Working Memory in Text Comprehension: Interrupting Difficult Text

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Abstract

We compare the effects of interrupting text dealing with familiar or unfamiliar domains with either arithmetic or sentence reading tasks. Readers were interrupted after each of the eight sentences, at the end of each sentence, or in the middle of each sentence. Previous findings of minimal effects of interruptive tasks on comprehension measures (e.g., Glanzer & Nolan, 1986) were replicated in this study. Also, as found by Glanzer and his colleagues, interruptions after each sentence of a familiar text by an unrelated sentence increased reading times by approximately 400 ms per sentence. In contrast, for difficult, unfamiliar texts, mid-sentence interruptions significantly lengthened reading times by 1262 ms for sentence and 1784 ms for arithmetic interruptions. These findings are explained in terms of Ericsson and Kintsch's (1995) memory model which proposes that skilled memory performance relies on the use of long-term memory as an extension of working memory, or long-term working memory.

Introduction

Reading is by its very nature sequential. The glue of memory is needed, therefore, to hold the various elements of the sequence together. The eye moves from word to word, and in general each word is integrated with the previous ones as rapidly as possible (e.g., Just & Carpenter, 1987). According to Kintsch and van Dijk's (1978) model of text comprehension, sentences or phrases also form processing units, which are linked together via a short-term memory buffer. Evidence for the operation of such a buffer has been obtained in various experiments (e.g., Fletcher, 1981; Glanzer & Razel, 1974). However, reading comprehension is still possible when the use of the short-term memory buffer is prevented. For instance, Glanzer and his colleagues (e.g., Fischer & Glanzer, 1986; Glanzer, Dorfman, & Kaplan, 1981; Glanzer, Fischer, & Dorfman, 1984; Glanzer & Nolan, 1986) have used an interruption procedure to interfere with short-term memory processes during reading. They did this by inserting unrelated material (e.g., unrelated sentences or arithmetic problems) after each sentence of a paragraph. The purpose of the intervening material was to interfere with the short-term retention of the just-read sentence. This interruption procedure produced far from dramatic effects. Although reading time for the next sentence in the paragraph was slowed by 300-400 ms, comprehension was totally unaffected.

Since the intervening sentence (or arithmetic problem) certainly must have interfered with integration processes in the short-term memory buffer, Glanzer's subjects must have found some way to continue reading without the use of that buffer. Glanzer and his colleagues interpreted their results as evidence that readers have access to a verbatim memory trace of the text, even after an interruption, that allows them to resume normal processing. An alternative explanation of Glanzer's findings is provided by a recent theory of memory proposed by Ericsson and Kintsch (1995). Accordingly, subjects' ability to successfully read and comprehend interrupted text is attributable to the use of *long-term working memory*. Ericsson and Kintsch assert that skilled memory performance such as reading relies on the use of long-term memory as an extension of working memory (i.e., consciousness or focus of attention). Information in long-term memory that is linked by retrieval structures to cues in working memory forms an extended, long-term working memory. The theory of long-term working memory maintains that all material in long-term memory that is connected via retrieval structures to cues available in working memory is directly accessible via a single retrieval operation.

Retrieval structures are generated during comprehension as an integral part of the comprehension process. Comprehension consists of forming mental representations (textbases and situation models in the theory of van Dijk & Kintsch, 1983) which connect the various elements of the text representation in network-like structures. Thus, generating a text representation in itself creates a retrieval structure. Each successive sentence of a coherent text normally contains retrieval cues, such as related or repeated information (i.e., argument overlap), that provide access to that structure. Hence, the whole previous text structure is but a single retrieval operation away. Retrieval from long-term memory, if the retrieval cues are present in short-term memory, takes about 400 ms (e.g., Anderson, 1990; Yu et al., 1985). Indeed, Glanzer's interruption procedure costs the reader no more than a single retrieval operation, that is, about 400 ms.

