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Inference Processes During Reading: Reflections from Eye Fixations[1]

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Running Head: Reading and Inference Making

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Since reading and understanding are moderately complex human activities, they are often studied and described from various perspectives. Our own approach has focused on the mental processes that extract information from a text, and the processes that connect those elements to construct a coherent internal representation of the text content (cf. Carpenter & Just, 1977a, 1977b). These processes are influenced by certain linguistic properties of the text, such as foregrounding, pronominal reference, and lexical enlargements. Our approach has been to examine how these constructions initiate and guide comprehension processes. In this paper, we will describe some research on verb-based entailments.

Verb structures are a particularly rich domain that seem to play a central role in comprehension and inference-making (cf. Fillmore, 1968; Norman & Rumelhart, 1975; Schank, 1973). For example, the verb <u>to murder</u> entails an agent, a murderer. If a text contains the verb <u>murder</u>, followed at some point by the word <u>killer</u>, comprehension of the text involves computing the relation between the two words. The main object of this study is how and when a reader computes that <u>killer</u> refers to the entailed agent of <u>murder</u>. The methodology involves monitoring eye fixations as subjects read and comprehend simple paragraphs. The general goal of this research is to both investigate and use the relation between eye fixations and comprehension processes to develop aspects of a theory of comprehension.

Semantic Influence on Eye Fixations

What determines where and how long a reader fixates while reading a text? In principle, the locus and duration of reading fixations could be controlled by visual information processes, oculomotor processes, and semantic processes (Carpenter & Just, 1977a; Haber, 1976; Kolers, 1976). It is clear that the fixation behavior is at least partially dependent on the processing of visual input from the text, such as where the lines of print begin and end. Visual (but non-semantic) information, such as inter-word spaces, type-case and punctuation marks also appear to have some effect (Fisher, 1976; McConkie, 1976). The current experiments will focus on more cognitive processes--semantic influences on eye fixations. We propose that the semantic processes that extract the meaning relations from the text can influence reading eye fixations. The degree of guidance and control remains to be fully specified. However, the experiments to be reported on lexically-based inferences reveal some of the temporal relations between semantic processing and eye fixations.

There are two major dimensions that must be specified when considering how semantic processes might influence reading fixations. First, they could either influence the duration or the location of reading fixations, or both. Second, the processes might influence the characteristics of the ongoing fixation, subsequent fixations, or both. For example, information fixated during fixation _n_ could influence the duration of fixation _n_. Alternatively, the information fixated during fixation _n_ could influence the duration of fixations _n + 1_ or _n + 2_. In other words, there could be some lag between the time semantic information is initially fixated and its manifestation in the reading eye fixations. Such a lag could reflect a lag between initial encoding and some subsequent semantic computation, or it could reflect a lag between the semantic computation and the manifestation in fixation behavior. The experiments to be reported explore issues of both dimensions.

Fixation Duration and Semantic Processing

Historically, fixation duration has not been associated closely with semantic processing during reading. Fixation duration has been assumed to be an insensitive index of cognitive processing for a number of reasons. One reason is that fixation durations are erroneously assumed to be fairly constant, so there would be little variability to correlate with semantic processing. Perhaps the cause of this misconception is that average fixation duration is fairly constant across subjects in simple reading tasks. The standard deviation of subjects' average fixation durations are often as low as 25 msec (Tinker, 1951) with an average duration of about 250 msec. However, this does not mean that one reader's fixations within one passage will all have the same duration. On the contrary, in an ordinary reading situation the variability of fixation durations within a subject is quite large, with standard deviations of about 100 msec and a range of about 150 to 375 msec (Walker, 1933). But because early researchers were attempting to account for the average fixation durations rather than the individual fixation durations, they had difficulty in relating the temporal characteristics of fixations to cognitive processes.

But there are other indications that the duration of individual fixations may only weakly reflect cognitive processes. The average duration is not strongly correlated with more global tests of comprehension performance (r = .11, Buswell, 1937; r = -.05, Anderson, 1937). Poor readers have mean fixation durations that are only 10% - 20% longer than those of good readers, e.g., 295 msec vs. 246 msec (Anderson, 1937; Buswell, 1937). Moreover, training in reading decreases the number of fixations a poor reader executes, but does not significantly decrease mean fixation duration (Buswell, 1937). Fixation duration does increase somewhat with the difficulty of the text or task but is not affected as much as the number of fixations (Tinker, 1951). One reason why fixation duration may be less flexible than the number of fixations is that there may be a lower bound set by physiological constraints and basic perceptual processes. While fixation duration may increase in response to task demands, decreases below some lower bound may be attenuated by these other constraints. Thus, there appears to be only a small or indirect relation between fixation duration and reading ability.

