff indicates the maximum fixation duration that the system is willing to tolerate. The programming deadline indicates the point in time when saccadic programming must begin in order to meet the fixation cutoff. The point of no return (PONR) indicates the last point in time when a saccadic program can be modified. When the foveal stimulus is easy (functions *a* and *b*), the latency between the shift of attention and initiation of the eye movement is 80 ms. When the foveal stimulus is more difficult, the attention-shift criterion is not reached prior to the programming deadline (function *c* and *d*). If the attention-shift criterion is reached soon afterward, attention will shift and the program will be modified, but the time between the attentional shift and the eye movement will be reduced (function *c*). Finally, if the shift criterion is not reached by the PONR, then the foveal stimulus will be refixated.

ming deadline must be set up that occurs x ms prior to the deadline, where x is equal to the average programming latency. In the illustration, I arbitrarily assume that the programming latency has a mean of 80 ms (with some unspecified variance), so that the programming deadline occurs 80 ms prior to the cutoff. When the foveal stimulus is relatively easy to process, the attention shift criterion will be reached prior to the programming deadline (as shown in curves *a* and *b*). In this case, the model will perform as originally outlined (see Figure 15.3).

When the foveal stimulus is more difficult, then the attention shift criterion will not be reached prior to the programming deadline (curves *c* and *d*). In this case, programming will begin at the programming deadline, even though attention has not yet shifted to the next stimulus. If the criterion is then reached soon after the programming deadline has passed, attention will shift to the new location prior to the eye movement. Attention will then be allocated to the extrafoveal stimulus for less than the full programming latency, so the preview benefit will be reduced.

The above account weakens a basic assumption of the sequential attention model in that it allows a decoupling between initiation of eye move-

ment programming and the shift of attention. Recall that in the original formulation, initiation of programming and reorienting of attention were simultaneous events. The modified model accounts for the reduced preview benefit found with a difficult foveal stimulus by proposing that eye movement programming can sometimes begin prior to the attentional shift. This raises the question, however, of how an eye movement can be programmed to a new location when attention has not yet shifted; recall that according to the model, the attended location is to be taken as the target of the saccade. One answer falls straightforwardly out of the model: when the programming deadline is reached and programming begins, the current focus of attention is still taken to be the target location. Because attention is focused on the foveal stimulus, the programming system will take the current fixation location as the target for the programmed movement. If foveal processing then reaches the criterion level soon after the programming deadline (curve *c*), then the program may be modified so that the new location is taken as the target. This is essentially the same parallel programming mechanism that was used to explain word-skipping behavior in reading (Morrison, 1984; Rayner & Pollatsek, 1989). This view leads to several interesting predictions concerning eye movement behavior in reading and scene perception. In particular, the parallel activation of several programs (one to the foveal stimulus and one to the next stimulus) that might occur when the programming deadline is reached prior to the attention shift criterion could lead to a brief refixation on the foveal stimulus followed by a saccade to the next stimulus, or a saccade to a location between the foveal and extrafoveal stimuli (see Becker & Jurgens, 1979). Both of these types of behavior are often observed (e.g., McConkie, Kerr, Reddix, & Zola, 1988). Finally, if the attention shift criterion is not reached prior to some point of no return for the programming system (curve *d*), then it will not be possible to modify the program to the foveal stimulus. In this case, the foveal stimulus would be immediately refixated and the cycle would begin again. Consecutive fixations on a stimulus are quite common in eye movement records. Often these refixations occur on slightly different parts of the foveal stimulus, for example on a different character in a word (Just & Carpenter, 1987; Rayner & Pollatsek, 1989) or a different part of an object (Henderson, 1992). This could be explained by noise in the programming system or by slight shifts in the center of the focus of attention within the stimulus.

Summary of the Modified Sequential Attention Model

According to the modified sequential attention model, at the beginning of each eye fixation visual attention is allocated to the stimulus at the center of fixation. When foveal processing reaches a preset criterion level of completion, attention shifts to a new location and eye movement pro-

programming is initiated that will bring the eyes to that location. The eyes then move to the new location following the eye movement programming latency. Because attention precedes the eyes to the new location by an amount of time equal to the programming latency, some attentive extrafoveal processing will take place. The amount of preview benefit derived from an extrafoveal stimulus will be a function of the programming latency (the amount of time that attention is focused on the extrafoveal stimulus before the eyes fixate that stimulus). If foveal processing is easy, then attention will precede the eyes by the full programming latency, and the preview benefit will be maximal. If foveal processing is difficult, eye movement programming may begin prior to a shift of attention. If attention then shifts before the program is complete, the amount of attentive extrafoveal processing prior to the eye movement will be reduced, and so will the preview benefit.

Conclusion

In this chapter I have reviewed the evidence concerning the relationship between covert allocation of visual attention and overt orienting of the eyes. I have argued that the evidence favors the view that there is a functional link between the allocation of visual attention and the direction of gaze of the eyes. Finally, I have presented a particular model of how and why visual attention and eye movements might be related. This model draws on and integrates work concerning both the acquisition of visual information and the cognitive control of eye movements during complex visual tasks.

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