A long-term working memory (Ericsson & Kintsch, 1995) explanation of the results obtained with the interruption procedure used by Glanzer (e.g., Glanzer & Nolan, 1986) implies that more serious disruptions of reading should be found (a) if there are no retrieval structures available, or (b) if there are no retrieval cues accessible in short-term memory. In the present experiment, an attempt

was made to prevent, or at least interfere with, the formation of retrieval structures during comprehension. For this purpose, the interruption procedure used by Glanzer was elaborated in two ways. First, in one condition, sentences were interrupted in mid-sentence rather than at the end. Since the sentence is incomplete at this point, it is more likely that the partially constructed mental representation would not connect to the earlier portion of the text. Second, for some subjects, difficult texts from unfamiliar domains were used instead of easy, familiar texts. Since the construction of a situation model is strongly dependent on the availability of relevant background knowledge, the use of unfamiliar texts further decreases the likelihood that a workable retrieval structure can be generated. Neither one of these manipulations will completely prevent readers from some understanding -- even difficult half-sentences will be understood to some degree. Nevertheless, a significant deterioration of understanding would be expected. To the degree that this happens: (a) no retrieval structure will be available; (b) the succeeding sentence fragment will not reinstate the previous text in long-term working memory with a single, 400 ms retrieval operation; and (c) more complex, time consuming, retrieval processes (e.g., deliberate search, construction of retrieval cues) will be required. If these retrieval processes are not successful, comprehension difficulties as well as longer reading times will result. If, on the other hand, these retrieval processes are successful, the reading time for the second sentence half will be lengthened by more than 400 ms.

Method

Subjects and Design

The subjects were 72 undergraduate students at the University of Colorado who participated for course credit. A 2 x 2 x (3) mixed factorial design was employed, with two between-subjects factors, text domain (familiar, unfamiliar) and interference task (sentence, arithmetic), and one within-subjects factor, interruption type (control, end, middle). Eighteen subjects were assigned to each of the four between-subjects conditions.

To obtain a more sensitive test of comprehension, a free recall test was used in the present experiment instead of comprehension questions, as in the original work by Glanzer and his collegues.

Apparatus and Materials

Text. The texts were presented either with Zenith Data Systems or IBM/PC computers. The experimental texts included ten paragraphs comprised of eight sentences, as well as 100 unrelated sentences obtained from various sources (e.g., encyclopedias, journals, books). The paragraphs were from domains that according to pilot studies were either highly familiar to undergraduate students (e.g., "body fat") or quite unfamiliar (e.g., "Fourier transformations"). Some of the paragraphs were reworded or altered to improve coherence or reduce length. The mean number of words per sentence for the familiar paragraphs, unfamiliar paragraphs, and unrelated sentences were 18.47, 16.12, and 17.02 words, respectively. Unrelated sentences were presented in random order, and each sentence was presented only once during an experimental session.

Arithmetic problems. The problems presented to the subjects in the arithmetic condition were presented in three possible randomly chosen formats: addition, subtraction, or multiplication. The integers of the arithmetic problems were randomly chosen with constraints so that all answers to the three types of problems consisted of two or three digits.

Interruption types. There were three interruption types: control, end, and middle. A total of 10 interference tasks (i.e., 10 unrelated sentences or 10 arithmetic problems) were presented in all three conditions. The procedure of the control and end conditions replicated that reported by Glanzer and his colleagues (e.g., Glanzer & Nolan, 1986). In the control condition, the paragraph sentences were presented in immediate succession, followed by a block of 10 interference tasks. In the end interruption condition, each sentence was followed by 1 interference task, except for the last sentence, which was followed by the remaining 3 interference tasks.

In the middle interruption condition, each sentence was interrupted in the middle by an interference task; the remaining 2 interference tasks then followed the last sentence of the paragraph. The interruption was placed between the subject and verb of the sentence, with the constraint that no fewer than three words (and at least two content words) preceded the break in the sentence. Sentences which began with "It is" were interrupted at a point such that there was an equal number of words in each of the two parts. If there were two equally important verbs in the sentence, the interruption was placed before the verb which resulted in the most equal division in the number of content words in the sentence. An example of a text from an unfamiliar domain with the interuption locations indicated with asterisks is presented below in Table 1.