Perhaps the individual fixation is not the appropriate unit of analysis to relate to comprehension processes. An alternative measure of the temporal characteristics of fixation behavior is the total amount of time that a reader spends looking at a unit of text at any one time. This measure is called the gaze; it is simply a temporal aggregation of individual fixations that comprise a single inspection of a particular word, phrase or sentence. The unit of analysis depends on the underlying theory. There is some evidence to suggest that gaze duration, rather than individual fixation duration, is closely related to comprehension processes. For example, it is known that text difficulty affects fixation behavior. As passages become increasingly difficult, some readers increase the number of fixations they make, some increase the duration of their fixations, while others increase both the number and duration of fixations (Walker, 1933). Thus, the gaze duration may be the measure that covaries most closely with text difficulty. Moreover, there is a high correlation between comprehension scores and the total time spent on a text (Tinker, 1939). In still another situation, one that involves reading a sentence and deciding whether it is true or false of an accompanying picture, gaze duration appears to be an appropriate measure. The task difficulty is most closely related to total gaze duration on the sentence, irrespective of the durations of individual fixations within the gaze (Carpenter & Just, 1976; Just & Carpenter, 1976a). What is important in all these situations is the time spent processing a particular symbol, not the number of fixations nor the duration of individual fixations.

In the following experiments, the main dependent measure is gaze duration. The individual word is used as the unit of analysis and consecutive fixations on that word are aggregated and treated as a single gaze. These gaze durations can be compared across different experimental conditions, defined by the semantic properties of the various sentences. Thus, we will examine the evidence for semantic influences on the temporal characteristics of the gaze.

Fixation Locus and Semantic Processing

While duration is one measure of reading performance, the issue of the semantic control of eye fixations traditionally has been defined primarily in terms of the locus of eye fixations. Does the computation of semantic information on the n^{th} fixation determine the location of the $n + 1^{st}$ fixation? This question is still unresolved in the domain of forward fixations (cf. O'Regan, 1975). However, we have already reported studies in which semantic processing directed the locus of regressive fixations (Carpenter & Just, 1977a). Regressive fixations are particularly susceptible to semantic control because the processor already has a record of the location of the relevant word or sentence.

Historically, regressive fixations have often been associated with poor readers (Buswell, 1937) and were considered an unimportant component of the normal reading process. However, some experimental constraints limited their occurrence, so that their frequency may have been underestimated. For example, some researchers instructed their subjects not to look back at previously-read lines of text. Others used eye trackers that detected only horizontal eye movements, so that upward regressions were not monitored. Finally, the reading tasks often did not require much integration across the various parts of the text, so there may not have been much reason to look back. With all these constraints, the type of regressive fixation that was most likely to show itself was the regression within a line of print, namely leftward eye movements. Many of these were semantically uninteresting, since they were corrections for undershoot of the return sweep from the right-hand extreme of one line to the left side of the next line. When some of these artificial constraints are removed (and perhaps new ones added), regressive fixations are often closely linked with comprehension processes.

Certain regressive fixations are indicative of comprehension processes and are correlated with the interpretation given the passage. For example, readers will tend to make regressive fixations to the referent of a pronoun (Carpenter & Just, 1977a). In that experiment, subjects read passages containing pronouns. The sentences preceding the pronoun contained two nouns that logically could have been the referent of the subsequent pronoun. The following is a typical example:

1) The guard mocked one of the prisoners in the machine shop.

2) The one who the guard mocked was the arsonist.

3) He had been at the prison for only one week.

The experiment focused on the interpretation of the pronoun <u>He</u> in sentence (3). There are two possible antecedents for <u>He</u>; one is the arsonist/prisoner and the other is the guard. The linguistic structure of the second sentence focuses on the arsonist. Linguistic analysis suggests that this noun, in general, should be interpreted as the pronominal referent. (Other factors like serial position and agent-object relations were taken into account.) When reading the pronoun sentence, subjects made regressive fixations to a potential referent about 50% of the time. Moreover, the regression was usually to the referent that was the focus of the preceding sentence. Furthermore, the pattern of eye fixations correlated with eventual recall. For example, subjects tended to recall the pronoun sentence in the example above as being about the arsonist. Thus some regressive fixations are semantically driven and indicate what is being comprehended and what is being stored.

