DOCUMENT RESUME

ED 221 832 CS 006 824


| | |
|---|---|
| AUTHOR | Carpenter, Patricia A. |
| TITLE | Cognitive Processes in Reading Comprehension. Final Report. |
| INSTITUTION | Carnegie-Mellon Univ., Pittsburgh, Pa. Dept. of Psychology. |
| SPONS AGENCY | National Inst. of Education (ED), Washington, DC. |
| PUB DATE | Sep 82 |
| GRANT | NIE-G-79-0119 |
| NOTE | 42p. |
| EDRS PRICE | MF01/PC02 Plus Postage. |
| DESCRIPTORS | *Cognitive Processes; *Context Clues; *Eye Fixations; *Language Processing; *Learning Theories; Models; Prior Learning; *Reading Comprehension; Reading Instruction; Reading Research; Schemata (Cognition); Simulation; Teaching Methods |
| IDENTIFIERS | Prose Learning; *Reader Text Relationship |



ABSTRACT

Part of a research project designed to develop a theory of the cognitive processes involved in skilled reading by the analysis of the location and duration of eye fixations, this paper concentrates on how eye fixations can be used to determine when encoding, lexical access, parsing, and integration processes are executed and how they are affected by various features of text. The paper first discusses the immediacy assumption, which holds that a reader tries to interpret each word of a text immediately upon encountering it, and the eye-mind assumption, which posits that the reader continues to fixate a word until all the cognitive processes initiated by that word have been completed to some criterion. It then reviews several global features of eye fixations in reading that provide support for these assumptions, noting that several run counter to common conceptions of reading. The paper next describes a general model of language comprehension based on a computer simulation that was developed both to formalize models of specific processes and to make the processes function collaboratively in an interactive system. This discussion is followed by a review of research on specific comprehension processes and an evaluation of the model. (FL)

# FINAL REPORT

Project No. 9-0982

Grant No. NIE-G-79-0119

## Cognitive Processes in Reading Comprehension

Patricia A. Carpenter

Department of Psychology

Carnegie-Mellon University

Pittsburgh, PA 15213

September, 1982

The research reported herein was performed persuant to a grant with the National Institute of Education, U. S. Department of Health, Education, and Welfare. Contractors undertaking such projects under Government sponsorship are encouraged to express freely their professional judgment in the conduct of the project. Points of view or opinions stated do not, therefore, necessarily represent official National Institute of Education position or policy.

U. S. Department of Health, Education and Welfare
National Institue of Education

This final report has three parts: a two page summary of the major research findings, a bibliography of research completed under the grant, and a more extended discussion of the research results.

## Research Summary

It has been known since the turn of the century that during reading, a reader's eyes make a series of jumps, called saccades, separated by pauses. The fixations allow the reader to register the print on the fovea of the eye -- the place of maximal visual acuity. The pauses constitute between 90-95% of the reading time and the saccades only 5-10%. Very little visual information is perceived during a saccade, although thinking processes presumably continue. It is during the pauses that most of the visual and cognitive processes occur. Where readers look and how long they spend on a word or phrase can often indicate whether that part of the text was easy or difficult to understand. By manipulating the text, for example, by using easier or more difficult words, familiar or unfamiliar topics, it is possible to examine the effects on the eye fixations and make inferences about the underlying perceptual and conceptual processes.

The major goal of this research was to develop a theory of the cognitive processes in skilled reading, based primarily on an analysis of the location and duration of eye fixations. As part of the project, we analyzed the effects of various text structures on syntactic and semantic processes, the effect of rapid reading training, sources of individual differences among adult readers, reading by young children, and most recently, dyslexic readers. The most complete statement of the theory is presented in the paper entitled "A theory of reading: From eye fixations to comprehension" in Psychological Reivew. The theory proposes a general architecture for comprehension and describes specific subprocesses. The general argument is that processes such as encoding, lexical access, and integration, are primarily reflected in the duration and location of eye fixations on the word that initiates the processes. This suggests that certain aspects of reading are a word-by-word affair, and that the reader does not buffer large amounts of text before encoding, accessing and integrating the information.

In a number of studies, we examined what occurred when readers were given "garden path" sentences, sentences that are initially interpreted one way, but only make sense when interpreted in some alternative way. One such passage discussed a modern-day Cinderella who was crying that she couldn't go to a dance because of her tattered clothes: "There were big tears in her brown dress." Most readers initially intepreted "tears" as referring to crying, but when they encoutered the word "dress", it didn't make sense. They immediately detected the inconsistency and attempted to resolve it, most often by refixating the word "tears". The fact that readers detected and repaired the inconsistency very soon after encountering it is evidence for the theory that readers do not buffer information.

Even basic processes, such as encoding, can be detected in the eye fixations. We have repeatedly found that readers spend more time, on average, on longer words. The time increases linearly with the length of the word, even for short words that are below the usual perceptual span (of 5 letters). This suggests that encoding time may increase with word length. In addition, we have also found that readers pause longer on less frequent words. In particular, the duration increases linearly with the logarithm of the word's frequency. Frequency is commonly thought to affect the accessibility of a word's meaning. Less frequent words take longer to retrieve from the mental lexicon than do more frequent words. Interestingly, if a word is long and generally infrequent, but it is the topic of the passage, reader's will not spent longer on its over repeated presentations.

Recently, we have explored how individual differences in reading skill interact with specific reading processes, such as the reader's ability to recover from misinterpretations or to retrieve facts from earlier portions of the text. Our proposal is that the functional capacity of working memoru plays an important role in reading comprehension performance. Traditional tests of short-term memory, such as digit span and word span tests, do not correlate with reading comprehension performance. The reason for the low correlation may be that such tests are primarily tests of passive storage capacity. We developed a test that included both processing and storage components. In the test, the subject reads a set of sentences and, at the end of the set, recalls the final word of each sentence. The subject's reading span is the number of sentences for which he/she can successfully recall the final words. We have found among college students, the range of reading spans is usually 2 - 5.5 sentences. This measure correlates between .7 and .9 with specific components of reading comprehension, such as the ability to infer the referent of a pronoun or retrieve an earlier mentioned fact. It correlates between .45 - .6 with more general verbal ability, as reflected in verbal SAT scores.

Most recently, we have begun an analysis of dyslexic readers. We have studied five college students who have good grades, but have extreme difficulty reading. They have attained their college grades through hard work and by having help from parents and friends with texts. The study of their reading processes is not yet been entirely analyzed. Nevertheless, there is a striking similarity among the five students in the nature of their reading difficulty. The words that they have difficulty with and the nature of their difficulties (reflected in their eye fixations and oral reading) are quite similar. Moreover, the do not appear to simply be at an earlier developmental stage than are mature, skilled readers. Comparisons between the dyslexics and third-grader readers shows quantitative differences in the nature of their difficulties.

# Bibliography of Research Papers Completed Under Grant


Carpenter, P. A., & Daneman, M. Lexical retrieval and error recovery in reading: A model based on eye fixations. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 137-160.

Carpenter, P. A., & Just, M. A. Cognitive processes in reading: Models based on readers' eye fixations. In A. M. Lesgold and C. A. Perfetti (Eds.), Interactive processes in reading. Hillsdale:N.J.: Lawrence Erlbaum Associates, 1981.

Carpenter, P. A., & Just, M. A. What your eyes do while your mind is reading. In K. Rayner (Ed.), Eye movements in reading: Perceptual and language processes. New York: Academic Press, 1982.

Daneman, M., Carpenter, P. A., & Just, M. A. Cognitive processes and reading skills. In B. Hutson (Ed.), Advances in reading/language research. Greenwich, Conn.: JAI press, 1982.

Dee-Lucas, D., Just, M. A., Carpenter, P. A., & Daneman, M. What eye fixations tell us about the time course of text integration. In R. Groner and P. Fraisse (Eds.), Cognitive processes and eye movements, North Holland, 1981.

Just, M. A., & Carpenter, P. A. A theory of reading: From eye fixations to comprehension. Psychological Review, 1980, 87, 329-354.

Just, M. A., Carpenter, P. A., & Woolley, J. D. Paradigms and processe in reading comprehension. Journal of Experimental Psychology: General, 1982.

McDonald, J., & Carpenter, P. A. Simultaneous translation: Idiom interpretation and parsing heuristics. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 231-247.

Thibadeau, R., Just, M. A., & Carpenter, P. A. A model of the time course and content of reading. Cognitive Science, 1982.

Just, M. A., & Carpenter, P. A. Reading skills and skilled reading in the comprehension of text. In H. Mandl, T. Trabasso, & N. Stein (Eds.), Learning and the comprehension of texts. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1982.

Carpenter, P. A. Methods, molds, and models in language research. To appear in D. Kieras & M. A. Just (Eds.), New Methods in the Study of Comprehension. Hillsdale, N. J.: Lawrence Erlbaum Associates, 1983.

## Unpublished Manuscripts

Just, M. A., Carpenter, P. A., & Masson, M. What eye fixations tell us about speed reading and skimming.

Masson, M., Carpenter, P. A., & Just, M. A. The comprehension of gist and details by speed readers and skimmers.

Daneman, M., & Carpenter, P. A. Individual differences in integrating information between and within sentences.

Carpenter, P. A., & Just, M. A. Recent progress in basic research in cognitive processes in reading. Report prepared for the National Institute of Education, 1982.

The apprehensive student perused the gallimaufry of people in the lecture hall and saw that the only remaining place to sit was in front of the lecturn. Resignedly, the student sat down before the avuncular professor in the rumpled suit entered. He was anxious to begin the test, but the student asked for additional time to prepare. After a minute but rapid examination of the book, he signalled the professor to begin.

The paragraph above was intended to make some reading processes especially difficult. For example, the unusual words, like gallimaufry (meaning hodgepodge), avuncular, and perused, made it more difficult to recognize words and determine their meaning. Syntactic analysis was made difficult by inducing the interpretion of before in line 3 as a locative preposition rather than a temporal conjunction, so that the verb entered at the end of the sentence was left without a subject. Another anomaly was induced by the phrase After a minute, since the more frequent "60 second" interpretation (rather than the correct "detailed" interpretation) made the subsequent phrase rapid examination nonsensical. Finally, there were cues that would initially mislead the reader about the correct referent of the pronoun He in the phrase He was anxious to begin....

The eye fixations of a person reading the opening paragraph would reflect many of these processes. The reader would spend more time fixating on longer words, such as apprehensive and resignedly, and on unfamiliar words, like perused, avuncular, and gallimaufry. The words before, minute, and He would not cause difficulty initially, but later words would not make sense and the reader would spend extra time fixating the mutually inconsistent parts while resolving the inconsistencies.

The fact that these inconsistencies are noticed just as soon as they arise supports the immediacy assumption -- the assumption that a reader (or listener) tries to interpret each word of a text immediately on encountering it, rather than waiting to make an interpretation until a number of words have been encountered (Just & Carpenter, 1980). "Interpret" refers to several levels of cognitive processing, such as encoding the word, accessing a meaning, assigning it to its referent, and determining its status in the sentence and the discourse.

We all know that it is often easier to interpret a word when the context that follows is known. Because of this, many accounts of natural language processing suggest that there is an invariant delay of a fixed number of words before interpretation is executed (see Kimball, 1973; Marcus, 1980). Such buffering schemes allow the interpretive processes to make use of some aspects of the context that follows a word. The immediacy assumption does not deny the use of context, but it proposes that interpretation is not invariably postponed until the succeeding context is known. Readers and listeners try to interpret each word as they encounter it, before knowing exactly what will follow. The fact that they are sometimes surprised by what follows, as in the opening paragraph, indicates that an initial interpretation had already been made. Attempts at immediate interpretation of each word of a text may be unsuccessful or produce an erroneous interpretation that later has to be revised. But the attempt is made, as our data show.