Metamorphic rocks are those that remain in the solid state ** while being changed by heat and/or pressure, with or without overall chemical change.
Most metamorphic rocks crystallize under stress, ** resulting in characteristic foliation or parallelism of the constituent grains, especially micas.
The contact metamorphic rocks, however, more commonly ** form without deformation, resulting in a massive texture.
Their proximity to a heat source and their characteristic spotted appearance resulting from the growth of new minerals ** aid in their recognition.

Table 1: Text example from an unfamiliar domain with asterisks marking the break for the middle interruption condition. *Only the first four of* the eight text sentences are shown.

Procedure

Subjects were tested individually. All subjects read a series of 10 paragraphs, each consisting of 8 sentences. The first was a practice paragraph, presented in the middle condition. The remaining 9 paragraphs were equally distributed across the three conditions according to a Latin-square design and presented in a random order.

Subjects were instructed to read the texts at their normal reading pace and not to attempt to memorize the sentences. Subjects read aloud both the texts and the interference tasks. Subjects were told that interruptions, either arithmetic problems or unrelated sentences, would occur alternatively after the last sentence in the paragraph, between each sentence in the paragraph, and in the middle of each sentence. They were informed that after they had read all of the sentences in a paragraph, they would be asked to write down as much of the text as they could remember. In the sentence interference task condition they were asked to recall both the sentences from the paragraph and the unrelated sentences.

The subjects in the arithmetic interference condition were allowed to use paper and pencil to solve the problems. As soon as an answer to the problem was entered, the next sentence of the text was presented. If they answered a problem incorrectly in less than 30 seconds, they were instructed on the computer monitor that their solution was incorrect and to try again; after 30 seconds, they were informed that the answer was incorrect and were presented with the next sentence of the text.

Results

Text Recall

For the purpose of scoring recall protocols each text was divided into idea units. For each unit subjects were given 1 point if they recalled the main gist of the unit and half of a point if they recalled only a fraction of the idea unit. An analysis of variance was performed on proportion recall including the two between-subjects factors, text domain (familiar, unfamiliar), and interference task (sentence, arithmetic), and one within-subjects factor, interruption type (control, end, middle). There was a main effect of the familiarity of the text, $F(1,68) = 61.2$, $p < .001$, reflecting greater recall for the familiar text ($\underline{M} = 0.30$) than for the unfamiliar text ($\underline{M} = 0.16$). There was also a main effect of interference task, $F(1,68) = 42.0$, $p < .001$, reflecting greater recall when the texts were interrupted by the math problems ($\underline{M} = 0.29$), than by the sentences ($\underline{M} = 0.18$). The interaction between text and interference task was not statistically significant, $F(1,68) = 2.1$, $p = .157$. There was no effect of interruption type, $F(2,67) < 1$, nor did interruption type interact with either of the between-subjects variables. Thus, subjects recalled the same amount of text regardless of whether the interference tasks occurred at the end of the paragraph ($\underline{M} = 0.23$), at the end of each sentence ($\underline{M} = 0.24$), or in the middle of each sentence ($\underline{M} = 0.24$).

In summary, subjects recalled more from the familiar than the unfamiliar texts, and recalled more when the texts were interrupted by the math problems than by sentences. These results were not affected by interruption types, and interruptions had no effect on text recall.

Sentence reading time

Sentence reading times by text domain (familiar, unfamiliar), interference task (sentence, arithmetic), and interruption type (control, end, middle) are presented in Table 2. An analysis of variance was performed on sentence reading times including the two between-subjects factors, text domain (familiar, unfamiliar), and interference task (sentence, arithmetic), and the two within-subjects factors, interruption type (control, end, middle), and sentence position (sentence 1- sentence 8). Neither text domain, $F(1,68) < 2$, nor interference task, $F(1,68) = 2.4$, $p = .126$, nor the interaction of the two, $F(1,68) < 1$, had reliable effects on sentence reading times.

