Memory & Cognition
1990, 18 (1), 65-71

An on-line assessment of causal reasoning during comprehension

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Fletcher and Bloom (1988) have argued that as readers read narratives, clause by clause, they repeatedly focus their attention on the last preceding clause that contains antecedents but no consequences in the text. This strategy allows them to discover a causal path linking the text's opening to its final outcome while minimizing the number of times long-term memory must be searched for missing antecedents or consequences. In order to test this hypothesis, we examined the reading times of 25 subjects for each clause of eight simple narrative texts. The results show that: (1) causal links between clauses that co-occur in short-term memory (as predicted by the strategy) increase the time required to read the second clause; (2) potential causal links between clauses that never co-occur in short-term memory (again as predicted by the strategy) have no effect on reading time; and (3) reinstatement searches are initiated at the end of sentences that are causally unrelated to the contents of short-term memory or that contain clauses that satisfy goals no longer in short-term memory. These results support the claim that subjects engage in a form of causal reasoning when they read simple narrative texts.

In the research reported here, we have examined the joint implications of two well-known claims about narrative comprehension. The first of these asserts that comprehension is a problem-solving process, in which the reader must discover a series of causal connections that link a text's opening to its final outcome (Black & Bower, 1980; Schank, 1975; Trabasso & Sperry, 1985; Trabasso & van den Broek, 1985). The second holds that a strategic process focuses a reader's attention on a subset of the information in his or her short-term memory after each sentence is read, and that comprehension is facilitated if an appropriate connection exists between this information and the sentence that follows (Fletcher, 1981, 1986; Kintsch & van Dijk, 1978; Miller & Kintsch, 1980; van Dijk & Kintsch, 1983). Fletcher and Bloom (1988) have argued that both claims can be correct only if the attention-focusing process identifies the most likely causal antecedent of the sentence that will follow and if the correct antecedent (or sometimes consequence) is reinstated from long-term memory whenever this process fails.

To discover how such a process might work, Fletcher and Bloom (1988) examined a sample of narrative texts and found that the most likely causal antecedent of any sentence is the preceding clause with antecedents, but no consequences, earlier in the text. They showed that an attention-focusing strategy that holds this information in short-term memory allows 61% of the causal connections in a text to be detected without ever searching long-term memory. Because this strategy focuses attention on the analogue of the *current state* in a state-space search problem (Newell & Simon, 1972), Fletcher and Bloom refer to it as the *current-state selection strategy*. They assert that the current state is identified at the conclusion of each sentence, and that the propositions that are essential to its causal role in the text are held in short-term memory as the following sentence is read. Unlike Kintsch and van Dijk (1978), they do not assume that the same number of propositions is held in short-term memory after each sentence.

To understand this strategy, consider the text in Table 1. When the first sentence is processed, a causal link is detected between the second clause, which opens the causal field (Mackie, 1980; Trabasso & Sperry, 1985; Trabasso, van den Broek, & Suh, 1989), and the first clause, which it motivates.[1] Because the first clause has an antecedent but no consequence, it remains active in short-term memory while the next sentence is read. This is a fortunate choice, since this clause is a causal antecedent to the second clause of the new sentence. As is shown in Figure 1, this strategy allows a reader to process nine of the ten sentences in the text without difficulty. The exception is the sixth sentence, whose causal role in the text cannot be understood without searching long-term memory for antecedents that are no longer active in short-term memory. It is important to note that, in the absence of such reinstatement searches, many of the causal connections in a text will be overlooked. This is illustrated

This research was supported in part by the Center for Research in Learning, Perception, and Cognition at the University of Minnesota, and by Grants MH42468-01 and AFOSR-86-0280 to Charles R. Fletcher. Portions of the research were presented at the 1987 convention of the Psychonomic Society in Seattle, WA. We are grateful to Alice Healy, Ed O'Brien, Tom Trabasso, and an anonymous reviewer for their comments on an earlier version of this paper. Requests for reprints should be addressed to Charles R. Fletcher, Department of Psychology, University of Minnesota, 75 East River Road, Minneapolis, MN 55455.