A second assumption discussed in our chapter is the eye-mind assumption. The assumption is that the reader continues to fixate a word until all the cognitive processes initiated by that word have been completed to some criterion. The eye-mind assumption does not require that the cognitive system consider only the word that is currently being fixated. Obviously, concepts from previous knowledge and from previously fixated words are available without any change in eye position.

**Organization of the chapter.** In this chapter, we show how eye fixations can be used to determine when encoding, lexical access, parsing, and integration processes are executed, and how they are affected by various properties of the text. First, we discuss some global features of eye fixations in reading — some of which run counter to common conceptions of reading. These features also provide support for the immediacy and eye-mind assumptions. Second, we describe a general model of language comprehension based on a computer simulation that has been developed to account for the eye fixation results. The simulation was developed both to formalize our models of specific processes and to make the processes function collaboratively in an interactive system. Third, we discuss our research on specific comprehension processes, including encoding, lexical access, syntactic parsing, and integrative processes. Our final discussion evaluates the approach and suggests some possible sources of the next generation of improvements.

## Eye Fixations During Normal Reading

Many readers believe that when they read normally, they fixate only two or three places on a line and rely on extrafoveal vision to encode the rest of the words around where they fixate. However, these intuitions are not correct; normal readers sample the text very frequently, usually fixating adjacent words or skipping no more than one word. Moreover, the time that a reader spends on a word reflects processes initiated by that word.

The support for these claims comes from an analysis of the eye fixations of 14 college students who read 15 short (130 word) texts, excerpted from Newsweek and Time magazines, that described scientific discoveries and technological developments. We asked the students to read normally, not to memorize or study the text, and to recall what they could of each paragraph after they had finished it (see Just & Carpenter, 1980, for the details of the method). The readers appeared to follow our directions. Their reading rates averaged 225 wpm, a typical rate for normal reading, and they made very few regressions to previously read parts of the text. Fixations on inter-word spaces were attributed to the word to the right and blinks that were bounded by fixations on the same location were attributed to that location. Other blinks, the durations of saccades, and regressions to reread earlier parts of the text were not included in the analyzed data. We computed the time each reader spent on each word for the passages in which the tracker maintained better than 1 degree accuracy (three character spaces), an average of 14 passages per reader.

## Gaze Duration

The mean time on a word was 239 msec, but there was considerable variation among the times on different words. We will argue that these times reflect several kinds of comprehension processes: encoding the word, accessing it, and performing syntactic, semantic, and discourse level processes. To quantify these effects, we used linear regression techniques to analyze two dependent variables. The first was the mean gaze duration, the average time spent looking at a word, irrespective of the number of individual fixations and averaged over all subjects (a 0 msec observation was entered if the reader did not fixate a word) (Just & Carpenter, 1980). The second was a conditionalized mean gaze duration, the time on a word averaged over only those readers who fixated the word for at least 50 msec. (This cutoff eliminates spurious observations of 16, or 33 msec caused by measurement noise or measurement during a saccade.) This second measure removes the variation due to the probability of fixating a word and analyzes only variation due to the gaze durations on the word. The two analyses yield fairly similar results for the types of words that almost all readers fixated, namely, the content words.

The analyses of both variables revealed several word-level and sentence-level effects. For example, readers spent more time on infrequent words and less time on modified nouns whose referent could be easily inferred. This variation can be seen in the gaze durations of a single reader. Table 1 presents a typical protocol (chosen because the proportion of words that the reader fixated overall approximated the mean across the 14 readers). Even in this small sample, one can see that the reader paused longer on harder and more important words, such as weightarm in line 3, fulcrum in line 5, and quarries in line 7. The analysis of the average gaze durations across readers indicated considerable systematicity. Eleven independent variables accounted for 79% of the variation in the mean gaze durations on words and 60% of the variance in the conditionalized mean gaze durations. The systematic relations between the gaze durations and the properties of the text provide support for the eye-mind assumption, and hence, for the immediacy assumption.

Insert Table 1 about here

## The Pattern of Fixation.

Simple inspection of the pattern of gazes in Table 1 makes it clear that this reader sampled the text very densely. To quantify this observation for the entire data base, we analyzed the distribution of successive unfixated words, focusing on the length of the run of unfixated words. The number of unfixated words is zero if the reader successively fixates two adjacent words. The length of the run is one if the reader skips exactly one word between successive fixations, and so on. Figure 1 shows the average number of runs of each length for each 1000 words of text.

Insert Figure 1 about here

Table 1

The Gaze Durations of a Typical Reader

```
384    267                   884            300       333       333
Another answer to the ever-intriguing question of pyramid construction

            517              267        283          200    350   283 283  733
has been suggested.  The Egyptian Engineer of 5,000 years ago may have

333  266   183      467     200        1201            333            367    1151
used a simple wooden device called a weightarm for handling the 2-1/2 to 7

 583     568          417     267    183      217                 600    167 200
ton pyramid blocks.  The weightarm is like a lever or beam pivoting on a

617          383         300      550  234  217  200       650    117
fulcrum.  Hundreds of weightarms may have been needed for each pyramid.

 267      267        250  283          234    384        216   350          267
Weightarms may have been used to lift the blocks off the barges which came

   250   433     899        300           400      217    217  633     83
from the upriver quarries.  Also, they would be needed to transfer the

383               634           350       333        333       267     267
blocks to skid roads leading to the base and for lifting the blocks onto

550              317           350  100  350    317               367   333
sledges.  The sledges were hauled up greased tracks to the working levels.

267         766           350      350 217       333     300       333       333
Again, weightarms were used to pick up the blocks from the sledges and put

 350   400                     316                467    2150
them on skidways where workers pulled them to their placements.
```

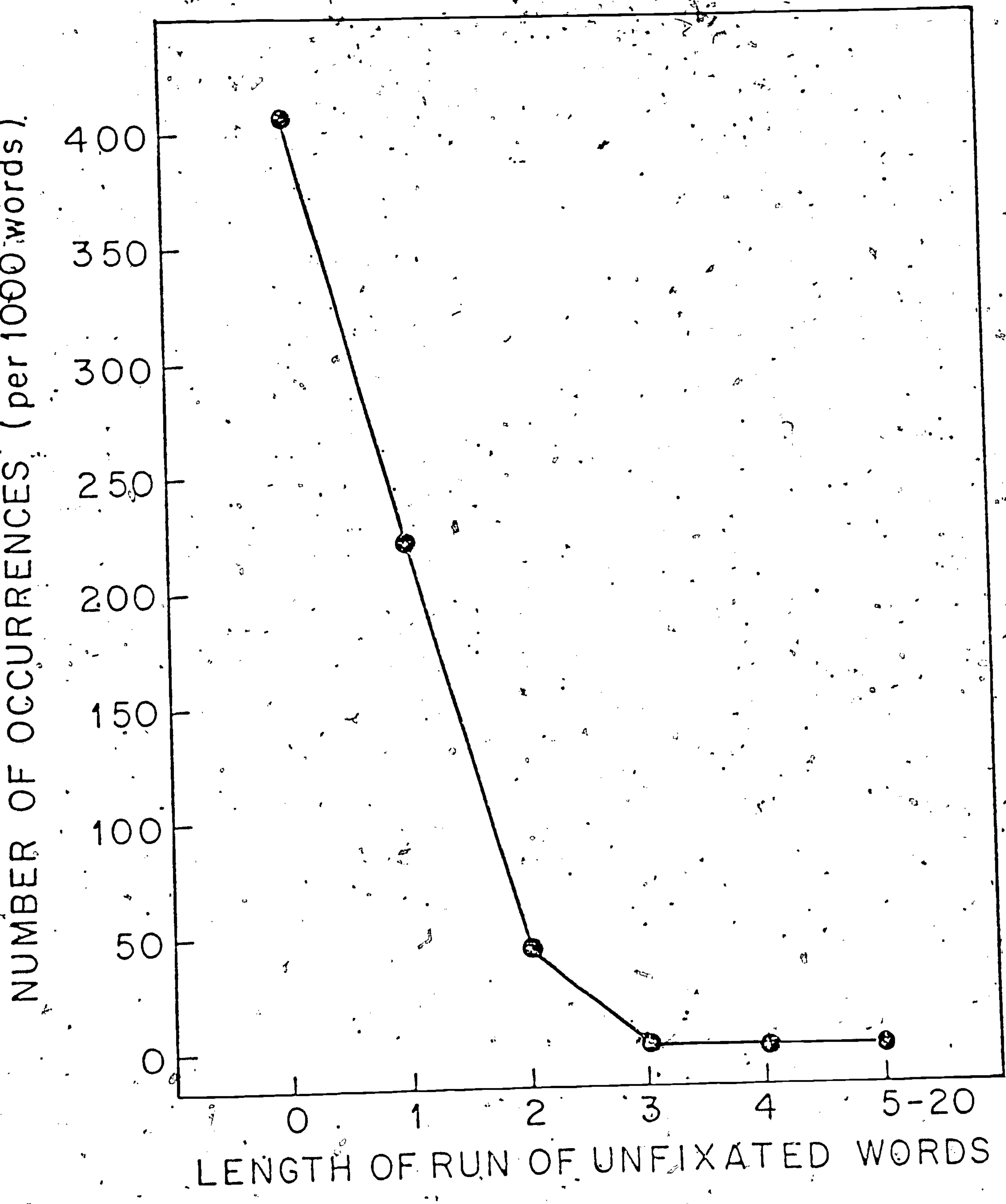


Figure 1. The length of the run of unfixated words between successive fixations, conditionalized on a passage of 140 words.

When readers move their eyes forward in the text from one word to some other word, most of the time (93%) they fixate the very next word or skip over only one word. For every 1000 words of text, the mean number of words fixated at least once was 678. On average, these 678 fixated words were distributed as follows: the gazes were on adjacent words in 410 cases, involved one skipped word between consecutive gazes in 221 cases, two skipped words in 43 cases, three skipped words in 3.6 cases, and almost never involved more than three skipped words. As the protocol in Table 1 suggests, the words that were likely to be skipped were short, function words, like a, of, the, to, and so on. Overall, readers fixated only 38% of the function words (conjunctions; articles; prepositions; modal, auxiliary, and copula verbs). By contrast, they fixated 83% of the content words (adjectives, adverbs, nouns, verbs, pronouns), and longer words were more likely to be fixated than shorter ones.

## Support for the Immediacy and Eye-Mind Assumptions

The clearest support for the immediacy and eye-mind assumptions is the copious evidence that the time spent looking at a word is strongly influenced by the characteristics of that word (e.g., Just & Carpenter, 1980). Additional tests of the immediacy and eye-mind assumptions can be made by determining whether the gaze duration on a given word is influenced by the characteristics of the preceding word. If the eye were exactly one word ahead of the mind, then the semantic processing of word N-1 would occur during the gaze on word N. In one set of analyses, the dependent variable was the conditionalized mean gaze duration on word N, given that the reader fixated both word N-1 and word N. In another set of analyses, the dependent variable was the gaze duration on word N given that the reader fixated word N but skipped word N-1. Each dependent variable was analyzed with three regressions that used as independent variables the length and frequency of (1) word N alone, (2) words N and N-1, and (3) word N-1 alone. Length and frequency were used as independent variables because these two variables are assumed to affect encoding and lexical access and their large effects should be detected easily. We restricted the analysis to words that were not at the beginning or end of a line, and not sentence initial or terminal, since such words tend to be processed differently (Just & Carpenter, 1980; Rayner, 1977, 1979).