The following experiments look more closely at the locus and duration of both regressive and forward fixations. The goal is twofold. On one hand, the results will be used to investigate the semantic influence on eye fixations. Here the issue is whether underlying semantic processes, such as inference making, influence the duration and location of forward and regressive fixations. The second issue is the substantive question of inference making. We will use the eye fixation behavior to track inference making and to determine when and how lexically-based inferences are made.

Inferences Based on Verbs

The primary interest of this research is how and when a reader infers the relation between a verb, like murder, and an entailed agent, like killer. (For convenience, we shall use the term agent to refer to all three kinds of entailments--agent, instrument, and manner.) Such an inference must take a certain amount of time to compute and this time might be influenced by the lexical relationship between the verb and agent. In particular, the closer the semantic relation between the two lexical items, the less time it should take to compute the relation. For example, the relationship between the verb murder and the agent killer is direct.

It is easy to integrate two sentences that refer to these concepts, for example:

1) The millionaire was murdered on a dark and stormy night.
   The killer left no clues for the police to trace.

By contrast, consider the relationship between die and killer. If someone dies, it does not necessarily mean that a killer is involved. Thus if one sentence refers to someone dying and the next refers to a killer, it might take more time to infer the relation, for example:

2) The millionaire died on a dark and stormy night.
   The killer left no clues for the police to trace.

This study examined whether such indirect inferences take longer and how the additional time is distributed during reading.

At this point one might hypothesize that semantic distance would account for inference making. Perhaps the ease or difficulty of making an inference depends only on how far apart two concepts are in the reader's semantic space. If so, then the computation time should not be affected by the order of mention of the two concepts to be related, since the distance between remains unaffected. To investigate this issue, we varied the serial order of the verb and agent sentences. The agent could either follow the verb sentence (as in the example 1 and 2 above) or the agent could precede the verb, as in example 3 :

3) The killer left no clues for the police to trace.
   The millionaire died on a dark and stormy night.

If the time needed to make an inference linking two concepts was simply dependent on the inter-concept distance, then the indirect inference condition (killer-died) should still be more difficult than the direct inference condition (e.g., killer-murdered).The additional time to make the indirect inference would be reflected in the extra time to read the indirect verb sentence. Alternatively, semantic distance may not be a sufficient explanation for inference making. For example, if the reader knows that there is a killer, then it may be equally easy to infer that someone else died or that someone was murdered. In other words, the "direct" and "indirect" inferences might be equally easy to make. In this case, the serial order of the agent and verb sentences would influence the relative ease of making an inference. The difference between the direct and indirect inferences might be eliminated when the agent sentence precedes the verb sentence.

Method

The main independent variable was the semantic relation between the verb in one sentence and the agent in another; the relation could be either direct or indirect. Examples of agents (in the sense described previously) and the directly and indirectly related verbs are: the killer, murder--die; the car, drove--went; the seller, bought--got; the will, inherited--received; the hill, climbed--walked. The second independent variable was the serial order of the verb and agent sentences.

Each paragraph had a total of five sentences: one containing the verb, one containing the agent, and three filler sentences. In half of the paragraphs, the filler sentence in the fourth or fifth position contradicted information in the earlier sentences, as illustrated below:

1) The millionaire was murdered on a dark and stormy night.
2) The killer left no clues for the police to trace.
3) The millionaire was found in his bed by the housekeeper.
4) There was no electricity in the house because of the storm.
5) It was the butler who discovered the body.

Each subject saw 32 paragraphs, half of which contained a directly related verb and half an indirectly related verb. In half of the paragraphs the verb sentence preceded the agent sentence and in the other half it followed. There were two versions of the design, differing only in whether the particular verb was directly or indirectly related to the agent sentence. Half of the subjects received one version and half received the other.

Procedure

The subjects' task was to read each sentence in a paragraph and determine whether or not it contradicted any information in a previous sentence. This task was used to ensure that the subject would integrate the sentences. The subjects' response latencies were recorded and their eye fixations were monitored as they read and responded to each sentence.

In this experiment and in the others that follow, eye fixations were monitored by a corneal-reflectance eye-tracking system (see Just & Carpenter, 1976b, for more details). This system beams a small spot of light onto the subject's cornea and captures the reflection. As the eye moves, the angle of reflection changes approximately linearly with the amount of movement. The system is calibrated for each subject so that the locus of the reflection corresponds to the locus of fixation.