—Accepted by previous editor, Alice F. Healy

Table 1
Danny's New Bike

No.	Clause	Reading Time (Per Word)	Free Recall Probability
1.	Danny wanted to have the red bike	272	.96
2.	that he saw in the window of the neighborhood bike shop.	249	.84
3.	Danny knew that first he had to have $50	238	.88
4.	to buy the bike.	290	.24
5.	He asked his parents if they would give him the money.	240	.76
6.	His parents denied his request.	266	.92
7.	They suggested that Danny earn the money himself	239	.44
8.	by getting a job.	244	.68
9.	Danny was mad at his parents	222	.56
10.	for not giving him the money,	242	.20
11.	but he was determined to get the $50 somehow.	238	.48
12.	He knew he would have to find a job,	232	.04
13.	so he called the newspaper	221	.60
14.	and asked for a paper route.	235	.52
15.	He started delivering papers in his neighborhood the next week	239	.84
16.	and earned ten dollars a week.	232	.88
17.	With this job,	232	.08
18.	Danny had $50 within a few weeks.	247	.88
19.	He took his hard-earned money to the shop,	227	.36
20.	bought the bike,	255	1.00
21.	and happily rode home.	275	.60

by Figure 2, which shows the idealized causal structure of "Danny's New Bike," derived using procedures described in Trabasso et al. (1989). The current-state strategy permits only 22 of the 33 causal links in Figure 2 to be detected without a resource-consuming search of long-term memory.

To demonstrate that their strategy provides a reasonable description of human performance, Fletcher and Bloom (1988) show that: (1) The more times the current-state strategy selects a clause for reprocessing, the better it is remembered. (2) The more causal connections a clause has to other clauses that theoretically co-occur with it in short-term memory, the better it is recalled. (3) Causal connections to clauses that do not co-occur with a target clause in short-term memory, again as predicted by the strategy, have no effect on its memorability.

These results are suggestive, but they cannot be considered conclusive, for two reasons: First, the free recall measure used by Fletcher and Bloom (1988) is only indirectly influenced by the comprehension process. It is a measure of the mental representation that results from comprehension, not of the comprehension process itself (see, e.g., Kieras & Just, 1984). Second, free recall scores reflect the influence of both comprehension and recall processes. As a result, we cannot rule out the possibility that Fletcher and Bloom's (1988) findings are the result of processes that have nothing at all to do with comprehension. In this paper, we present converging evidence for the psychological reality of the current-state selection strategy, using an on-line measure of comprehension that is immune to these criticisms.

Another goal of this research is to explore the possibility that the current-state strategy can be used to predict when a reader will search long-term memory to find causal connections that would otherwise go unnoticed. As shown above, one condition that necessitates such a search is the absence of any causal connections between the sentence being read and the contents of short-term memory. Under such circumstances, the sentence can only be understood if its missing antecedents and/or consequences are reinstated (see also Kintsch & van Dijk, 1978; Miller & Kintsch, 1980). Long-term memory might also be searched when one reads a clause that satisfies a goal no longer held in short-term memory. Van den Broek (in press) argues that causal links between goals and their outcomes play a central role in the mental representation of a text. As an example, consider Clause 20 in "Danny's New Bike." This clause clearly indicates that Danny has achieved his goal of purchasing the bicycle (Clause 4). Just as clearly, the causal connection between these statements is important to a proper understanding of the story. But Clause 4 has not been active in short-term memory since the second sentence, and therefore it must be retrieved from long-term memory. We will test the possibility that readers recognize these statements and reinstate the missing goal when one of them is encountered.