The major result, shown in Table 2, is that the gaze duration on word N is not affected by the length or frequency of the preceding word. The account of the variance in gaze durations on word N is not significantly improved by considering the characteristics of word N-1. This result holds regardless of whether the reader did or did not fixate word N-1. These results suggest that the reader generally has finished encoding and accessing the preceding word before fixating the next. This finding provides strong support for the eye-mind and immediacy assumptions.

---

Insert Table 2 about here.

---

The characteristics of the word to the right also have a negligible influence on the time spent on the fixated word. If the reader usually semantically processed word N+1 while fixating word N, the length and frequency of word N+1 should influence the time on word N. To test this, we separately analyzed those cases in which the readers fixated both word N and N+1, and those in which they fixated word N and skipped word N+1. As Table

Table 2

Variance in the Conditionalized Mean Gaze Duration on Word N Accounted for by Regression[a]

| Independent Variables: Length and Frequency of | Reader Fixated Word N-1 | Reader Didn't Fixate Word N-1 |
|---|---|---|
| 1) Word N | 23.8% | 25.1% |
| 2) Word N and N-1 | 24.0% | 25.6% |
| 3) Word N-1 | 0.4% | 0.2% |
| | **Reader Fixated Word N+1** | **Reader Didn't Fixate Word N+1** |
| 1) Word N | 24.2% | 18.1% |
| 2) Word N and N+1 | 24.7% | 19.9% |
| 3) Word N+1 | 0.4% | 0.5% |

[a] The total variance accounted for by these analyses is reduced from that of the orginial analysis because the mean gaze durations are based on less than half the number of observations as the original analysis and because there are fewer independent variables.

2 shows, the length and frequency of word N+1 have no appreciable effect on the gaze duration on word N, even when word N+1 is skipped. This suggests that readers usually do not encode and access words to the right of the word that they are fixating, suggesting that the span of semantic processing is fairly small. In cases in which the next word is encoded and accessed, the processing takes either a small amount of time or a constant amount, relative to the processes associated with the currently fixated word.

Although the span of semantic processing is small, there are some cases in which the reader encodes and accesses a word during the fixation on a preceding word. We hypothesized that this was most likely to have occurred in those cases in which the reader had fixated a function word and then skipped over an immediately following content word. The conjecture was that the content word was encoded parafoveally and processed during the gaze on the function word. We analyzed this subset of the data and found that the length and frequency of the skipped content word accounted for 6% of the variance in the gaze duration on the function word. The length and frequency of the function word accounted for only 1% of this variance. These cases are relatively infrequent; only 3.5% of the gazes were on function words adjacent to a skipped content word (at locations that were not at the beginning or end of a line or sentence).

**Skipping function words.** There was additional evidence that readers could sometimes semantically process words adjacent to the word they were fixating. The evidence was that readers were somewhat selective about which words they skipped. When word length is held constant by considering only three-letter words, three-letter function words still have a significantly lower probability of fixation (.40) than do three-letter content words (.57), $F(1, 265) = 45.37$, $p < .01$. This analysis was restricted to 267 three-letter words in the text that neither began nor ended a line or a sentence. The probability of fixation was .29 for 37 and's, .40 for 122 the's, .47 for 47 other three-letter function words (such as was, may, can, but, for, off, has), and .57 for 61 three-letter content words (such as act, red, use, ant, run, two, not). This result replicates O'Regan (1979), who found readers were less likely to fixate the than three-letter verbs. The result suggests that readers sometimes encode at least some aspects of a word without directly fixating it and that this occurs more frequently for short, predictable function words.

It should not be assumed that all unfixated words are completely visually encoded, in the sense that their constituent letters enter into the recognition process. In some cases, the context plus some minimal visual information such as word length and shape may be sufficient cues for lexical access. This may be particularly true for common function words (like a, the, and and). Some unfixated words may be inferred on the basis of prior and subsequent context. Finally, some words may not be processed at all. We have all had the experience of reading something that just did not make sense and rereading it to discover that we just "didn't see" a word. In skimming, many words are not encoded, semantically processed, or inferred (Just, Carpenter, & Masson, Note 1), and some of the skipped words in normal reading may fall into this category as well.

## The role of parafoveal encoding

Research on perceptual processes has shown that different information is available at different distances from the locus of fixation. Rayner (1975) found that gross word shape and word length information are available perhaps as far away as 12 character spaces. However, semantic interpretation may only occur for a word that is directly fixated or immediately adjacent. Rayner's (1975) study found that when a non-word was embedded in a text, the fixation duration was considerably elevated if the reader directly fixated the non-word, the duration was much less elevated if the reader fixated on the last two letters of the adjacent word to the left, and it was not elevated at all if the reader fixated farther to the left of the non-word, suggesting a very small span of semantic processing.

The analysis of our eye fixation results and the results reported by Rayner (1975) allow us to outline in more detail how parafoveal encoding processes may interface with cognitive processes. Our approach must deal with the possibility that a reader is processing some word proximal to the one he is fixating, and must attempt to estimate the probability of such events and the extent (i.e. depth) of the processing when they do occur.

There are several ways to obtain evidence that a reader is processing some word other than the one he is fixating. One way is to change the word at some point between the time when the word could be processed extra-foveally and the time when it is directly fixated, and then measure some aspect of performance that indicates that the subject noticed the change. This is a paradigm that Rayner (1975) used, and an elevation in the fixation duration following the change was an indication that the reader noticed the information that had been present prior to the change. Since there was a reliable elevation if the reader had fixated close enough to the changed word on the preceding fixation, it can be concluded that on some proportion of the trials, some proportion of the readers had encoded the word before having fixated it. However, this result does not permit us to estimate the frequency of occurrence of such encodings.

Another way to obtain evidence that a word adjacent to the fixated one is being processed is to find that the gaze duration on a given word is influenced by the properties of the neighboring words. We reported that in general the gaze duration on word N is unaffected by the length and frequency of word N-1 or word N+1, with two exceptions. One exception is Rayner's (1975) result, described above, in which a fixation within three character spaces to the left of a non-word was somewhat elevated. A second exception are the occasional gazes on a function word followed by a skipped content word. The gaze duration on the fixated function word is modestly influenced by the length and frequency of the skipped content word, accounting for 6% of the variance.

A third index of the processing of words that are not fixated is the systematic skipping of certain classes of words, which could occur only if some discriminative property of the words (their position in the sentence, length, shape, constituent letters, and so on) is encoded before they are fixated. The analyses of three-letter words suggests on some occasions, they receive some processing while the reader is on the adjacent word. But we do not know how often this occurs, nor do we know what kind of information is being encoded. It is possible to recognize a great proportion of the three-letter function words on the basis of the prior syntactic context and the length and shape of the two words, "the" and "and".

The conclusion from all the results above is that there is some probability of encoding sufficient information from a word adjacent to the fixated word so that it can be accessed. This is more likely to occur for short function words. When it does occur, the gaze duration on the fixated word generally is not influenced.

The general pattern of results above can be explained as follows. The reader encodes and accesses the word he fixates, in keeping with the immediacy and eye-mind assumptions. In addition, he can encode the initial letters of an immediately adjacent word, but only in those cases where his locus of fixation happens to be very close to the boundary of the currently fixated word.[2] First consider the case in which the immediately adjacent letters constitute a short function word (the) or phrase (and the). These may be encoded and accessed concurrently with the processing of the fixated word. Such function words and phrases are short, frequent, relatively predictable, and semantically impoverished and so would contribute little to the processing duration of the current word. In some contexts, a short content word may be sufficiently frequent, predictable and impoverished, and hence, be more likely to be skipped. If the processing of an unfixated word is completed before the fixated word is entirely processed (as would generally be the case if the unfixated word were a short frequent word), then the next saccade tends to be longer, to skip over the adjacent word that has been processed without fixation. If the unfixated word requires processing time beyond that required by the fixated word, then the next saccade is targeted at the unfixated word that was not processed to completion. The fact that not all short inferrable words and phrases are skipped may partially reflect the fact that readers' fixations are not always close to the beginning of the next word. In this scheme, many short function words are skipped because they have been processed.

Now consider the case where the adjacent word is long, less predictable, less frequent, or semantically richer -- a description that is true of most content words and some function words (e.g., however). The adjacent word generally can not be encoded or accessed before the currently fixated word has been processed to completion. The current word is processed and a saccade is programmed to bring the word on the right into foveal position. Thus, the word on the right will have almost no influence on the duration of the currently fixated word, although, it may influence the decision about where to fixate next.

The decision of where to fixate next is not entirely a function of the information received in the current fixation. It is also influenced by more global factors, such as the readers' attentiveness, whether they are reading carefully, carelessly, or skimming. As we mentioned earlier, not all skipped words are necessarily semantically processed in normal reading. In addition, the decision of where to fixate may also be influenced by the local difficulty and importance of the segment (see Just et al., Note 1). If the exact same words occur in a more difficult context or at a point where the information is cued as important, readers appear to fixate more densely. The decision about where to fixate may also be influenced by word length and shape information, which are available farther into the periphery. Finally, it also appears to be influenced by individual and developmental differences among readers

(Daneman & Carpenter, Note 3; Jackson & McClelland, 1975).

We have proposed a detailed account of the processing of unfixated words that is consistent with the available evidence. The skipping phenomenon seems to be an integral part of reading an orthography like English. However, we also stress that content words in these passages are generally fixated, and in any case, words that are skipped have little effect on the gaze durations on fixated words. The next sections show how the gaze durations on the fixated words can be used to examine specific processes and the influence of the text on their duration.

## A General Theory and a Specific Reading Model

A central characteristic of reading and of most complex cognitive tasks is that it requires collaboration among a variety of processes. Consequently, any general theory of reading must provide a structured forum for the interaction of processes, as well as mechanisms to account for the specific computations that are based on word, sentence, and text-level information. In this section, we describe both components. The first is a theory of human processing that has general properties that are applicable to more than reading. The second component is a specific model of reading, called READER, that operates within the general theory and was developed to account for the time course and content of reading. The reading simulation was motivated by the human experimental work (Just & Carpenter, 1980), and it is described in more detail elsewhere (Thibadeau, Just, & Carpenter, Note 2).

### CAPS

The general theory is a <u>C</u>ollaborative <u>A</u>ctivation-based <u>P</u>roduction <u>S</u>ystem (CAPS). Production systems are formalisms in which the procedural knowledge is embodied in a set of condition-action rules (Newell, 1980). The condition part specifies what element(s) should be present in (or absent from) working memory to enable the action. For example, one parsing production in READER specifies that if an article (<u>the</u>, <u>an</u>, or <u>a</u>) has been encoded (condition), a slot for a noun phrase should be established (action).

Productions are executed in recognize-act cycles. On each cycle, the contents of working memory are assessed and all productions whose conditions are satisfied are executed concurrently, modifying the contents of working memory. Then the new contents of working memory are assessed and another cycle occurs, and so on. This processing mode corresponds to the immediacy assumption in that a process is executed as soon as the enabling conditions are present. READER, for example, does not routinely buffer information; a production will execute as soon as working memory contains sufficient information to initiate it.

CAPS allows several productions to fire at the same time, meaning that several computations may occur concurrently. For example, having encoded <u>hammer</u> and accessed the concept, the reader can simultaneously compute that it is used as a noun, that it is an instrument, and that it may be coreferential with a previously mentioned hammer. The fact that several computations may go on concurrently allows different processes to influence each other, not only by feeding the results of one computation into another, but also by being exposed to (and potentially influenced by) each other's partial results in working memory.