	Familiar Text	
	Sentence	Arithmetic
Control	8.700	9.785
End	9.110	10.785
Middle	9.243	10.917
	Unfamiliar Text	
	Sentence	Arithmetic
Control	9.642	10.028
End	9.891	10.887
Middle	10.904	11.812

Table 2: Average sentence reading times in seconds by text (familiar, unfamiliar), interference task (sentence, arithmetic), and interruption condition (control, end, middle).

There was, however, a significant main effect of interruption type, $F(2,67) = 21.2$, $p < .001$. This finding reflects both longer sentence reading times for sentences interrupted in the middle ($\underline{M} = 10.72$ s), compared to both the end and control interruption conditions ($\underline{M} = 9.85$), $F(1,68) = 25.6$, $p < .001$, and longer sentence reading times for those interrupted at the end of each sentence ($\underline{M} = 10.17$) compared to those which were not interrupted at all ($\underline{M} = 9.54$), $F(1,68) = 12.0$, $p < .001$. Thus, the average interruption effect (i.e., the overall increase in reading time compared to the control condition) was 1180 ms when the sentences were interrupted in the middle, versus 630 ms when the sentences were interrupted at the end. Neither text domain, $F(2,67) = 2.5$, $p = .095$, nor interference task, $F(2,67) < 2$, reliably interacted with interruption type. However, a planned-comparison test showed that the contrast

between the middle interruption and the two other interruption types (i.e., control and end) interacted significantly with text, $F(1,67) = 5.0$, $p = .030$, reflecting the finding that the middle interruption had a greater effect on reading time for the unfamiliar texts than for the familiar texts (see Figure 1). The contrast orthogonal to this comparison, between the end and control interruption conditions, did not reliably interact with text familiarity, $F(1,68) < 1$.

In summary, for familiar texts interrupted by sentences, we found a 410 ms increase in reading time. This result, in conjunction with our finding little effect of interruptions on recall, replicates Glanzer's earlier findings. We also found that interrupting sentences in the middle had a greater impact on reading times than did interrupting at the end of the sentence. Moreover, this difference depended on the familiarity of the texts -- subjects' reading times were most affected when reading unfamiliar texts with an interruption in the middle of each sentence.

There was also a significant main effect of sentence position, $F(7,62) = 34.8$, $p < .001$, reflecting greater sentence reading times for the sentences at the beginning than at the end of the paragraph. Sentence position did not reliably interact with interference task, $F(7,62) < 2$, nor with interruption type, $F(14,55) < 2$, but did significantly interact with text familiarity, $F(7,62) = 12.8$, $p < .001$. As can be seen in Figure 2, which presents sentence reading times for unfamiliar and familiar texts, it takes longer to read sentences at the beginning of a text dealing with an unfamiliar domain than with an easier, more familiar text domain, whereas these differences diminished towards the end of the paragraph.

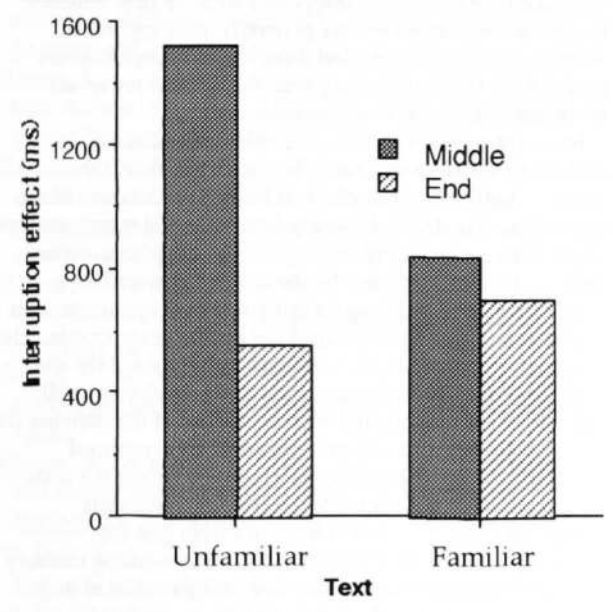

Figure 1: Interruption effects in reading time (i.e., difference from control reading times) for the middle and end interruption conditions by text (averaged over the arithmetic and sentence interference task conditions)