The subject's eye fixations were monitored while he read each successive sentence of a paragraph on a video monitor and decided whether it was consistent or contradictory with the previous sentences. Each sentence was started on a new line of the video display. Before a sentence was displayed, a fixation point was presented at the starting position of that sentence. The trial did not start unless the subject was fixating that point and simultaneously pressed a "ready" button. Half a second later, the current sentence appeared, along with all of the preceding sentences. When the subject made a judgment about the current sentence, the entire display was blanked. Thus, only the first sentence was displayed during the first trial, the first and second sentences during the second trial, etc. Reading and judging the five sentences of the paragraph constituted five separate trials.

The average length of the agent word was 5.5 letters. The third and fourth words averaged 4.7 and 4.4 letters, respectively. The viewing distance was adjusted for each subject to equalize the excursion of the eye spot, but on average it was 82 cm. The average visual angle subtended by the agent word 2.5° and the angle subtended by the first four words of the agent sentence was 8°.

Twenty subjects were run, ten in each version of the experiment. The subjects were volunteers from an introductory psychology course.

Total Response Time

First we will consider total reading time when the agent sentence followed the verb sentence. As predicted, subjects took longer to process the agent sentence in the indirect inference condition. The response time for the indirect inference condition (3277 msec) was 454 msec longer than the response time for the direct inference condition (2823 msec), $F'(1, 31) = 8.14$, $p < .01$. This supports the view that inferences are more difficult in the indirect condition. The greater response time in the indirect condition was found for 17 of the 20 subjects and for 14 of the 16 agent sentences.[2]

When the agent was specified first and the verb sentence second, there was no difference between the indirect and direct inference conditions. Subjects took about the same amount of time to read the verb sentence in the indirect inference condition (3188 msec) and the direct inference condition (3220 msec). Thus, the order of the verb and agent sentences did influence the relative difficulty of making an inference. This suggests that semantic distance alone cannot account for the difficulty of inference making. Semantic distance is symmetrical; the distance between concepts A and B is the same as the distance between B and A. Distance considerations alone would predict that indirect inferences would take longer, regardless of whether the verb precedes or follows the agent. A more adequate explanation will consider the information entailed by sentences. For example, the existence of a killer entails someone's death by murdering. When a subsequent sentence refers to either of these concepts, they are equally available. The reader can construct a link back to the concept of killer. By contrast, when the verb is specified first, different information is entailed in the direct and indirect condition. Thus, subsequent relating of an agent is differentially easy in the two conditions.

An alternative possibility is that there may be some asymmetry in the comprehension of nouns and verbs that interacts with their order in a paragraph. For example, many theories postulate that verbs play a central role in establishing the framework of the passage (cf. Norman & Rumelhart, 1975). Hence, a particular verb could influence the comprehension of subsequent sentences more than any particular noun. While several theories distinguish between noun-like structures and verb-like structures, such an explanation requires much more investigation.

The agent sentence in the first position provides a control demonstrating that there was no a priori differences among the agent sentences. The reading time should be equivalent for the direct and indirect conditions, since the same sentences were used in both conditions.

In fact, the two response times are similar, 3162 msec in the indirect condition and 3227 msec in the direct condition.

Eye Fixation Anaylsis

The distribution of eye fixations on the agent sentence might indicate when a reader makes the linking inference. The assumption underlying this analysis is that the reader will tend to make the inference at the same time in the direct and indirect inference conditions. However, the inference is more difficult in the indirect condition so the reader spends more time fixating the agent sentence. The locus of this additional time indicates when the inference was made. Thus, the fixation analysis compares the distribution of gazes on the agent sentence in the direct and indirect inference conditions.

Fixations within the agent sentence were classified as either forward or regressive fixations and aggregated into gazes. The easiest way to explain the classification is to consider a hypothetical sequence of fixations where the numbers 1 to 11 indicate the sequence of fixations:

2 1 4 3 5 6 7 8 10 11 9
The killer left no clues for the police to trace.

Fixations 1 and 2 would be aggregated into the first gaze on killer. The total gaze duration would be the sum of the durations of fixations 1 and 2. Fixation 3 would be a gaze on left. Fixation 4 would be classified as a regressive gaze to killer. Fixations 5 to 9 are forward gazes on their respective words. Fixations 10 and 11 would be aggregated into a regressive gaze on police.

