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Eye Movements, Cognitive Processes, and Reading

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Abstract In this article, I briefly review research on the size of the perceptual span in reading and on lexical effects on fixation times in reading. For readers of English, the perceptual span extends from the beginning of the currently fixated word (but no more than 3~4 letters to the left of fixation) to about 14~15 letters to the right of fixation. For readers of Chinese, the span extends about 1 character to the left of fixation to about 3 characters to the right. For readers of English, variables like frequency and predictability have strong influences on how long the eyes remain fixated on a word. We know far less about which variables most influence fixation times for Chinese. Finally, the E-Z Reader model can account for lots of eye movement data for readers of English. The issue of whether E-Z Reader could account for the eye movement data of readers of Chinese is discussed.

Key words eye movements, perceptual span, integration across saccades, eye movement control.

It is very clear that eye movement data have been extremely influential in shaping what a model of skilled reading should be like [1,2] . Eye movement data have also yielded valuable insights concerning the most appropriate ways to teach reading [3,4] . Given that my own research has involved the use of eye movement data for many years, I am often asked what the most significant findings that have emerged from our lab. In this article, I will focus on what I view to be the most important findings and developments from the research that we have done over this extended 30 year period. Because our research has obviously dealt with the reading of English, most of my comments will be related to English. However, I will also strive to make relevant points about Chinese wherever appropriate.

I will focus on four findings/developments that I believe to be the most important that we have obtained/produced. First, I will discuss our findings concerning the perceptual span or effective visual field in reading. Here, the main question has been: how much information do readers process in a single eye fixation? In this section, I will discuss the development of the gaze contingent display change paradigm since it has provided the most definitive information with respect to the question about the size of the perceptual span. Second, I will discuss our findings concerning the fact that lexical processing seems to drive the eyes through the text as people read. In this section, I will also discuss the development of a new type of gaze contingent manipulation that enables us to examine lexical effects when the fixated word has been masked or disappears [5] . Third, I will discuss our findings demonstrating that language processing can be effectively studied by the use of eye movement data. Fourth, I will discuss the development of the E-Z Reader model which effectively simulates a wide range of eye movement behavior in reading.

The Perceptual Span in Reading

Before addressing the issue of the perceptual span, let me first briefly discuss two illusions with

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respect to eye movements and reading. First, it generally feels to us like our eyes glide across a line of text as we read. In reality, of course, we alternate between fixations (when the eyes are relatively still) and saccades (very rapid movements of the eyes to a new location) . During the saccade, vision is suppressed and no new information is acquired. Yet, we are not aware of this short period during the saccade when no new information comes into the processing system. It all seems so continual, yet that impression and the feeling that the eyes are gliding across the page is an illusion. Second, we feel that we can see the entire line of text on each fixation. This too is an illusion since our visual acuity drops off dramatically from the center of vision (the fovea) outward. The information that is needed for reading is typically obtained from the fovea (the 6~8 letters in the center of vision) and the parafovea (the region beyond the fovea where acuity is not as good as in the fovea) . In peripheral vision (more than 5 degrees of visual angle from the fixation point, or more than 15 letters away) , acuity is simply not good enough to get useful information to read. The fact that vision is severely degraded from the fovea out is very important for English. Presumably, it is important for Chinese as well, but as we´ll see below, parafoveal vision isn´t used as much in reading Chinese as English and other alphabetical languages. Finally, it is important to note that for reading of alphabetic languages, the appropriate metric to use when considering how far the eyes move is letter spaces and not visual angle [1] .

Let´s turn now to the main question regarding the perceptual span: How much useful information does a reader process in a single eye fixation? This question has been around for a long time. Indeed, in his classic book, Huey [6] had an entire chapter devoted to the question and a number of different techniques were developed to try to answer it. As I have argued elsewhere [7,8] , all of these techniques are inadequate in one way or another; either they make highly questionable assumptions or they involve the use of strategies that are quite different from reading. Given this, George McConkie and I[9] developed the gaze-contingent moving window paradigm to further examine the issue of the size of the perceptual span in reading. In this paradigm, readers are able to see normal text wherever they fixate within an experimenter-defined window region; outside of the window, the text is altered or masked in some way (see Figure 1) . The window can be as small as a single letter (so only the letter that the reader fixates on is available) or it can be quite large (so a 35 letter window would allow 17 letter spaces to the left and to the right of fixation) .