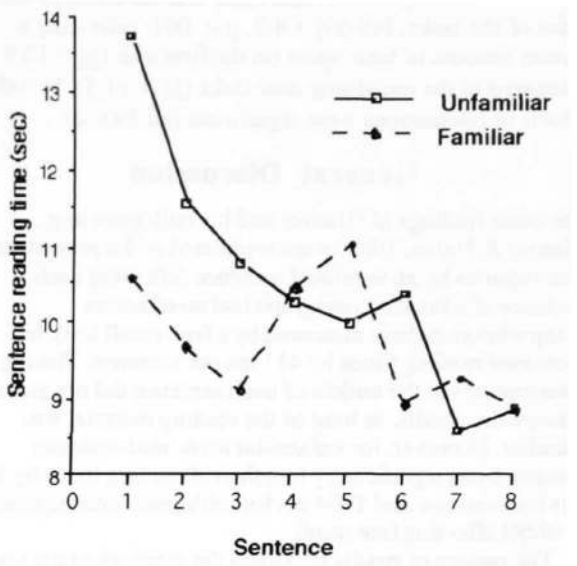

Figure 2: Sentence reading times by text.

For the condition in which sentences were interrupted in the middle, we were interested in whether there were differences in reading time for the two parts of the sentence. The beginning of the sentence was uninterrupted, and thus should take less time to read, than the second, interrupted part of the sentence. We were also interested in whether this difference was augmented by the familiarity of the text or by the type of interference task. A separate analysis of variance was performed for only the middle interruption condition including two between-subjects factors, text domain and interference task, and one within-subjects factor, sentence part (interrupted, uninterrupted). There was neither a main effect of text, $F(1,68) = 2.7$, $p = .110$, nor an effect of interference task, $F(1,68) = 2.7$, $p = .106$. As predicted, there was an effect of sentence part, $F(1,68) = 89.8$, $p < .001$, reflecting shorter reading times for the beginning of the sentence ($\underline{M}$ = 4770 ms) than for the last interrupted part of the sentence ($\underline{M}$ = 5949 ms). This difference did not depend on the familiarity of the text, $F(1,68) < 1$, but did interact with the type of interference task, $F(1,68) = 12.7$, $p < .001$. It took longer to read the second part of the sentence following an arithmetic task ($\underline{M}$ = 6494 ms) than after reading an unrelated sentence ($\underline{M}$ = 5404 ms). These results indicate that the effect of the middle interruption task is greatest for the clause following the interruption, and that this increase is augmented for the arithmetic task compared to the sentence reading task.

Interference tasks

An analysis of variance was performed on task completion times including the two between-subjects factors, text domain, and interference task, and two within-subjects factors, interruption type, and task order (1-10). The mathematics problems required significantly more time to complete ($\underline{M}$ = 14.8 s) than the sentences ($\underline{M}$ = 8.4 s),

$F(1,68) = 153.5$, $p < .001$; and there was an effect of the order of the tasks, $F(9,60) = 4.2$, $p < .001$, reflecting a greater amount of time spent on the first task ($\underline{M} = 12.9$ sec) compared to the remaining nine tasks ($\underline{M} = 11.5$). No other effects or interactions were significant (all $Fs < 2$).

General Discussion

The main findings of Glanzer and his collegues (e.g., Glanzer & Nolan, 1986) were replicated in the present study: Interruptions by an unrelated sentence following each sentence of a familiar paragraph had no effect on comprehension (here measured by a free-recall test), but increased reading times by 411 ms per sentence. Placing the interruptions in the middle of each sentence did not greatly change the results, as long as the reading material was familiar. However, for unfamiliar texts, mid-sentence interruptions significantly lengthened reading times by 1262 ms for sentence and 1784 ms for arithmetic interruptions, without affecting free recall.