The distribution of gazes on the agent sentence was analyzed for 14 of the 20 subjects.[3] Figure 1 shows the average duration of gaze on the first four words of the agent sentence for both the direct and indirect inference conditions for each subject. Twelve of the fourteen subjects spent more time on the agent word in the indirect inference condition. This effect was present for 12 of the 16 agent sentences.

Insert Figure 1 about here

Figure 2 shows the effect averaged over subjects. The gaze on the agent word itself was 65 msec longer in the indirect condition, $F'(1, 25) = 4.03$, $p < .06$. The gaze on the definite article preceding the agent word was 13 msec longer in the indirect condition. The gaze on the word following the agent was 24 msec longer in the indirect inference condition and on the fourth word, it was 44 msec longer. In all, subjects spent almost 145 extra msec in forward fixations on the agent sentence in the indirect inference condition. These data suggest that on some trials readers infer the relation between the agent and prior sentence immediately upon fixating the agent word itself.

Insert Figure 2 about here

Regressive fixations were of two kinds; there were regressions within the agent sentence and regressions to the preceding verb sentence. Within the agent sentence, subjects spent 84 msec longer on regressive fixations to the agent word in the indirect inference condition, as shown in the bottom of Figure 2. They also spent about 10 msec longer on _The_ and 61 msec longer on the third word, the word following the agent word. Thus, regressions accounted for 155 msec of the difference between the indirect and direct inference conditions.

Subjects also made regressive fixations to the opening sentence that contained the verb. As in a previous experiment (cf. Carpenter & Just, 1977a), subjects spent more time on the verb sentence in the indirect inference condition (288 msec) than in the direct inference condition (131 msec).