Moving Window Paradigm

We thought that the young student was very surprised

Xxxxxxxxxxxxxxxxhe young studxxxxxxxxxxxxxxxxxxxxxx

+

Xxxxxxxxxxxxxxxxxxxxxung student wxxxxxxxxxxxxxxxxx

+

Xxxxxxxxxxxxxxxxxxxxxxxxxxxxdent was veryxxxxxxxxxx

+

Moving Mask Paradigm

We thought that the young student was very surprised

We thought that the xxxxxxxtudent was very surprised

+

We thought that the young sxxxxxxxwas very surprised

+

Boundary Paradigm

We thought that the young rfnbcuf was very surprised

+

We thought that the young student was very surprised

+

Disappearing Text Paradigm

We thought that the young student was very surprised

+

We thought that the   student was very surprised

+

We thought that the young student was very surprised

+

We thought that the young   was very surprised

+

Figure 1 Examples of the moving window paradigm, the moving mas paradigm, the boundary paradigm, and the disappearing text paradigm. In the moving win-dow paradigm, three consecutive fixations are shown with a window size of 13 letter spaces; in the moving mask paradigm, two consecutive fixations are shown with a mask size of 7 letter spaces; in the boundary paradigm, a random string of letters initially occupies the target location, and when the reader´s eyes cross an invisible boundary (the last letter of the word young) the random letters are replaced with the target word (in this case, student) ; in the disappearing text paradigm, the fixated word (young) disappears after 60ms and only reappears when the reader fixates another word (student) which then also disappears after 60ms. In all cases, the +below an example sentence represents fixation location.

The rationale for the moving window is quite simple: when the window is large enough for readers to acquire all of the useful information that can be obtained, reading performance will not differ from a control condition in which no window is present (i.e., the text is presented normally) . Conversely, when the window is smaller than the effective field, reading will be disrupted in some way. The results of a large number of studies in our lab and other labs [1] have demonstrated that the perceptual span when reading English (and other alphabetic orthographies) extends from the beginning of the currently fixated word (or 3~4 letters to the left of fixation) to about 14~15 letters to the right of fixation. Thus, the perceptual span is asymmetric in the direction of reading. This latter conclusion is bolstered by the fact that for readers of Hebrew (which is printed from right-to-left) , the perceptual span extends 3~4 letters to the right of fixation to about 11 letters to the left of fixation [10] . The span is generally smaller for Hebrew than English because the orthography is more densely packed in the former case [1] . Furthermore, the span does not extend below the currently fixated line during reading, though it does if the task is visual search [1] .

Other variations of the gaze-contingent paradigm (see Figure 1) , the boundary paradigm[7] and the moving mask paradigm [11] , have been used to further characterize the nature of the perceptual span and the type of information acquired different distances from fixation. The most important conclusions from these other paradigms is that (1) information used for word identification on the current fixation is variable but extends no more than about 7~8 letters to the right of fixation when reading English and (2) the type of information that is integrated across fixations (and is thus the source of the fact that readers do get preview information from words not yet fixated) is primarily based on abstract letter codes and phonological codes.

The research results thus basically demonstrate that the perceptual span is not hard wired (since it differs for English and Hebrew, and difficulty of the text can alter the size of the span) [12] , but is due to attention factors and processing limitations. Further evidence for this comes from recent research on the size of the perceptual span when reading Chinese. Obviously, there are many differences between English and Chinese, but critically informational density is much greater in the latter than the former. Thus, it is not surprising that recent moving window experiments with Chinese readers have demonstrated that the perceptual span is considerably smaller for Chinese than English. Inhoff and Liu found that for Chinese, the span extends 1 character to the left of fixation to 3 characters to the right when reading from left-to-right [13,14] .

To summarize this section, the development of the gaze contingent paradigm and the results of the studies using it have provided very important information about reading. Indeed, the results of such studies place a number of constraints on the form that a model of reading should take. Finally, the cross-cultural results using the gaze contingent paradigm reveal important differences in reading behavior due to the characteristics of the writing system.

Lexical Processing and Eye Movements in Reading

There has been a long and sometimes contentious debate in the area of eye movements and reading as to whether lexical processing activities or low-level oculomotor factors are primarily responsible for driving the eyes through text. It now seems quite clear that low level factors have important influences on where the eyes move in reading. Thus, in reading English and other alphabetic scripts, it is clear that the spaces between words provide important information about where to fixate next [1]. On the other hand, it is now also very clear that the decision about when to move the eyes is very much influenced by properties of the fixated word. While a number of variables, such as the predictability of the word [15] and the age-of-acquisition of a word [16], influence fixation time on a word, the most robust finding is that the frequency of the fixated word influences how long readers stay on that word.

Just and Carpenter and Rayner [17,18] first noted the word frequency effect (i.e., longer fixations on low frequency words than high frequency words), but in those demonstrations frequency and word length were confounded (since this occurs naturally in language: shorter words tend to be more frequent, while longer words tend to be more infrequent). However, Rayner, Duffy and Inhoff [19,20] subsequently demonstrated that with word length controlled, readers fixated longer on low frequency words than high frequency words. Rayner subsequently demonstrated that it wasn't the case that the effect was due to a few low frequency words receiving long fixations [21]; indeed, it was demonstrated that there was a shift of the distribution with the low frequency distribution shifted relative to the high frequency distribution. Furthermore, Rayner and Sereno demonstrated that the frequency effect was evident in single fixations, the first of two fixations, and the second of two fixations, and was independent of where the reader fixated in the word [22,23].