In conducting this research, we have made a number of common assumptions: First, we take it as given that a connection (causal or otherwise) between two parts of a text can only be established if both parts are in the reader's short-term memory at the same time (see, e.g., Kintsch & van Dijk, 1978; Miller & Kintsch, 1980). Sec-

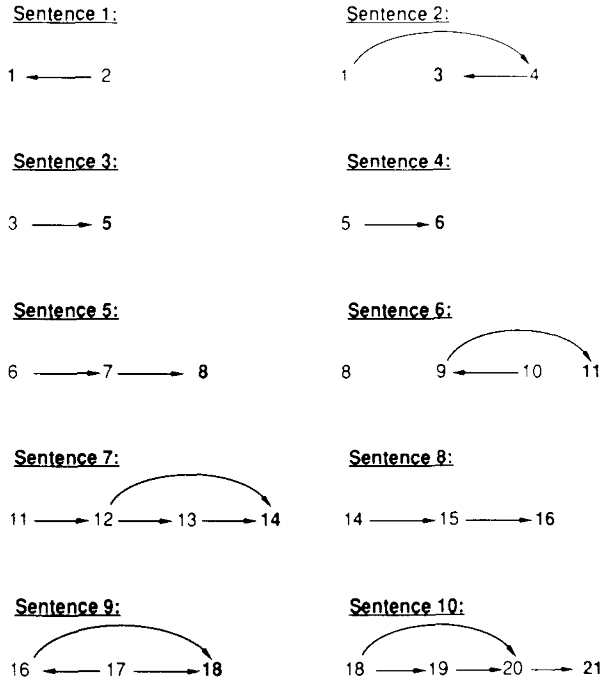

Figure 1. Causal relations discovered as each sentence of "Danny's New Bike" is processed. An arrow from Clause 2 to Clause 1 indicates that 2 causes 1. Clauses selected by the current-state selection strategy are shown in bold face type.

ond, we assume that a causal connection is encoded as soon as both the antecedent and the consequence are available. This is a variant of Just and Carpenter's (1980, 1984) immediacy assumption. Third, we assume that the process of encoding a connection in memory requires time. This assumption is supported by Kieras (1984). Fourth, we take it for granted that searching long-term memory for information from a text that is no longer available in short-term memory requires time (once again, see Kintsch & van Dijk, 1978; Miller & Kintsch, 1980). Fifth, we assume that all reinstatement searches are conducted at the end of a sentence (see, e.g., Just & Carpenter, 1980, 1984; Kintsch & van Dijk, 1978). Sixth, and last, we assume that the eye's fixation on a clause corresponds to the reader's mental processing of that clause. This is a variant of Just and Carpenter's (1980, 1984) eye-mind assumption.

Given this set of assumptions, the current-state selection strategy allows us to make the following predictions: (1) A causal link between two clauses that co-occur in short-term memory (as predicted by the strategy) should increase reading time, reflecting the effort required to represent the link in memory. (2) When no causal connection exists between a sentence and the contents of short-term memory, reading time for the last clause of the sentence should increase, because readers will need to search long-term memory for an appropriate connection. (3) When a sentence contains a clause that satisfies a goal no longer in short-term memory, reading time for the last clause of the sentence should increase, reflecting the time required to retrieve the goal from long-term memory. (4) A potential causal connection between clauses that never co-occur in short-term memory should have no impact on reading time.

METHOD

Subjects

Subjects for this experiment were 25 students from introductory psychology courses at the University of Minnesota who received course credit for their participation. All subjects were assigned to a single experimental condition.

Materials

Two practice texts and eight experimental texts from Fletcher and Bloom (1988) were used for this experiment. These texts are short narratives that deal with a wide variety of topics—one example is shown in Table 1. Each text includes four hierarchically embedded goals. The organization of these goals was manipulated across texts to produce variation in the proportion of causal links involving nonadjacent clauses. This proportion ranged from a low of .36 to a high of .53, with a mean of .48. The number of clauses per text ranged from 15 to 23, with a mean of 19.8. The number of words per clause ranged from 3 to 17, with a mean of 7.8. The number of words per text ranged from 137 to 180, with a mean of 154.6.