The pattern of results remained the same when the texts were interrupted by arithmetic operations instead of unrelated sentences, except that considerably larger increases in reading times were obtained. It may be the case that switching from arithmetic to reading requires a constant switching time which is responsible for this increase. Recall was much better in the arithmetic condition than in the sentence condition, in spite of the fact that the arithmetic tasks actually took longer on the average than reading the interpolated sentences. This result has to be expected, in part because reading unrelated sentences produces more verbal interference, and in part because in the sentence task subjects had to recall both the main paragraph and the interpolated sentences.

We also found that it takes longer to read the initial sentences of a text. In terms of theories of text comprehension this result implies that the formation of the initial textbase (Kintsch, 1988; van Dijk and Kintsch, 1983) or the laying of the text structures' foundation (Gernsbacher, 1990) requires more mental processes than does adding on to this structure. More importantly, the reading times at the beginning of the paragraphs were significantly greater for unfamiliar than familiar texts. This result implies that the formation of the initial textbase foundation requires a greater amount of time for unfamiliar texts than it does for texts dealing with more familiar information.

The present study confirms previous results obtained with the interruption procedure of Glanzer. It also extends these results by testing a critical prediction of the long-term working memory theory of Ericsson and Kintsch (1995) against the alternative interpretation of these data offered by Glanzer (e.g., Glanzer & Nolan, 1986). The reading interruption procedure used by Glanzer does not impair comprehension and merely results in a relatively modest increase in reading time. Glanzer explained this finding by assuming that readers have access to a verbatim memory trace (and not thematic information), even after an interruption, that allows them to resume normal processing. This interpretation cannot account for the significant interaction between text familiarity and mid-sentence interruption: If what is reinstated after the interruption were a raw, uninterpreted, verbatim trace of the sentence, this trace would be equally available for familiar and unfamiliar texts. On the other hand, the theory of long-term working memory predicts just such an interaction.

According to models of text and discourse comprehension (e.g., Kintsch, 1988; van Dijk & Kintsch, 1983), as well as other structure-building models (e.g., Gernsbacher, 1990), comprehending a text involves the construction of a coherent mental text representation. Ericsson and Kintsch (1995) postulate that this text representation allows the text to be accessed in long-term working memory via a single retrieval operation. This retrieval operation takes about 400 ms if the appropriate retrieval cues are present in working memory. Ericsson and Kintsch (1995) have reviewed data indicating that retrieval from long-term memory requires 1 to 2 seconds when the appropriate cues are not in the focus of attention (e.g., Charness, 1976; Ericsson & Staszewsky, 1989). In the present experiment, the mid-sentence interruption effect for unfamiliar texts was 1.3 seconds in the sentence condition and 1.8 seconds in the arithmetic condition. Thus, this delay is about what one would expect for long-term memory retrieval -- in contrast to the 400 ms observed for retrieval using long-term working memory. If readers are interrupted in mid-sentence when they are reading an unfamiliar text for which they lack the knowledge to readily access the information needed to construct a situation model, they cannot generate a coherent text representation and hence do not have a retrieval structure to reinstate the previous text after the interruption. They must, therefore, use strategic retrieval operations. One example of such a retrieval operation would be a deliberate search for background knowledge (i.e., situation knowledge) and/or previous sentence fragments to be integrated with the new sentence fragment. Skilled readers are generally quite capable of adopting such strategies, but these mental operations are much more time consuming than the 400 ms retrievals involving long-term working memory.

Interrupting reading with an unrelated sentence or arithmetic problem must interfere with the short-term memory buffer. Nevertheless, as long as readers are able to understand a text (i.e., form a coherent mental representation of the text), interrupting reading merely lengthens reading time for the next sentence by the amount required for a single long-term working memory retrieval operation. This is true even when subjects read unfamiliar texts, or when the interruption occurs in mid-sentence rather than at the end of each sentence. In either case, apparently, readers are still capable of forming mental representations of the sentence (or sentence fragment) that can serve as efficient retrieval structures. Only when readers were given unfamiliar texts combined with mid-sentence interruptions was their comprehension impeded to such an extent that the preconditions for retrieval from long-term working memory were no longer present. In this case, subjects had to rely upon strategic retrieval operations to access information from long-term memory, requiring significantly more time.

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