One would think that the robust frequency effects that have been observed should be convincing of the position that lexical processing is responsible for the decision of when to move the eyes. Yet, somewhat strangely from my point of view, the position that low level factors are more influential in determining when the eyes move, and that lexical/cognitive processing only occasionally intervenes to inhibit a saccade [24,25] has been vigorously defended.

In this context then, it is very interesting that we [26,27] have recently demonstrated that word frequency still exerts a very strong influence on fixation time, even when the fixated word disappears or is masked after 60ms (see Figure 1). So, even though the low frequency word had disappeared (or was masked) 60ms after the onset of a fixation (and was therefore not present for over 200ms given that single fixations averaged about 267ms), readers' eye remained longer on the low frequency words than the high frequency words. We find this very convincing evidence against the position that low level visual information influences fixation times and very strong evidence that lexical processing does.

To summarize this section, the finding that lexical variables (most notably word frequency) strongly influence fixation time on a word is a second highly notable finding. Although the uptake of visual information is important and necessary for reading to occur, the visual information necessary for reading is input to the language processing system in the first 50~60ms of a fixation and it is therefore the mental operations on that information that drive the eyes through the text. Finally, with respect to Chinese, it will be important to determine what the most important variables are for deciding when to move the eyes. Is it character frequency or word frequency? Chen has reported some evidence suggesting that character frequency is the more important factor, but more research is clearly needed [28].

Language Processing and Eye Movements

It is now very clear that eye movement data can be used very effectively to study various moment-to-moment language processing activities. Research by Frazier and Rayner [29,30] demonstrated that eye movement data could be used to infer how readers parse syntactically ambiguous sentences. Since those first demonstrations, there have been a large number of studies using eye movement data to investigate various issues with respect to language processing.

At times, various claims have been made to the effect that certain types of self-paced reading techniques (in which readers are able to see successive segments of text by pushing a button) can provide as much information as eye movement data can. However, this is an illusion as self-paced reading does not provide the full temporal record that eye movements do. In self-paced reading, either readers can not look back to correct miscomprehension or if they do look back that time is confounded with the time on the current word or segment of text. The reality of the situation is that eye movements have become the gold-standard with respect to studying moment-to-moment language processing activities.

Development of the E-Z Reader Model

Given that we have been working on eye movements and reading in my lab for over 30 years and we have learned a great deal, it occurred to me a few years ago that we ought to be able to develop a model or computer program that would effectively mimic the eye movements of skilled readers. Thus, my colleagues and I [31-34] have spent considerable effort developing a model called the E-Z Reader model. I will not go into the details of the model here; the interested reader is invited to consult any of the primary sources describing the model. Rather, I would like to point out that the development of our model has stimulated a number of others to develop competitor models [34]. The virtue of E-Z Reader is that it has given a good quantitative account of effects produced by variables like frequency and predictability on various eye movement measures, such as gaze duration and the probability of skipping a word. We think we have made some highly plausible assumptions in the model that have good psychological reality, and the time factors fit well with what is known about eye movements. Furthermore, the model is very transparent. Thus, it is easy to assess failures of prediction of the model and why they occur [35]. Finally, the model has clearly generated a considerable amount of research.

As I just noted, while E-Z Reader does a good job of accounting for lots of data with respect to eye movements when reading English and other alphabetic writing systems [34], an interesting question is the extent to which E-Z Reader might be able to account for eye movements in reading Chinese. My best guess at this point is that we need more information and hard data regarding (1) exactly which variables most influence fixation times in Chinese and (2) what determines where the eyes move next when reading Chinese.

Summary

In this article, I have argued that two of the most significant, if not the most significant, findings in the area of eye movements in reading are related to results (1) concerning the size of the perceptual span and (2) demonstrating that lexical processes have important influences on fixation times in reading. Furthermore, I have suggested that eye movement data represent the best way to study various moment-to-moment language processing activities. Finally, I have argued that the development of the E-Z Reader has been an important stimulus for the development of other models of eye movement control in reading and has also stimulated a good amount of research.

With respect to the perceptual span when reading English, we know that the size of the span extends to about 15 letters to the right of fixation. For Chinese, the span is much smaller extending only about 3 letters to the right of fixation. With respect to lexical processing, we know that a number of variables influence fixation time on a word in English; we know far less about which variables might have an influence in Chinese.

While eye movement data have proven to be veryinformative with respect to moment-to-moment language processing with English readers, it will be interesting to see if the same holds true with Chinese readers. Finally, the E-Z Reader model (and other competitor models) is able to effectively simulate the eye movements of readers of English. It is the case that more data are needed from Chinese before we will know if a model like E-Z Reader could likewise simulate the eye movements of readers of Chinese.

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