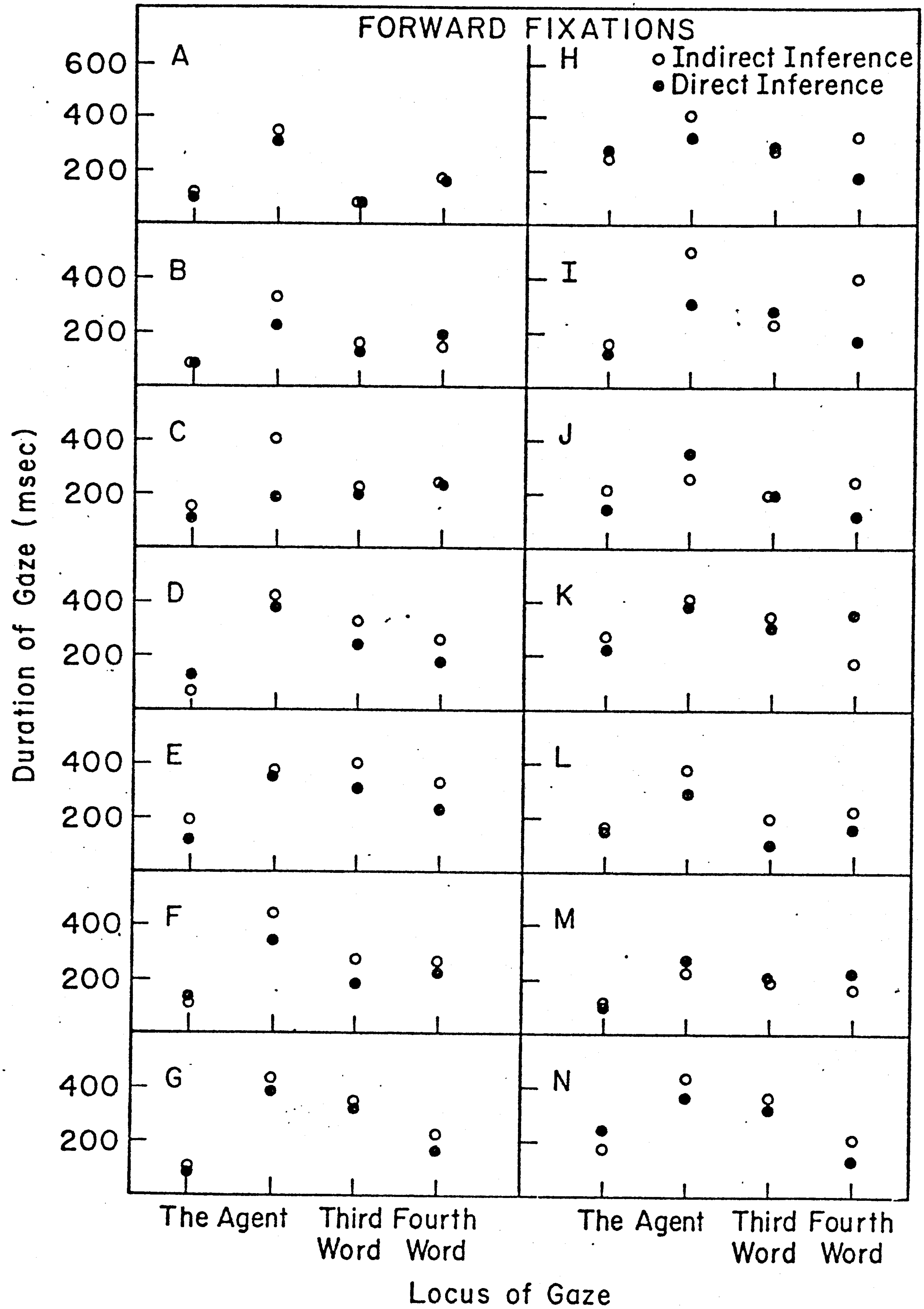

Fig. 1. The gaze duration computed from forward fixations for each of 14 subjects (labelled A through N). The duration is shown for each of the first four words of the agent sentence for the indirect and direct inference conditions.