READER's knowledge base consists of propositions in the form of concept-relation-concept triples, constituting a semantic network. Every proposition has an associated numerical activation level or confidence value that can be modified (incremented or decremented) by the productions. The modification is often linearly related to the activation level of one of the production's condition elements. Thus, a production can direct activation to a given proposition, with the size of the modification determined by the activation level of another proposition. It is possible for several different productions to collaboratively increase READER's belief in a particular piece of information to some threshold level, where one production alone would have failed to do so. If there are two or more alternative interpretations of some proposition, each interpretation may accumulate supporting evidence until one of their activation levels reaches threshold and becomes the accepted interpretation. For example, in the reading simulation, the word-concept before might be retrieved with two associated interpretations; the temporal interpretation would have a certain activation level (say .5), and the locative interpretation would have a lower activation level (say .3), reflecting their relative frequencies in American English. However, a preceding context concerning location could increase the activation of the locative hypothesis and bring it to threshold, thus ending the subthreshold debate.

## READER

READER works within the CAPS framework, using concurrent productions, directed activation, and subthreshold debate. READER consists of 225 productions that embody the lexical, syntactic, semantic, and schema-level knowledge necessary to read one passage and construct a representation of the information. Each traditional "stage" of reading such as encoding, lexical access, parsing, and so on, is realized as a number of productions in its long-term procedural knowledge base. Currently, READER has a vocabulary sufficient to read only one passage. However, as we show, many of READER's mechanisms are quite general and can be used to explain a variety of processes we have found in human reading. Like human readers, READER identifies and accesses individual word concepts. It determines how word meanings combine to produce the meaning representation of a sentence by doing something resembling a conceptual dependency analysis (Schank, 1972). It checks for noun-verb agreement, assigns case roles, and identifies referents of described objects. In addition, READER possesses a schema of a scientific text that specifies the general categories of information to expect, such as the mechanism's name, purpose, operating principles, applications, examples, and so on. The schema guides the inference processes during reading and organizes the subsequent recall.

The structure of CAPS and READER allow both quantitative and qualitative comparisons between READER's performance and human reading data. The number of cycles READER requires to interpret various words and phrases can be compared to human gaze durations. In addition, READER constructs a representation of the text and uses it to recall the text so that the content of what READER recalls can be compared to what human readers recall. We have found that READER provides a good account of both the reading times and recall (Thibadeau et al., Note 2). In the next sections, we describe the mechanisms and their empirical underpinning in more detail.

## The Mechanisms of Reading

**Word Encoding.** The first mechanisms that we discuss are those that encode words from their written form into an internal representation of the word percept. The major results are from the experiment described earlier, in which undergraduate students read scientific passages. One very striking result from the analysis of the reading times is that gaze duration increased linearly with word length, whether length was measured in number of letters or number of syllables. Figure 2 shows both the mean gaze duration and the conditionalized mean gaze duration on a word as a function of its length (measured in number of characters) and the logarithm of its normative frequency. While number of letters accounted for slightly more of the total variance than did number of syllables, there were clear syllable effects. For example, digits consistently took longer than would be predicted on the basis of the number of characters (see also Pynte, 1974). The most likely resolution is that both letters and syllables are functional units in reading. The word length effects are extremely robust. Not only have they been found with these scientific texts, but similar effects were found in another study involving long narratives (2,000 words) taken from Reader's Digest and long expository passages from Scientific American (Just et al., Note 1).

Insert Figure 2 about here

The proposed mechanism to account for the word length effects is that word encoding processes operate on successive parts of a word, such that the duration of the encoding process is sensitive to subword orthographic length. There is a strong bias in favor of processing the units from left to right. The subword units could be syllables or letters, but READER currently uses letters.

There exists an alternative but less satisfactory account of the word length effect that does not depend entirely on a sequential encoding process. The alternative account is that long words are difficult to see with sufficient acuity within a single eye fixation, so that longer words are more likely to require more fixations. For example, if a reader fixates near the beginning of a long word, he might be more likely to require a second fixation to bring the letters at the end of the word into clear vision. Two sources of evidence suggest that this alternative account is not satisfactory. The first is that word length effects are present even for very short words having less than five characters. As Figure 2 shows, two-letter words take less time than three-letter words, and these take less time than four-letter words, and so forth. This is true even for the conditionalized mean gaze durations, where the dependent variable does not include differential probabilities of fixation. Words that are two, three, four, or five letters long are within the span of apprehension, and there should be little need for a second fixation to make all the letters visually perceptible. The encoding hypothesis easily accounts for this word length effect, while the acuity hypothesis does not.

The second kind of data that are difficult to reconcile with an acuity explanation come from an experiment with a different mode of presenting the text, one that did not require the reader to make eye movements to read the text. Instead, successive words were presented one word at a time, centered on the screen and the reader pressed a button to terminate the presentation of the word and to begin the presentation of the next word (Just, Carpenter,

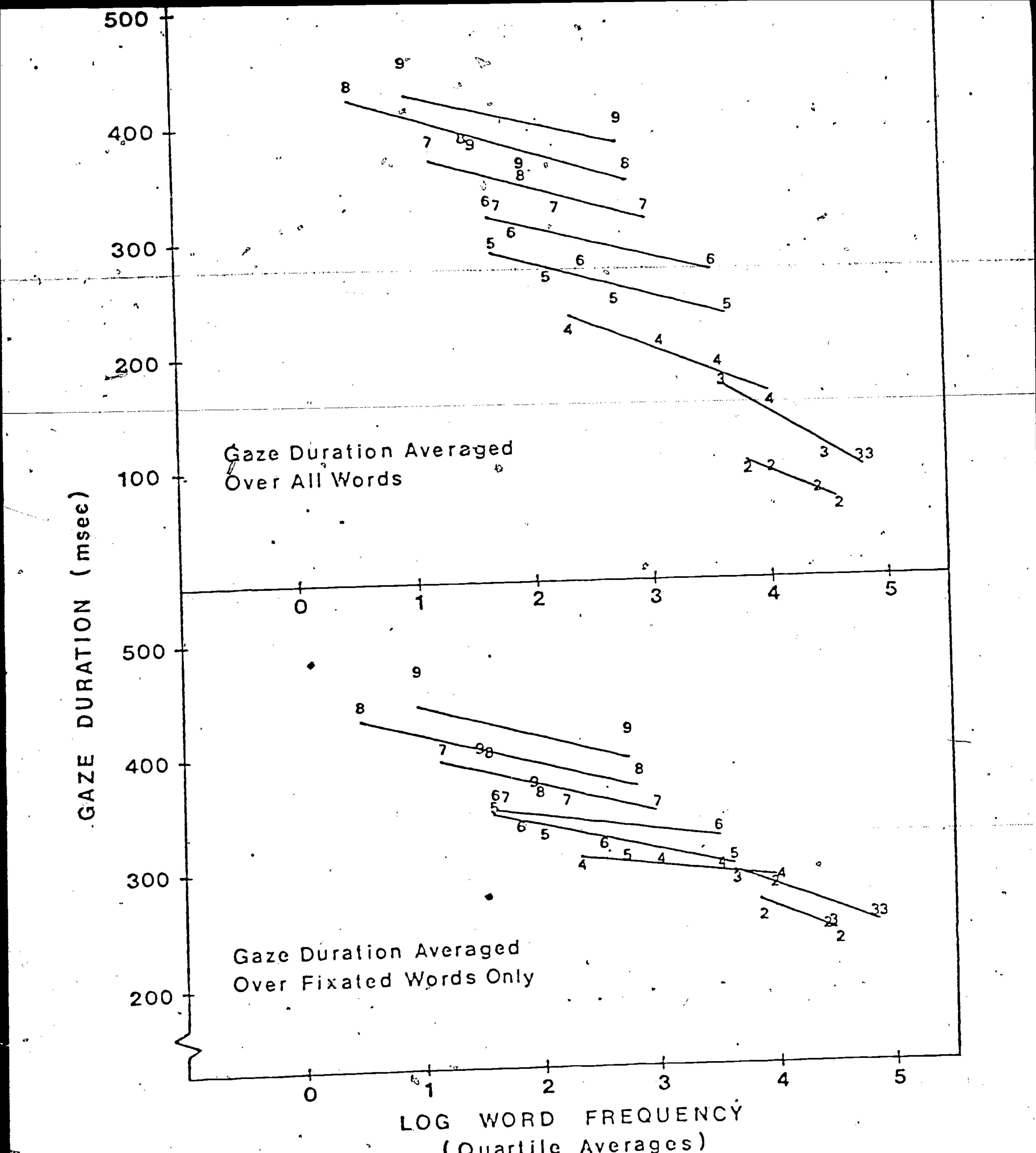


Figure 2. (a.) The mean gaze duration on a word as a function of the logarithm of its frequency and its length in number of characters (the parameter on the curves). Each point represents the mean of a quartile of the words of that length. (b.) The same function except that the dependent measure is the conditionalized mean gaze duration. (From Thibadeau, R., Just, M. A., & Carpenter, P. A. A model of the time course and content of human reading. Pittsburgh, Pa.: Carnegie-Mellon University, 1981.)

& Woolley, in press). The time between successive button presses reflects the duration of processes operating on the displayed word. Even in this condition, in which eye movements play a minimal role, the time readers spent on a word was linearly related to its length. The effect was present for even short words, two, three and four characters long. Both results suggest that the source of the length effect is best explained by a sequential constituent encoding process.

READER generates word length effects because it encodes a word letter-by-letter, forming chunks and looking for subword units and then for word units. When a word has more letters or syllables, READER has more encoding cycles and may form more chunks. Hence, the time that READER spends on a word tends to increase with the length of the word, similar to what is observed in the human reading times. Some very short and frequent words, like <u>the</u> and <u>and</u> might be coded as a single chunk; but overall, frequency has effects that are independent of length.

**Lexical Access.** As Figure 2 illustrates, over the entire range of lengths, less frequent words were fixated for a longer duration. This was true for both the unconditionalized and conditionalized gaze duration. The effect followed a log function; that is, small differences among infrequent words had comparable effects to large differences among frequent words. The effect of frequency, like that of word length, is robust. A very similar function was found in the button-pressing paradigm described earlier and in the eye fixation experiment with long narrative and expository texts.

**Lexical access mechanisms.** Length and frequency effects are additive, suggesting that they may arise from different processes. The locus of the frequency effect for READER is in lexical access, retrieving a word's meaning. In READER, lexical access is direct access, rather than search through a dictionary. The access mechanism is based on the idea of self-activation. Each concept in READER's lexicon has a base level of activation that is linearly related to the normative frequency of the corresponding word. When a word is encoded, the word-percept directs activation to the underlying concept; the concept then starts activating itself over successive cycles, such that the added activation is proportional to the immediately preceding level of activation. So, if the base level activation were .6, after one cycle of self-activation the level would be $(.6 + .6\underline{x})$, where $\underline{x}$ is some constant. This continues until the concept reaches a fixed threshold that is the same for all words. In this scheme, the number of cycles of self-activation necessary to reach threshold is a log function of a word's normative frequency.

**The effect size issue.** Word length and frequency account for a relatively high proportion of the variation in the mean gaze duration on words. In the experiment involving scientific texts, the two variables alone account for 69% of the variance, the other variables alone account for 37%, and all 11 variables together account for 79%. The other variables coded whether the word introduced a topic, began a line, was at the end of a sentence or paragraph, was totally new, was a digit, a modified noun, an inferrable function word, or the first content word in the passage. For the conditionalized mean gaze duration, length and frequency alone account for 40%, the other nine variables alone account for 39%, and all 11 variables account for 60%. (The variances accounted for are not additive because some variables are intercorrelated).