Apparatus and Procedure

Stimulus presentation and reading-time measurement was controlled by an IBM personal computer and a Zenith video monitor. Words typed in upper- and lowercase letters were presented on the video monitor using a moving window procedure (see, e.g., Haberlandt, Graesser, Schneider, & Kiely, 1986; Just, Carpenter, & Woolley, 1982). When text presentation began, all of the letters in the text were replaced with dashes. Punctuation and spaces were not altered in any way. Each reader progressed through the text at his or her own pace by pressing a button. Only one word was visible at a time. After each buttonpress, the visible word was replaced with dashes and the following word was presented. The reading time for each word was defined as the interval between successive keypresses.

All subjects read two practice texts followed by a unique random sequence of the eight experimental texts. They were instructed to read each text at their normal reading rates. They were then re-

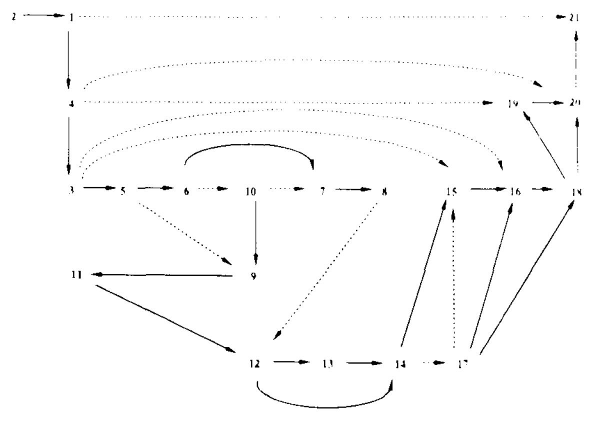

Figure 2. Idealized causal structure of "Danny's New Bike." Connections made without searching long-term memory are shown by solid arrows. Other causal connections are shown by dashed arrows.

quired to write down everything they could recall from it before proceeding to the next text. An experimental session lasted about 50 min.

RESULTS

Aggregate Reading Times

Reading times were collected for a total of 1,237 words for each subject, and the mean reading time per word was calculated for each of the 158 clauses from the eight texts. On the average, the subjects spent 247 msec per word on each clause, with a standard deviation of 23 msec per word. Table 1 shows the average reading time (per word) for each clause of "Danny's New Bike."

Multiple regression analyses were carried out on the mean reading time per word for each clause. Seven predictor variables were included in the analyses. The first of these, sentence links, codes the number of causal connections between each clause and earlier clauses within the same sentence. The second, STM links, codes the number of causal links between each clause and the contents of short-term memory—as predicted by the current-state strategy. In "Danny's New Bike," the link between Clauses 1 and 2 is an example of a sentence link, whereas the connection between Clauses 1 and 4 is an STM link. The third independent variable, potential links, measures the number of additional causal links that could be discovered through a search of long-term memory. In Figure 2, these are the dashed arrows. The fourth independent variable, coherence break, codes the last clause of each sentence that (according to the current-state strategy) has no causal connection to the contents of short-term memory. The fifth independent variable, goal reinstatement, codes the last clause of each sentence that includes the outcome of a goal no longer held in short-term memory. The sixth independent variable, distance from top, is set to zero for all clauses except those that, theoretically, initiate a search of long-term memory. For those clauses, this variable codes the length of the shortest causal path that separates the opening of the text from any clause that provides the missing causal information. For a goal reinstatement, this would be any statement of the missing goal. For a coherence break, it would be any clause with a causal relationship to the sentence being processed. As an example, the value of distance from top for Clause 11 would be 4—the length of the shortest path separating Clause 2 (the opening of the text) from Clause 5 (which provides a causal link between the sixth sentence and the preceding text). The final independent variable, distance from STM, is analogous to distance from top. It codes the length of the shortest causal path separating the contents of short-term memory (as predicted by the current-state strategy) from any clause that satisfies the conditions of a reinstatement search. Thus, for Clause 11, distance from STM would have a value of 1, since only one link separates Clause 8 (which is still held in short-term memory) from Clause 7 (which provides a causal connection between the sixth sentence and the previous text).