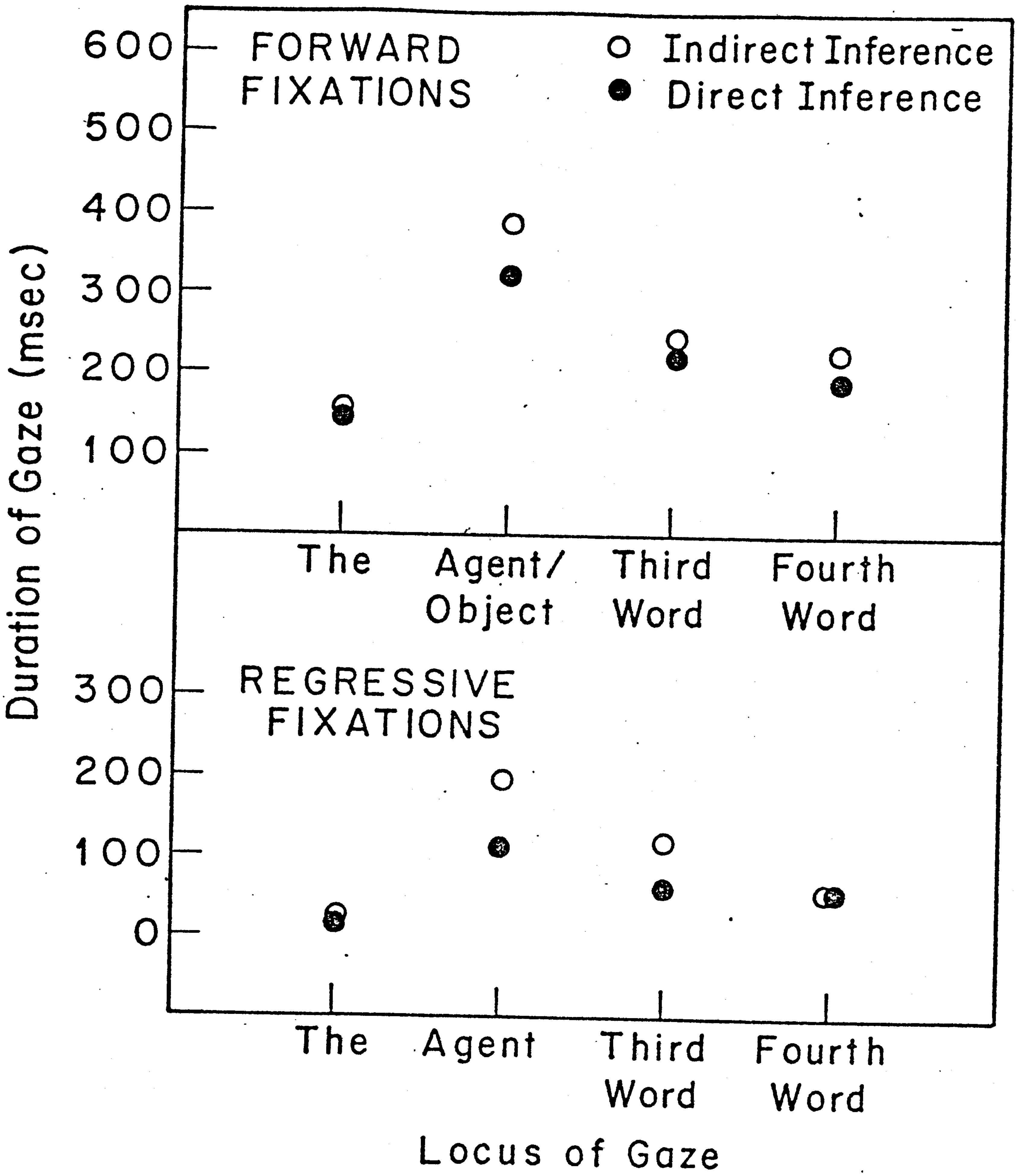

Fig. 2 The gaze duration averaged across subjects. The top panel shows the gaze duration computed from forward fixations. The bottom panel shows the gaze duration computed from regressive fixations.

These regressions were generally made after reading the entire agent sentence. Thus, regressions within the agent sentence and regressions back to the verb sentence accounted for a total of 310 msec of the 652 msec difference between the two conditions.

The results indicate that readers sometimes make the inference relating an agent to a prior verb immediately upon encountering the word denoting the agent. This inference process takes longer in the indirect inference condition and some of the additional time is reflected in the longer gaze duration on the agent word and the immediately adjacent words. The rest of the additional time is spent in regressive fixations to the sentence containing the verb. As the semantic path between the two concepts is constructed, the related words tend to be fixated.

The Effect of the Task

The next experiment examined the generality of these results in another task environment, one that did not involve consistency judgments. It examined the same inference-related variables in the context of a reading task. The subject read each sentence and pressed a button when he had understood the sentence. There were no consistency judgments and no inconsistent sentences were presented. At the end of a paragraph, the subject was asked to recall as much as he could, although memory performance was not stressed. Again, the primary question was the processing of indirect and direct inferences.

Method

The design was similar to that of the previous experiment. However, in the current experiment, the particular verb used was the same in both versions of the experiment but the serial order of the verb and agent sentences was varied. In one version of the experiment, the verb sentence appeared first and the agent second. In the second version of the experiment, their order was reversed although the same verb was used. Half of the verbs were from the indirect inference condition and half from the direct inference condition.

Ten subjects were run in each version of the experiment. None of the subjects had participated in the previous experiment.

Results

The major results replicate those found in the consistency judgment task. When the agent sentence followed the verb, reading times were 182 msec longer in the indirect condition (3124 msec) than in the direct condition (2942 msec). However, the difference was much more variable and not statistically reliable, $F'(1, 18) = 1.25$, n.s. Again, when the verb sentence followed the agent sentence (e.g., killer-died), the indirect and direct inference conditions took equally long. Reading times for the verb sentence were 3090 msec in the indirect condition and 3123 msec in the direct condition. Thus, the same asymmetry in the first experiment was present in this task also. When the reader already has information specified about a killer, it is no more difficult to make an inference relating that to a death than it is to make the inference relating it to a murder.

The portion of the experiment where the agent sentence followed the verb sentence replicated the major results of the previous experiment. However, the difference between the direct and indirect inference conditions was smaller than the one observed in the last experiment and was less consistent across subjects. One possibility is that the consistency judgment task in the preceding experiment assured that subjects integrated the sentences within a paragraph. In the current task, there was no way to insure that subjects would integrate the sentence.

Eye Fixation Analyses

The analysis focused on six subjects, three from each version of the experiment, whose protocols had the least amount of noise and head-movement and who had large differences between the direct and indirect inference condition. Their average difference between the direct and indirect inference conditions was 430 msec.

Insert Figure 3 about here

Figure 3 shows the gaze durations on each of the first four words of the target sentence (when it appeared in the second position). All six subjects showed an increase in gaze duration on the target sentence in the indirect inference condition. For most of the subjects there is also an increase on the third word, the verb or auxiliary following the agent word. However, by the fourth word, the difference between the direct and indirect conditions is less consistent. Figure 4 shows the results averaged over all six readers. The time spent on the agent word is 105 msec greater in the indirect inference word. There is also slightly more time spent on the following word (55 msec). The time on the definite article shows essentially no difference (12 msec), and the time on the fourth word shows essentially no difference (-11 msec). Thus, the gaze duration does show a selective increase as found in the previous experiment.