There is a temptation to equate proportion of variance accounted for by a variable with the theoretical importance of the underlying process, but such an inference is unwarranted for at least three reasons (see Sechrest, 1979, for a discussion of "effect size" issues). First, the variance accounted for by a factor is not an inherent property of the factor; it depends on the variation of that factor relative to other factors in the task. The current texts involved words of widely varying lengths and frequencies. If a text were constructed of words of a small range of lengths and frequencies, then word length and frequency would account for a much lower proportion of the variance. Second, these variables may account for a relatively high proportion of the variance because we know how to measure them; as the metrics improve for describing higher level factors, they may account for more of the variance. Finally, it is clear that encoding and accessing words are not sufficient processes for reading; it is also necessary to interrelate concepts to form the meanings of phrases, clauses, sentences, the text, and the referential domain.

In spite of these caveats, there is a theoretically interesting implication of the finding that length and frequency effects are generally more robust than the effects of the other variables. The processes influenced by length and frequency appear to be more uniform across readers and texts; a given word is encoded and accessed relatively similarly by all readers. In contrast, the higher level processes may be more variable across readers in several aspects, such as their time of enablement, their duration, and their content. One way to reduce the variability is to experimentally manipulate when a higher level process is executed or to make it especially difficult, so that almost every reader will take extra time. Later sections of the chapter describe experiments that manipulate the difficulty of higher level syntactic and semantic analyses and examine the effects on the pattern and duration of eye fixations.

**The interpretation of regression weights.** The way a regression weight is interpreted depends on whether the theory specifies that the process operates concurrently with other processes or sequentially. If it is believed that two processes are executed sequentially, the interpretation of the regression weights is straightforward; the regression weight indicates the amount of extra processing time per stimulus unit. For example, a regression weight of 32 msec associated with word length is interpreted as an extra 32 msec of encoding time per letter. However, a regression weight is given a different interpretation if the underlying process is assumed to be executed concurrently with other processes. In that case, the regression weight indicates the increase (or decrease) in the the total processing time when that process is executed; the weight does not indicate the total duration of the process. For example, if the regression weight for sentence-final words is 100 msec, we can infer that these words are associated with extra processing whose absolute duration is unknown but which extends 100 msec longer than the other concurrent processes.

**Novel words.** Some words in the scientific passages, such as staphylococci and thermoluminescence, were probably entirely new to the readers. These words were fixated for an especially long time, 802 msec beyond what would be predicted by their infrequency and their length. We hypothesized that when such a word is encountered, the reader tries to infer its meaning and construct a dictionary entry with information that includes its orthographic, phonological, syntactic, and semantic properties (as far as they can be determined). This entry will help the reader identify the word if it is encountered again later in the text, and the entry will aid the reader in later recalling the word.

READER also spends extra cycles on entirely novel words. If the word is not in its lexicon, READER tries first to identify the word by segmenting out subwords, prefixes, and affixes. Thus, READER can identify the plural of a noun or the past tense of a verb even if it never saw that particular variant before. But if these processes fail, READER creates a new word-concept, taking considerable additional time, just as in the case of human readers.

If the additional time on a novel word results because the reader is creating a new lexical entry, then the next time the reader sees this word the time should be less. The human reading data support this. Processing a novel word the second time is much faster. We also found a more general repetition effect; certain other words were also fixated for less time on the second and subsequent occurrences (Thibadeau et al., Note 2). Interestingly, the repetition effect was limited to topical words, like red fire ant, fluorocarbons, radioisotopes, vitreous humor, Pteranodon, glial cells. Non-topical words did not show repetition effects. This suggests that the repetition effect is not due entirely to faster encoding, but in part, may be due to relating topical words to a schema.

## Immediacy in Lexical Access

Frequency alone does not determine the time course and outcome of the lexical access process. It also depends on the preceding context. One of our eye fixation studies examined how context interacts with frequency to determine which meaning is chosen as the interpretation of an ambiguous word. The second focus of the study was inconsistency detection -- when does a reader detect an inconsistency and how does he or she recover from it (Carpenter & Daneman, 1981).

We will describe the experimental paradigm in some detail because it is used in a number of experiments. Our subjects read "garden path" passages, such as the following:

> The young man turned his back on the rock concert stage and looked across the resort lake. Tomorrow was the annual, one-day fishing contest and fishermen would invade the place. Some of the best bass guitarists in the country would come to this spot. The usual routine of the fishing resort would be disrupted by the festivities.

If asked to read this passage aloud, most people initially give bass in line 3, the pronunciation corresponding to the "fish" meaning, the meaning primed by the earlier references to fishing. But the "fish" interpretation is inconsistent with the subsequent disambiguating word, guitarists, and a resolution requires the reinterpretation of bass to mean "a low music note". These processes, the initial interpretation, the detection of the inconsistency, and its resolution, can be seen in a reader's pattern of eye fixations.

**A protocol.** A typical reader's eye fixations, shown in Figure 3, illustrate the major processes. The subject read the target sentence (indicated in large print) embedded in the paragraph given above. The reader's oral protocol, indicated in small print, gives both his initial interpretation and subsequent reinterpretation of the ambiguous word. The sequence of eye fixations is denoted by the numbers above and below the words in the sentence. The fixation duration is indicated in milliseconds below the sequence number. The reader made a series of forward fixations until he came to the word guitarists, then he reread the word bass (fixations 6 and 7) and finished the sentence (fixations 8 to 12).

Insert Figure 3 about here

We have interpreted the gaze duration on the ambiguous word as the time that it takes to encode the word, retrieve an interpretation, and integrate it with the representation of the text. The long duration on the disambiguating word (fixation 5) is interpreted as reflecting the reader's attempt to integrate the word guitarist and his discovery of the inconsistency. At that point, he regressed to the word bass, indicating that he had found a source of inconsistency. The oral reading indicates that this reader successfully recovered by discovering and integrating the alternative meaning.

One interesting point in this protocol is that it illustrates the delay between eye and voice, and the lack of delay between eye and mind. The voice lags behind the eye, giving rise to the typical eye-voice span. It also indicates that the eye-mind span is short. The reader typically detects the inconsistency when he fixates the first word that is inconsistent; that word is usually verbalized at a later time. Thus the eye and mind are close together in time, while the voice lags behind both of them.

**Accessing concepts.** As we described in the section on lexical access, retrieving a concept is not an all or none process. There is a subthreshold state in which more than one candidate interpretation may receive at least some activation. The first one to reach threshold becomes the accepted interpretation. There are two major sources of activation that determine which concepts reach threshold. One is the prior context, which includes structures in working memory derived from information in the prior text and from previous knowledge about the topic. For example, the context in the sample paragraph above included references to fishermen and a fishing resort. These help to partially activate the fish concept before the word bass is fixated.

As the study with scientific texts indicated, a second determinant of activation is a word's frequency. However, in the case of polysemous words, activation of alternative meanings depends on the relative frequencies of each meaning. The effect is striking with ambiguous words that have one very common interpretation and one uncommon interpretation, such as the "drain" and "tailor" interpretation of sewer. In the sentence There is also one sewer near our house..., most readers interpret sewer to mean "drain" rather than "tailor;" because the "drain" interpretation is more frequent. In the READER model, this also occurs because the interpretation with the higher base activation level will reach threshold sooner.

**The oral interpretation results.** To study how these processes influence lexical access, we developed passages like the one above, using ambiguous words such as bass, sewer, tears, and wind, and had 20 college students read them aloud while we monitored their eye fixations. As we predicted, readers

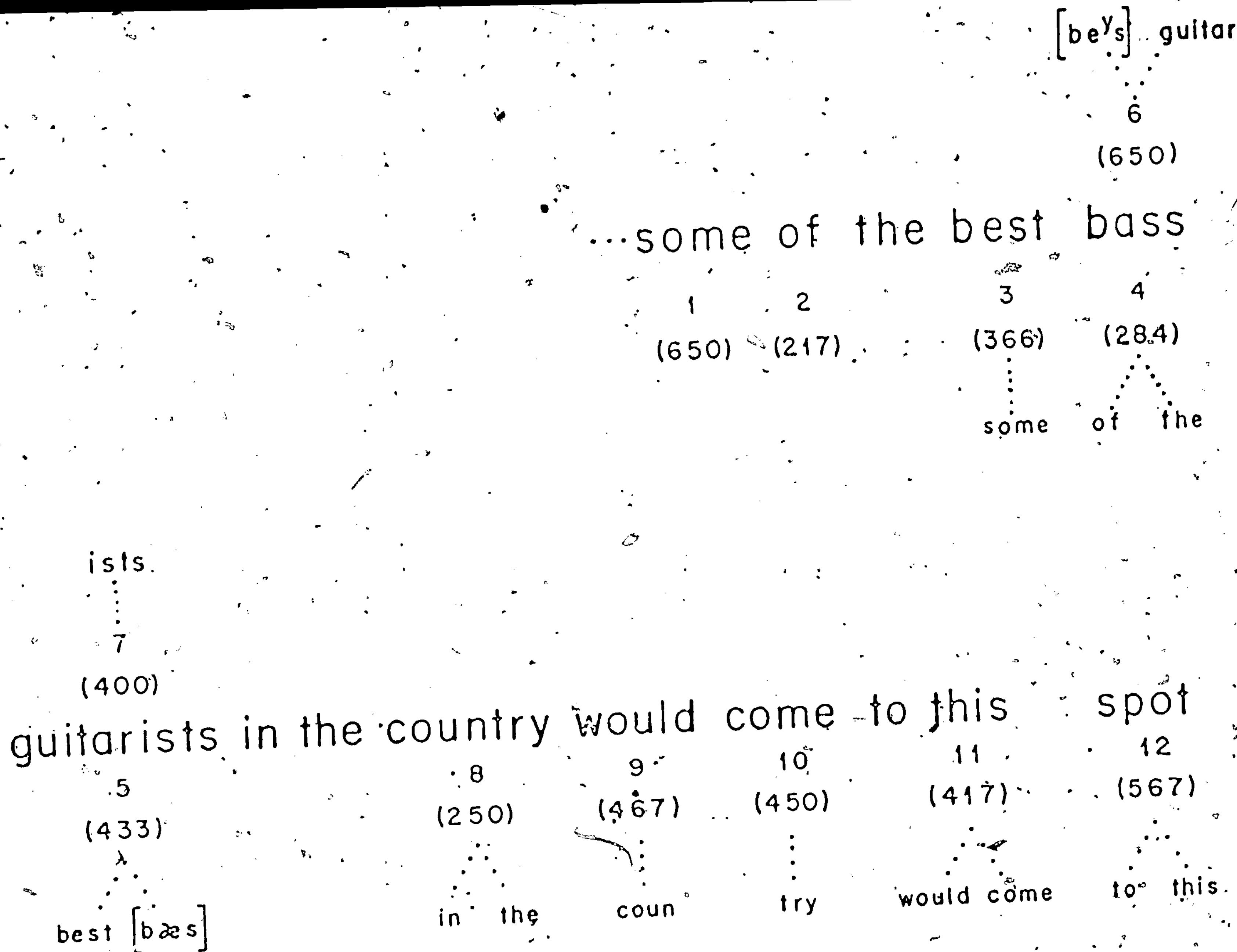


Figure 3. The bass target sentence with a reader's eye fixations and read-aloud protocol in small print. The numbers 1-12 indicate the sequence of fixations; the forward fixations are indicated by the numbers below the fixated word, and the regressive fixations are indicated by the numbers above the fixated word. The numbers in parentheses indicate the gaze duration (in milliseconds). The read-aloud protocol shows that bass was initially interpreted as [b ae s], meaning "fish," and then revised to [beʸ s], meaning "music note." (From Carpenter, P. A., & Daneman, M. Lexical retrieval and error recovery in reading: A model based on eye fixations. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 137-160)

generally gave the ambiguous word the pronunciation that was consistent with the context. However, the relative frequencies of the two interpretations also had an influence. For words like sewer, readers chose the infrequent meaning only 5% of the time in paragraphs that primed the infrequent meaning. In contrast, when the context primed a meaning with a moderate or high frequency, it was given 80% of the time. The fact that the very infrequent meanings are seldom chosen reflects the strong bias that readers have towards common interpretations; even context effects cannot entirely compensate for this bias. This result suggests that context may play a different role in helping to select one interpretation of a polysemous word, depending on whether or not the various interpretations are approximately equally likely. If the two meanings have similar frequencies, both meanings may be retrieved, with context selecting the more appropriate one (Swinney, 1979). But if the two meanings have very different frequencies, the less common meaning may not be retrieved at all and a strong context is necessary to bring it to threshold (see also Simpson, 1981).