All analyses were conducted on the eight texts combined, as well as independently. Because there were no effects of text, only the results for the combined texts will be presented. Due to the theoretical relatedness of the independent variables, a check for multicollinearity was conducted, using procedures suggested by Graesser and Riha (1984) and Pedhazur (1982). This check yielded no evidence of multicollinearity among the predictor variables.

To determine which of the independent variables were significant predictors of reading time, we examined the unique variance contribution of each (i.e., the squared semipartial correlations). Six interaction terms were also included in this procedure: coherence break × potential links, coherence break × distance from top, coherence break × distance from STM, goal reinstatement × potential links, goal reinstatement × distance from top, and goal reinstatement × distance from STM. All variables and interactions with nonsignificant unique variance contributions were removed from the final regression model. Table 2 summarizes the results. The slope coefficients in the table estimate the amount of change in reading time per word associated with one unit of change in each independent variable. The beta weights indicate how robustly the reading times are predicted by each variable (Graesser & Riha, 1984; Pedhazur, 1982).

An examination of the table reveals a number of important findings. First, each causal connection within a sentence (sentence links) increases reading time by 33 msec per word. This supports the assumption that representing a causal link in memory requires time. Second, the most striking result of the analysis is the strong effect of STM links. This variable accounts for 38% of the variance in the reading-time data, even after the influence of the other predictors has been removed. This finding provides strong empirical support for the current-state selection strategy. Third, the significant effect of co-

Table 2
Multiple Regression Analysis on Mean Word Reading Time Per Clause

Predictor	Slope Coefficient	Beta Weight	Unique Variance
Full model = .51†			
Sentence links	33	.17	.03*
STM links	58	.67	.38†
Coherence break × Distance from STM	68	.17	.03*
Goal reinstatement × Distance from STM	10	.20	.03*

$^*p < .01$. $^\dagger p < .0001$.

herence break × distance from STM indicates that when no causal connection can be found between the contents of short-term memory and a new sentence, long-term memory is searched to find a connection that preserves the causal coherence of the text. Furthermore, it appears that this search begins with the contents of short-term memory (as predicted by the current-state strategy) and proceeds backward through the causal structure of the text. Fourth, the reliable effect of goal reinstatement × distance from STM indicates that long-term memory is searched in exactly the same manner after the reading of a sentence that includes the outcome of a goal no longer held in short-term memory. Fifth, and last, the finding that potential links has no effect on reading time suggests that causal connections between clauses that (according to the current-state strategy) never co-occur in short-term memory are not detected by readers.

Individual Subjects' Reading Times

To examine the generality of our results, separate multiple regression analyses were performed on the reading-time data from each individual subject, using the same predictors as in the preceding analysis. A total R^2 was computed for each subject, resulting in a mean R^2 of .40. The regression model explains a significant proportion of reading-time variance for all 25 subjects ($p < .0001$).

Table 3 summarizes the outcome of these analyses. All variables that failed to account for a significant portion of at least 1 subject's reading-time data have been excluded from the table. The generality of each remaining effect was assessed with a single group t test, to determine whether the 25 individual subject beta weights associated with it were reliably different from zero (Lorch & Myers, in press). The results reveal a remarkable degree of consistency across subjects. Each variable and interaction that has a statistically reliable effect on the aggregate reading times also has a reliable effect on the reading times of the individual subjects ($p < .0001$). Of the remaining variables and interactions, none accounts for a significant proportion of unique variance in the reading times of a single subject.

Free Recall Data

Fletcher and Bloom (1988) demonstrated that the current-state selection strategy can be used to predict how a text will be recalled. Specifically, they showed that the longer a segment of text remains in short-term memory (as predicted by the strategy) and the more causal connections it forms as a result, the better it will be remembered. These effects are assumed to reflect the representation of a text in memory, and to show that the construction of that representation is constrained in a manner described by the current-state strategy. Here we consider an alternative explanation: that the differences in memorability reflect differences in reading time.