The time readers take to encode, access, and integrate the ambiguous word should be less if the retrieved interpretation has a high frequency and matches the preceding context. These processes should be reflected in the time readers spend on the ambiguous word. The results clearly confirmed the predictions. Readers spent less time on the ambiguous word when the interpretation they chose (as indicated by the oral protocol) was the higher frequency interpretation and was consistent with the context. The fact that both context and a concept's frequency affect the time readers spent on the ambiguous word provides further support for the immediacy and eye-mind assumptions -- readers are encoding the word, selecting a meaning, and trying to integrate it while fixating the word itself.

## Detecting Inconsistencies and Revising Interpretations

In order to recover from having previously chosen the wrong interpretation of a word, a reader must realize that some inconsistency exists, determine that the problem resides with an earlier word, and then revise that earlier interpretation. For example, the reader who interpreted sewer as "drain" would find who anomalous in the sentence There is also one sewer near our house who makes terrific suits. The source of the inconsistency between sewer and who resides in the interpretation of sewer. Detecting the inconsistency and attempting to recover should take extra processing time, reflected in longer gazes. If readers detect the inconsistency on the disambiguating word, there should be longer gazes on that word and more regressions after it is fixated. The results supported the hypothesis. Readers spent more time on the first disambiguating word and on the entire disambiguating phrase when it was inconsistent, and they were more likely to regress to the previous ambiguous word.

Readers had relatively little difficulty recovering from inconsistencies if the interpretation they had incorrectly rejected was relatively frequent, as in the bass example. They had much more difficulty and often did not recover if the incorrectly rejected interpretation was very infrequent, such as in the case of sewer, minute, buffet, and row. These cases are also interesting because the patterns of eye fixation reveal different recovery processes.

A protocol for one sentence can be used to illustrate the general results. Figure 4 shows the time on each word of the sentence There is also one sewer near our home who makes terrific suits for two groups of readers. One was primed to interpret sewer as "drain", and the other, as "tailor". The three panels in Figure 4 show three different gaze duration measures. The top panel is the mean gaze duration on each word, composed of forward fixations and averaged across readers, counting 0 msec for a reader who did not fixate the word. The second panel shows the average time spent in regressions after readers encountered the first disambiguating word, who. The bottom panel shows the duration of regressions before the disambiguating word was fixated.

---

Insert Figure 4 about here

---

Irrespective of the context, everyone initially pronounced sewer according to the more frequent "drain" meaning. Readers who had the "tailor" context had more difficulty in accessing and integrating "drain," as reflected in the longer time in forward fixations on the word sewer (the top panel) and the greater time spent in regressions (the bottom panel). Both groups had difficulty with the phrase who makes terrific suits, because it was inconsistent with their prior interpretation. The difficulty is reflected in the longer forward gazes on this phrase (the top panel) and the long times spent in regressions (the middle panel).

Readers who initially had problems integrating their interpretation of the ambiguous word were more likely to recover. (Recovery was assessed from their oral reading and by questions asked after the passage was read, such as "Who made terrific suits?".) The eye fixation protocol shows that these readers spent more time on sewer after the disambiguation. The readers who had less trouble initially accessing and integrating sewer, because they had been primed to interpret it as "drain," spent less time on sewer after encountering the inconsistency, spent more time on the disambiguating phrase, and were less likely to recover. This suggests that error recovery processes focus on places that contain a trace of earlier difficulties.

**Individual Differences**

Recently, we have explored how individual differences in reading skill interact with the text to determine whether a reader recovers from a misinterpretation (Daneman & Carpenter, Note 4). Our proposal is that the functional capacity of working memory plays an important role in reading comprehension performance. Traditional tests of short-term memory, such as digit span and word span tests, do not correlate with reading comprehension performance. The reason for the low correlation may be that such tests are primarily tests of passive storage capacity. For example, in a digit span test, the subject must recognize and encode very familiar digits and try to maintain some record of their order of occurrence. This traditional test reflects a view of short-term memory as primarily a storage place with a fixed number of slots, with the number varying among individuals. In contrast, current conceptions of working memory view it as having both processes and storage components (Baddeley, & Hitch, 1974; Hunt, 1978). What is needed to test the proposal regarding functional capacity was a task that requires more taxing processes, especially processes that are related to reading itself.

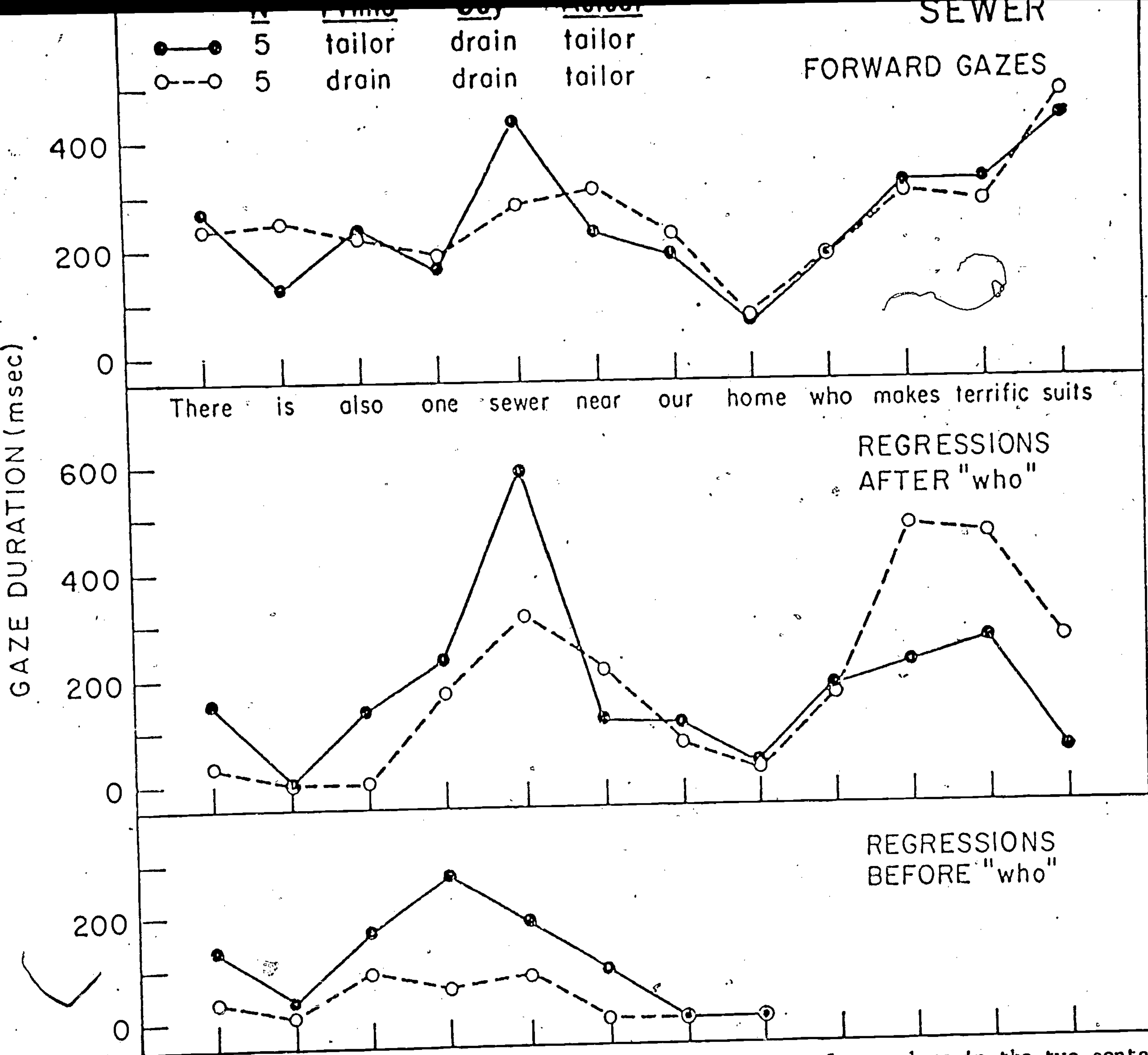


Figure 4. The mean gaze duration on each word of the sewer target sentence for readers in the two context condition .1 10 subjects initially read sewer as meaning "drain." The top panel shows the forward gazes; the middle panel shows regressions after readers fixated who; the bottom panel shows regressions before readers fixated who. (From ... Daneman, M. Lexical retrieval and error recovery in reading: A model based on eye fixations)

We developed a reading span test that includes both processing and storage components (Daneman & Carpenter, 1980). In the test, the subject reads a set of sentences and, at the end of the set, recalls the final word of each sentence. The subject's reading span is the number of sentences for which he or she can successfully recall the final words. We have found that among college students, the range of reading spans is usually 2 - 5.5 sentences. Unlike the traditional digit span and word span tests, reading span does correlate with global reading comprehension test scores; a correlation typically lies between .45 and .6 (Daneman & Carpenter, Note 3). The correlation between reading span and comprehension is even higher (.7 to .9) when the comprehension test taps specific comprehension abilities, such as the ability to answer a question about a fact mentioned in the passage or the ability to relate a pronoun to a distant prior referent (Daneman & Carpenter, 1980).

Reading span also correlates with the ability to recover from inconsistencies in garden path passages. Readers with low spans recover less often than do readers with intermediate or high spans. Poorer readers have particular difficulty if a sentence boundary intervenes between the ambiguous word and the subsequent inconsistency. For example, these poorer readers have more difficulty with There is also one sewer near our home. He makes terrific suits. than with There is also one sewer near our home who makes terrific suits. The explanation is that ends of sentences are often places where readers do additional wrap-up processes that may tax working memory and purge it of at least part of the verbatim representation (Jarvella, 1971; Just & Carpenter, 1980). The processing of a sentence boundary taxes the readers with a small working-memory capacity, making it less likely that they recover from an inconsistency whose resolution requires information from a preceding sentence.

## Parsing Processes

A central aspect of comprehension is the parsing process -- determining the syntactic and semantic roles and boundaries of sentence constituents. One major approach to parsing has been a syntactically oriented one, in which determining the syntactic roles of the words in a sentence constituted the core of comprehension (see Fodor, Bever, & Garrett, 1974; Kimball, 1973; Marcus, 1980). This approach often focuses on function words, suggesting that these words narrow the range of possible roles that an upcoming content word may play. At the other extreme is the semantic approach which emphasizes how the semantic properties of the major constituents plus schematic and pragmatic knowledge will often determine the roles of the constituents in a sentence (Schank, 1972). For example, a reader can infer the roles of boy, apple, and ate without the benefit of syntactic information. However, neither the syntactic nor the semantic approach alone is entirely satisfactory. Our research on parsing suggests that syntactic cues, semantic relations, and referential interpretation all play a role in computing the role of a constituent in a clause or sentence and determining the boundary.