For purposes of this analysis, all subjects' free recall protocols were scored by two judges. A clause was scored as correctly recalled only if it—or a close paraphrase of it—was explicitly present in the protocol. This relatively strict criterion is recommended both by Turner and Greene (1978) and by Bovair and Kieras (1985). Agreement between the two judges was 93%, and all discrepancies were resolved through discussion. The results were used to calculate the free recall probability for each of the 158 clauses, resulting in a mean of .63 and a standard deviation of .26. As an example, Table 1 shows the free recall probabilities for each clause of "Danny's New Bike."

Two separate regression analyses were performed on these free recall probabilities. In the first, mean reading time per word was the only predictor variable. In the second analysis, we employed the same independent variables as did Fletcher and Bloom (1988): the number of processing cycles that a clause remains active in short-term memory, as predicted by the current-state strategy (cycles in STM), and the number of causal connections between a clause and the other clauses with which it co-occurs in short-term memory (causal connections allowed).

The results of the first analysis indicate that reading time is not significantly related to free recall probability ($r^2 = .02$). But in the second analysis, both causal connections allowed and cycles in STM account for significant proportions of unique variance, and they produce an overall $R^2 = .16$ (see Table 4). These results are important for two reasons. First, they replicate the findings of Fletcher and Bloom (1988). Second, they demonstrate that those results cannot be explained as an indirect influence of the reading-time differences described here.

It is worth noting that the 16% of free recall variance accounted for here is 17% less than Fletcher and Bloom (1988) accounted for with the same texts. Part of this difference appears to result from the units of analysis adopted in the two studies. Fletcher and Bloom analyzed individual propositions, but since reading times cannot be calculated for individual propositions, the results reported in the present study are for clauses. When

Table 3
Multiple Regression Analyses on Mean Word Reading Time Per Clause for Individual Subjects

Predictor	Slope Coefficient Mean	Slope Coefficient *SD*	Beta Weight Mean	Beta Weight *SD*	Proportion with Positive Slope	Beta *t* Test
Sentence links	33	16	.14	.04	1.00	20.3†
STM links	58	20	.58	.06	1.00	46.9†
Coherence break × Distance from STM	68	43	.14	.06	1.00	10.7†
Goal reinstatement × Distance from STM	10	5	.18	.06	1.00	15.5†

†$p < .0001$.

Table 4
Multiple Regression Analyses on Free Recall Probabilities Per Clause from This Experiment and from Fletcher and Bloom (1988)

Predictor	Slope Coefficient	Beta Weight	Unique Variance
This Experiment			
Full model = .16†			
Causal connections allowed	.01	.22	.05*
Cycles in STM	.18	.35	.11†
Fletcher and Bloom (1988)			
Full model = .24†			
Causal connections allowed	.09	.32	.10†
Cycles in STM	.11	.26	.08†

$^*p < .01$. $^\dagger p < .0001$.

Fletcher and Bloom's data are reanalyzed at the clause level (see Table 4), the difference is reduced to 8%. This remaining difference may indicate that the moving window procedure used in this research causes a slight disruption in the normal reading process (see Danks, 1986), resulting in a poorer fit between the data and our theoretical predictions.

DISCUSSION

The purpose in this research was to evaluate several hypotheses derived from the current-state selection strategy of Fletcher and Bloom (1988). The first of these hypotheses asserts that a causal link between two clauses that co-occur in short-term memory, as predicted by the strategy, should increase the reading time for the second clause. This hypothesis is clearly supported by the data, which show that each such connection produces a significant increase in average reading time. More importantly, this effect is observed in all 25 subjects, even when connections within sentences are eliminated from consideration. At first glance, this result appears to contradict several well-known studies, which have shown that causal coherence decreases the time required to read a sentence (see, e.g., Haberlandt & Bingham, 1978; Keenan, Baillet, & Brown, 1984; Myers, Shinjo, & Duffy, 1987). Consider, for example, the following materials from Myers et al. (1987):

1a. Cathy felt very dizzy and fainted at her work.
1b. Cathy had begun working on a new project.
2. She was carried unconscious to a hospital.