**Parsing ambiguous phrases.** Detection of constituent boundaries depends in part on the ability to find a referent for the candidate constituent. This point is illustrated very clearly in a study that examined parsing processes in a translation task (McDonald & Carpenter, 1981). Bilingual translators read passages in English and translated them into spoken German as quickly as possible as they read. Embedded in the passages were idioms such as kick the bucket and hit the nail right on the head. Such phrases are of interest because they have different parsings and different interpretations depending on whether they are used idiomatically or literally. When interpreted idiomatically, each such phrase is a single constituent; when interpreted literally, each phrase has more than one constituent, such as (((hit) (the nail)) (right (on (the (head))))). We constructed passages that primed either one interpretation or the other, and found that translators produced very different patterns of eye fixations in the two cases, reflecting the different constituent boundaries of the two types of interpretations. Translators visually scanned each major constituent of a sentence twice. During the first pass, which presumably reflected English comprehension, the translators read at normal speed and paused at the constituent boundary. Then, the gaze returned to the beginning of the constituent for a second, much slower pass during which the translator output the German equivalent. The place at which the translator stopped between the first and second passes indicated how he or she parsed a segment of text.

A typical passage, one that primed a literal translation of hit the nail right on the head, described a man, David, who was having problems building a bookshelf and asked his friend, Mike, to help him: Mike picked up the hammer to show David some basic woodworking techniques. Mike hit the nail right on the head.... During the first pass, the translators scanned to the end of Mike hit the nail, stopped, and returned to the beginning of the sentence to translate it. They parsed this as a clause. However, when the context primed an idiomatic meaning, the individual words did not have plausible literal referents. In those cases, the translators did not stop and translate idioms at an internal phrase boundary; they continued until they reached the end of the idiom. The differential parsing pattern reflected in the eye fixations predicted whether the oral translation would be literal or idiomatic. The study suggests that the interpretation of such ambiguous phrases is determined as the phrase is read, as part of the reader's attempt to integrate the currently processed information with the preceding representation.

**Specific heuristics.** We are currently exploring the interaction of syntactic and semantic information in some specific parsing heuristics (Carpenter & McDonald, Note 5). Our initial research has focused on the words before and after, which can be prepositions or conjunctions. As a preposition, before introduces a phrase that modifies the immediately preceding verb phrase; (e.g. He stood before the jury). The prepositional phrase is "right-attached" to the verb phrase in a tree structure diagram. As a conjunction, before introduces a new clause (e.g. He stood before the jury entered). According to one parsing theory, the right-attachment interpretation is preferred, because it results in a simpler structure (Frazier & Fodor, 1978; Kimball, 1973). However, according to the READER model, the preceding context should interact with this syntactic bias to determine which intepretation is chosen.

The experiment that examined the parsing processes used the garden path procedure, priming one interpretation of an ambiguous word and later presenting confirming or inconsistent information. The stimulus set is illustrated by the sentence in the opening passage of this chapter, which discussed where the student would sit, Resignedly the student sat before the avunular professor in the rumpled suit entered. A reader who made the preposition interpretation should spend more time on entered than one who made a conjunction interpretation. The subjects read texts using the button-pressing paradigm described earlier. This paradigm provides a measure of processing time for a word or phrase. It also forces the reader to rely exclusively on working memory to recover from an inconsistency, because the previous words are not visually available. We assessed the readers' ultimate interpretation by asking comprehension questions about the target sentence after the passage had been read.

Both the reading times and question-answering data showed that readers had a strong bias to interpret words in accordance with the principle of right-attachment but that contextual and semantic cues could modify the interpretation. In addition, the effects were found early in the inconsistent phrase, suggesting that the syntactic analysis does not lag behind the word being fixated.

**An overview of parsing effects.** Parsing difficulties have a large effect on performance in experiments that intentionally make the syntactic assignments difficult. They are also reliably found in normal texts, such as the scientific texts. However, the parsing effects in naturally-occurring texts are generally small, and account for much less of the variance than do the variables that affect encoding and lexical access. This suggests that parsing processes are concurrent with other processes that are longer or more variable in duration, so that parsing effects are not visible under most circumstances. Nevertheless, an analysis of certain systematic parsing effects has revealed some parsing procedures and suggested that they differ from a popular syntactically based parser, the Augmented Transition Network (ATN).

One parsing effect in the scientific texts was that readers spent less time on nouns that contained multiple modifiers, such as <u>red fire ant</u>. On the first occurrence, readers spent a relatively long time on <u>ant</u>; however, on subsequent occurrences, the average gaze duration was considerably shortened. One explanation is that the reader could begin constructing a referent for the noun phrase as soon as one or two modifiers were read, such as the words <u>red fire</u>, and it was not necessary to wait for the entire phrase. This strategy differentiates human parsing schemes from those proposed by ATNs. As an ATN grammar processes a constituent, it puts the components on a push-down stack until the end of the constituent is reached, at which point it "pops" the stack and processes the entire constituent. This model would suggest that, if anything, nouns that are modified would take longer, since the reader would process the noun and its modifiers after encountering the noun. However, the reading time data suggest that this hypothesis is incorrect and that readers attempt to process constituents as soon as possible, sometimes before the last part of the noun phrase is fixated.

Other parsing effects were found if a phrase caused some momentary difficulty. For example, in the phrase <u>Flywheels are one...</u>, readers pause longer than would be expected on <u>one</u>, presumably because it is inconsistent in number with the plural subject and verb.

READER's parsing processes were developed to simulate the human reading data (Thibadeau et al., Note 2). READER attempts to parse constituents, interpret them, and assign them to referents as soon as possible. It has about 130 productions that constitute the parsing routines for the passage. About 30 of these productions are a "core parser" that is robust over passages. The semantic productions do a conceptual dependency analysis (Schank, 1972), while the syntactic productions analyze the sequential aspects of the surface structure. While READER does not have a complete parser for English, we see no inherent obstacles to expanding READER, while maintaining the qualitative features of its design.

## End of Sentence Processing

While it is clear that readers attempt to interpret words as they are encountered, there also is evidence that some processes are executed at ends of sentences. We have labeled this the sentence wrap-up effect. One source of evidence came from a study in which the texts involved verb-based inferences (Just & Carpenter, 1978). For example, one set of readers received a text that described the discovery of the body of a millionaire who had died. Another group read that he had been killed. Both groups read a later sentence that described the search for the murderer. The first group of readers took longer to read the sentence involving murderer, because they had to make a more difficult inference to relate died and murderer. Part of the longer reading time for the later sentence was localized to the word murderer itself, agreeing with the immediacy assumption. However, part of the extra reading time was spent at the end of the sentence. End of sentence effects were also evident in the processing of garden path sentences with ambiguous words like sewer and bass (Carpenter & Daneman, 1981). Readers sometimes initiated regressions after the first inconsistent word, but at other times, not until the end of the sentence. In some instances, they may have expected that the rest of the sentence would resolve the difficulty. We also found end of sentence effects in the scientific passages (Just & Carpenter, 1980). Finally, end of sentence effects were found in a study involving narrative texts, but only in those sentences that involved a switch in surface topic from the preceding sentence (Dee-Lucas et al., in press).

All the evidence cited above for wrap-up processes at ends of sentences has come from correlational studies, in which the effects of other variables such as normative word frequency and word length were statistically controlled using multiple linear regression. Recently, we have also assessed end of sentence effects in an experimental study (Daneman & Carpenter, Note 4). The experiment used texts that were identical up to the sentence boundary. For example, one text was He found a bat. It was very large and..., and the comparison text was He found a bat that was very large and .... In one set of conditions, the target word was ambiguous (such as bat); in another set of texts, the target was an unambiguous control word, but one that constituted a topic switch (like bird). The sentences were presented word by word in the button-pressing paradigm described earlier. There was a significant increase in the time on a word that occurred at the end of a sentence, compared to the time on the same word when it was not sentence terminal. The size of the effect was between 150 to 200 msec in the silent and oral reading conditions, respectively. Thus, sentence wrap-up effects can be relatively large.

End of sentence effects appear to occur if a sentence contains an extra processing burden. In the scientific passages, the additional processing was caused by the large proportion of novel and important concepts. In the narrative passages, additional processing was required when a sentence introduced a new topic. In the garden path experiments, the extra processing was caused by the ambiguity and the error recovery. By contrast, we have examined other texts and tasks in which readers do not spend extra time at the end of sentences. The texts had a relatively low proportion of novel concepts and described very predictable events (Just, et al., Note 1). This contrast suggests that ends of sentences themselves do not necessarily require additional processes and that they may only be places to finish up integrative processes that could not be completed in mid-sentence. Furthermore, task requirements and individual differences in functional working memory capacity may also affect the probability of some wrap-up processes being held over until the end of the sentence.

## Schemas and Inferential Processes

Comprehension depends only in part on the information provided by the text itself; the reader also uses his or her knowledge of the topic. READER makes use of a schema, a frame and slot structure, to organize the information from the scientific texts. Since READER has been developed to comprehend a scientific exposition, READER's schema is specific to this domain. Nevertheless, the general principles of what kind of information is stored and how it is used may be more widely applicable.

To read a passage, READER uses a schema called the Mechanism schema, which specifies the kinds of information a reader expects to find about man-made devices and biological mechanisms as they are used by human or animal agents. The schema consists of slots that specify the general types of information to be expected, and the slots are filled in the course of comprehension. For example, one slot is that of the mechanism's Name. Another slot is its Goals, which specify the end state that the mechanism is used to achieve. A third slot is for the Principles that relate the mechanism's physical properties and actions to its goals. Another slot is the Exemplar slot, which contains specific instances of the mechanism.

READER attempts to match what it is reading with the schema slots. One way this is done is by making inferences on the basis of the sentence-level representations. For example, if a sentence describes something as a purpose or goal, READER can relate this information to its Goals slot. In other cases, READER must make inferences based on probable categories of information and specific cues in the text. Finally, some slots may be filled with default values; if the text does not specify some particular piece of information, READER will assume a likely filler.

Human readers tend to spend different amounts of time on different kinds of information in a schema. For example, we found that readers spend extra time on relatively important pieces of information, like Names and Goals, relative to Exemplars. This is time above and beyond that accounted for by the word-level variables (Just & Carpenter, 1980). The explanation is that readers use this additional time to ensure that such information is correctly encoded and will be accessible in memory for later recall.

READER mimics this aspect of human reading. As successive words of a text are encountered, they are evaluated as a potential basis for action by all the productions, including those that attempt to fit the new information into schema slots. The schema-level integration actions are actually evoked as soon as enough of the sentence has been processed to indicate how it fits into the schema. The place where the schema production will be evoked depends on the sentence wording and structure. Sometimes, an entire clause or sentence must be read to determine its relation to the schema. At other times, an arbitrary word within the sentence-structure will evoke the production. This is consistent with the results reviewed earlier that integrative processes sometimes occur at the end of the sentence and at other times within the sentence itself (Carpenter & Just, 1977; Dee-Lucas et al., in press).

## Conclusions

The general characteristics of human reading are compatible with the overall theory of the processing architecture embodied in CAPS, and the specific results we have obtained can be accounted for by the READER model. The immediate, collaborative nature of the processes in READER captures important features of human reading. The scope of the model, from perceptual to schema-level processes is sufficiently broad to accommodate many other temporal properties of human reading. The specific mechanisms of encoding, lexical access, parsing, and integration are compatible with a variety of detailed empirical results. The research also illustrates the advantage of using eye fixations to study the conceptual aspects of reading, in addition to the more commonly studied perceptual and motor aspects. In this section we discuss some of the issues that arise in using our research approach and suggest directions for the next generation of improvements.

### The Gaze Duration Measure

The main dependent variable in the studies we have discussed is mean gaze duration on each word. This measure is appropriate to the grain of the theory. The theory focuses on the comprehension processes that operate at a conceptual level that roughly corresponds to the word, although the theory also involves processing units at levels corresponding to letters, subword units, phrases, clauses, sentences, and schemas. But it is at the level of the word that the main semantic information is indexed. Measuring the processing time on each word simplifies the analysis of effects presumed to affect word-level processes. Previous efforts to relate cognitive processes to smaller units of behavior such as individual fixations have been far less successful (e.g., Gaarder, 1975). Moreover, processing times on larger units can easily be derived from word gaze durations simply by aggregating over durations on individual words. In general, the compatibility between the theory and the performance measure in their unit of analysis is probably a major determinant of the success of a detailed modeling enterprise.

### Immediacy and Eye-Mind Revisited

The immediacy and eye-mind assumptions address two issues that have been important to reading theories. The first issue concerns the possible delay between the perceptual and cognitive systems. Some theorists have argued that because of saccadic suppression and the necessity for programming subsequent fixations, the cognitive system probably does not operate on the input of the perceptual system soon enough to influence either the duration of the current fixation or the location of the next. Our own research shows that this is not true; the currently fixated word does influence the time spent on that word, either by increasing the fixation duration or influencing where the next fixation is made (on the same word or on other words).

The second issue concerns the processing of information in units larger than words, which we will refer to as <u>bins</u>. By binning we mean collecting input from several words before processing any one of them. When a bin is filled, either all its constituents are processed, or in a moving bin strategy, only some of the earliest constituents are processed. At the perceptual level, words could be binned by being visually chunked or grouped before being encoded. At the cognitive level, word concepts could be grouped or binned before being interpreted. Positions related to each of these levels have been espoused by various researchers.

One example of a cognitive binning strategy is the "look ahead" strategy of Kimball (1973) and Marcus (1980), who have proposed that readers look one or two words ahead before deciding the syntactic status of a given word. Looking <u>N</u> words ahead of the word at issue means using a moving bin of size <u>N+1</u>. Kimball's scheme has another level of bins as well. Once a word's syntactic status is determined, it is held in a buffer (bin) until the current phrase is complete, at which time it along with the other constituents of the phrase are shunted off for semantic processing. Similarly, it has been suggested that clauses are the functional unit in language processing and that clause boundaries are important enabling conditions for syntactic and semantic analyses (Fodor, Bever, & Garrett, 1974). Buffering the words of a phrase or clause before analyzing them is an instance of using a variable size stationary bin.

Bouma and deVoogd (1974) have argued for both perceptual and cognitive bins on the grounds of empirical evidence they have collected. They found that readers' self-reported ability to comprehend a text was unaffected by a wide range of variation in the spatial and temporal arrangement of the words. They presented a few words of a text at a time, varying both the number of words per display and the duration of the display. Bouma and deVoogd concluded that the processing was impervious to the temporal distribution of the input because the words were being buffered before being cognitively processed. One binning mechanism might be an iconic store that allows the cognitive system to lag behind the perceptual system by about two words. Another binning mechanism might be a store in which activated word meanings are held until a lagging syntactic or semantic analysis operates on them. One problem with the results of this experiment is that although subjects reported being able to comprehend the text, they were unable to do so if they expected a comprehension test at the conclusion of the reading. This suggests that the comprehension was unusual, at best, and grossly below normal, at worst. Thus, it is very unclear that the critical criterion of actually being able to comprehend was satisfied in this experiment.

The immediacy of the effects in our data (i.e. the gaze duration response occurs on the very word that provides the stimulus) suggests that mandatory binning does not occur. Interpretive processes of all levels occur as soon as they are enabled. Lower level processes are usually enabled as soon as the word is encoded. However, the point at which higher level integrative processes are enabled is unpredictable. But if the higher level processes are possible to execute immediately (i.e. without the benefit of information to follow), then they <u>are</u> executed immediately. This finding clearly shows that binning is not mandatory or fixed.

Contextual influences on immediacy can be illustrated with any word whose interpretation partially depends on another word which has not yet occurred. For example, the extensive meaning of the adjective large cannot be computed without knowing what concept it modifies, (e.g. large insect versus large house). A reader might have to wait until he reads the head of the noun phrase to know what large modifies, in which case the extensive interpretation would not be immediate. Alternatively, a reader could guess the referent on the basis of the previous context. If a passage repeatedly referred to a large house, even the extensive meaning of large might be computed immdiately on fixating the word large. The immediacy assumption states that the interpretation of the current word is computed as soon as possible, rather than routinely waiting until all possibly relevant information from succeeding words has been collected.

What the various bin theories have failed to recognize is that very often the interpretation of a word can be computed immediately. By focusing on sentences out of context, these theories have failed to appreciate that the semantic and pragmatic context, plus biases constructed over years of a person's language use, make the reader's interpretations correct much more often than incorrect. By focusing on infrequent sentence types, they have failed to discover the default strategy of immediate interpretation that succeeds on most sentence types.

## Mental Chronometry in Comprehension

The studies reported in this chapter have shown that analyses of the temporal characteristics of comprehension are useful in modeling the underlying processes. Chronometric techniques, including the study of gaze durations and word and sentence reading times in subject-paced presentations, allow for monitoring the comprehension processes as they occur, rather than making inferences about comprehension on the basis of memory-based measures, such as recall, recognition, or question answering. But the primary limitation of chronometric techniques is that they do not reveal the content of the comprehension processes. That must come from another source, either another methodology (such as computer simulation) or the intuitions of the researcher. The content of comprehension refers to what inference the reader made, what interpretation he gave an ambiguous word, what information he took to be the topic, and so forth. The methodologies that give the most insight into these involve qualitative measures, such as oral reading, recall, recognition, and question answering performance. The weaknesses of each methodology can be partially compensated by using it in concert with other methods with complementary properties and converging results. Thus, it is important not only to trace the eye movements of a reader, but also to determine what he understood, and what he can remember or reconstruct. A theory of reading should account for both the time course of the on-line processes, as well as the products of those processes.

## Reference Notes


1. Just, M. A., Carpenter, P. A., & Masson, M. Eye fixations and cognitive processing during rapid reading. Pittsburgh, PA: Carnegie-Mellon University, 1981.

2. Thibadeau, R., Just, M .A., Carpenter, P. A. A model of the time course and content of human reading. Pittsburgh, PA: Carnegie-Mellon University, 1981.

3. Daneman, M., & Carpenter, P. A. Developmental differences in reading and detecting semantic inconsistencies. Pittsburgh, PA: Carnegie-Mellon University, 1981.

4. Daneman, M., & Carpenter, P. A. The functional role of working memory in recovering from semantic inconsistencies. Pittsburgh, PA: Carnegie-Mellon University, 1981.

5. Carpenter, P. A., & McDonald, J. L. Syntactic and semantic influences in parsing ambiguous phrases. Pittsburgh, PA: Carnegie-Mellon University, 1981.

# References


Baddeley, A. D., & Hitch, G. Working memory. In G. H. Bower (Ed.), The psychology of learning and motivation (Vol. 8). New York: Academic Press, 1974.

Bouma, H., & deVoogd, A. H. On the control of eye saccades in reading. Vision Research, 1974, 14, 273-284.

Carpenter, P. A., & Daneman, M. Lexical retrieval and error recovery in reading: A model based on eye fixations. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 137-160.

Carpenter, P. A., & Just, M. A. Reading comprehension as eyes see it. In M. A. Just, & P. A. Carpenter (Eds.), Cognitive processes in comprehension. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1977.

Daneman, M., & Carpenter, P. A. Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior, 1980, 19, 450-466.

Dee-Lucas, D., Just, M. A., Carpenter, P. A., & Daneman, M. What eye fixations tell us about the time course of text integration. In R. Groner, & P. Fraisse (Eds.), Cognition and eye movements. Amsterdam: North Holland and Berlin: Deutscher Verlag der Wissenschaften, in press.

Fodor, J. A., Bever, T. G., & Garrett, M. F. The psychology of language: An introduction to psycholinguistics and generative grammar. New York: McGraw-Hill Co., 1974.

Frazier, L., & Fodor, J. D. The sausage machine: A new two-stage parsing model. Cognition, 1978, 6, 291-325.

Gaarder, K. R. Eye movements, vision and behavior. Washington, D.C.: Hemisphere Publishing Corporation, 1975.

Hunt, E. Mechanics of verbal ability. Psychological Review, 1978, 85, 109-130.

Jackson, M. D., & McClelland, J. L. Sensory and cognitive determinants of reading speed. Journal of Verbal Learning and Verbal Behavior, 1975, 14, 565-574.

Jarvella, R. J. Syntactic processing of connected speech. Journal of Verbal Learning and Verbal Behavior, 1971, 10, 409-416.

Just, M. A., & Carpenter, P. A. Inference processes during reading: Reflections from eye fixations. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), Eye movements and the higher psychological functions. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1978.

Just, M. A., & Carpenter, P. A. A theory of reading: From eye fixations to comprehension. Psychological Review, 1980, 87, 329-354.

Kimball, J. P. Seven principles of surface structure parsing in natural language. Cognition, 1973, 2, 15-47.

Marcus, M. P. A theory of syntactic recognition for natural language. Cambridge, MA: The MIT Press, 1980.

McDonald, J. L., & Carpenter, P. A. Simultaneous translation: Idiom interpretation and parsing heuristics. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 231-247.

Newell, A. Harpy, productions systems and human cognition. In R. Cole (Ed.), Perception and production of fluent speech. Hillsdale, N.J.: Lawrence Erlbaum Assoc., 1980.

O'Regan, K. Moment to moment control of eye saccades as a function of textual parameters in reading. In P. A. Kolers, M. E. Wrolstad, & H. Bouma (Eds.), Processing of visible language (Vol. 1), New York: Plenum Press, 1979.

Pynte, J. Readiness for pronunciation during the reading process. Perception and Psychophysics, 1974, 16, 110-112.

Rayner, K. The perceptual span and peripheral cues in reading. Cognitive Psychology, 1975, 7, 65-81.

Rayner, K. Visual attention in reading: Eye movements reflect cognitive processes. Memory and Cognition, 1977, 5, 443-448.

Rayner, K. Eye movements in reading: Eye guidance and integration. In P. A. Kolers, M. E. Wrolstad, & H. Bouma (Eds.), Processing of visible language (Vol. 1), New York: Plenum Press, 1979.

Schank, R. C. Conceptual dependency: A theory of natural language understanding. Cognitive Psychology, 1972, 3, 552-631.

Sechrest, L., & Yeaton, W. E. Estimating magnitudes of experimental effects. Unpublished manuscript, Florida State University, 1979.

Simpson, G. B. Meaning dominance and semantic context in the processing of lexical ambiquity. Journal of Verbal Learning and Verbal Behavior, 1981, 20, 120-136.

Swinney, D. A. Lexical access during sentence comprehension: (Re)consideration of context effects. Journal of Verbal Learning and Verbal Behavior, 1979, 18, 645-659.

# Footnotes

[1] This research was partially supported by Grant G-79-0119 from the National Institute of Education and Grant MH-29617 from the National Institute of Mental Health.

Meredyth Daneman, Diana Dee-Lucas, Janet McDonald and Robert Thibadeau collaborated in many aspects of the research reported here and their contributions are gratefully acknowledged.

[2] We have described the encoding process as though only the word to the right can be processed and not the word to the left. Evidence suggests that such a bias is present in readers of English, at least for content words.