These researchers found that Sentence 2 above is read more quickly when it is preceded by Sentence 1a than when it is preceded by 1b. They argue that this difference reflects the time needed to infer (or try to infer) a series of steps that provide a causal link between Sentence 1b and Sentence 2. Thus, reading time is faster with Sentence 1a, not because more causal connections are made, but because the causal antecedent is readily available. As a result, these data are quite consistent with the results presented here.

The second hypothesis under consideration holds that when no causal connection exists between a sentence and the contents of short-term memory, reading time for the last clause of that sentence should increase, reflecting the time required to retrieve an appropriate connection from long-term memory. This situation is similar to that in the experiments by Haberlandt and Bingham (1978), Keenan et al. (1984), and Myers et al. (1987) considered above. The primary difference is that here the missing information is available in long-term memory, whereas in the previous studies it had to be inferred. Once again, data from all 25 subjects (together and separately) support this hypothesis.

Our third hypothesis asserts that when a sentence includes the outcome of a goal that is no longer in short-term memory, reading time for its last clause should increase. Again this reflects the need to search long-term memory for missing information, and again the hypothesis is supported by the data from all 25 subjects. Both van den Broek (in press) and Suh and Trabasso (1988) have argued that these outcome statements are unique in that they are not sufficiently motivated without the corresponding goal. This contrasts with coherence breaks when the information in short-term memory is neither sufficient nor necessary. Van den Broek (in press) has hypothesized that this lack of necessity and/or sufficiency initiates a reinstatement search, and that the search stops as soon as a clause that satisfies these conditions has been located.

Our data also offer some insight into how long-term memory is searched. The fact that the observed increase in reading time during coherence breaks and goal reinstatements does not depend on the number of potential links between the target sentence and the preceding text suggests that reinstatement searches are not exhaustive. The fact that it does not depend on the shortest causal path separating the opening of the text from the to-be-retrieved information suggests that the search does not begin at the beginning of the text. The finding that the increase in time does depend on the shortest causal path separating the contents of short-term memory from the to-be-retrieved information suggests a search process that begins with the current contents of short-term memory and proceeds backward through the causal structure of the text, halting as soon as information that restores the causal coherence of the text is encountered. Similar results have been reported by O'Brien and Myers (1987).

The final hypothesis suggests that a potential causal connection between clauses that never co-occur in short-term memory should have no effect. The reading-time data also support this hypothesis—not a single subject showed any influence of potential links on reading time.

The reading-time data reported here also have implications for a variant of the current-state strategy that has been advocated by Myers (in press). According to this strategy, readers always hold both the current state and the most subordinate unsatisfied goal in short-term memory. But the significant goal reinstatement × distance from STM interaction appears to be inconsistent with this strategy. In addition, we fit this current-state-plus-goal selection strategy to our reading-time data and found that it produced a lower R^2 for 23 of the 25 subjects. The two exceptions were from the 3 subjects whose data was fit worst by both models.

Taken together with the free recall results of Fletcher and Bloom (1988—which we were able to replicate), the reading-time data reported here support the conclusion that subjects engage in a form of causal reasoning as they read. They continuously focus their attention on the most likely antecedent of the next sentence they will read. When this process fails, they search long-term memory until they find either an antecedent or consequence of the sentence they are trying to interpret. Moreover, when a reader encounters a clause that satisfies an earlier goal in the text, he or she attempts to reinstate the missing goal from long-term memory. These conclusions are consistent with the claim that comprehension is a problem-solving process in which the reader attempts to find a causal path linking a text's opening to its final outcome (Black & Bower, 1980; Schank, 1975; Trabasso & Sperry, 1985; Trabasso & van den Broek, 1985). At the same time, they demonstrate how this goal is accomplished within the known limits of the human information-processing system.

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NOTE

1. A is said to cause B if it is the case that B would not have occurred in the circumstances described by the text had A not occurred (Mackie, 1980; Trabasso & Sperry, 1985; Trabasso, van den Broek, & Suh, in press). By means of this criterion, enablement, motivation, psychological causation, and physical causation are all considered "causal" relations.

(Manuscript received April 7, 1988;
revision accepted for publication May 18, 1989.)