Insert Figure 4 about here

The second panel in Figure 4 shows the duration of regressive gazes on each of the first four words of the target sentence. These regressive gazes also demonstrated the effect of semantic processes on reading fixations. First, there were seldom any regressive fixations to

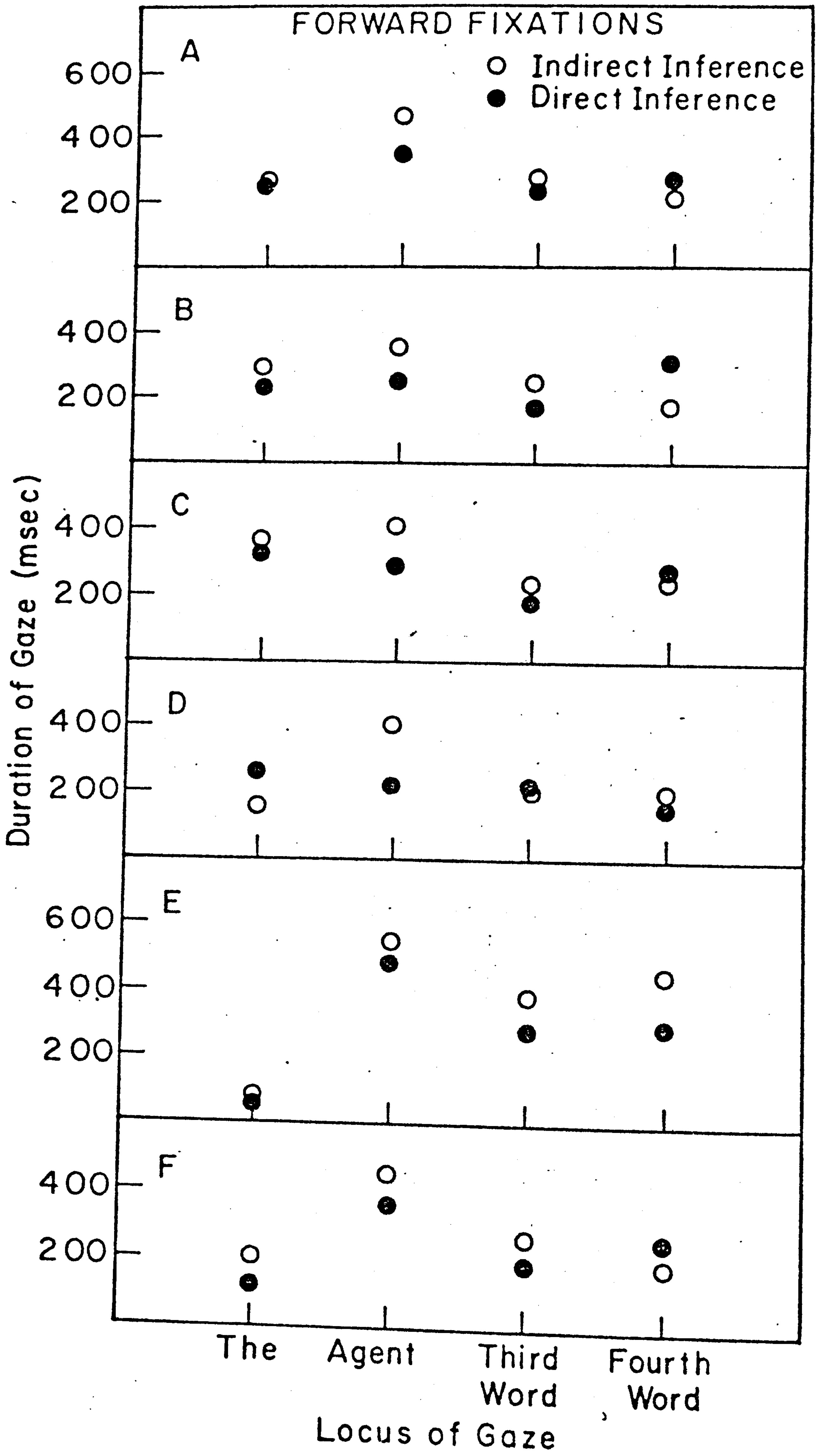

Fig. 3. The gaze duration computed from forward fixations for each of 6 subjects (labelled A through F). The duration is shown for each of the first four words of the agent sentence for the indirect and direct inference conditions.

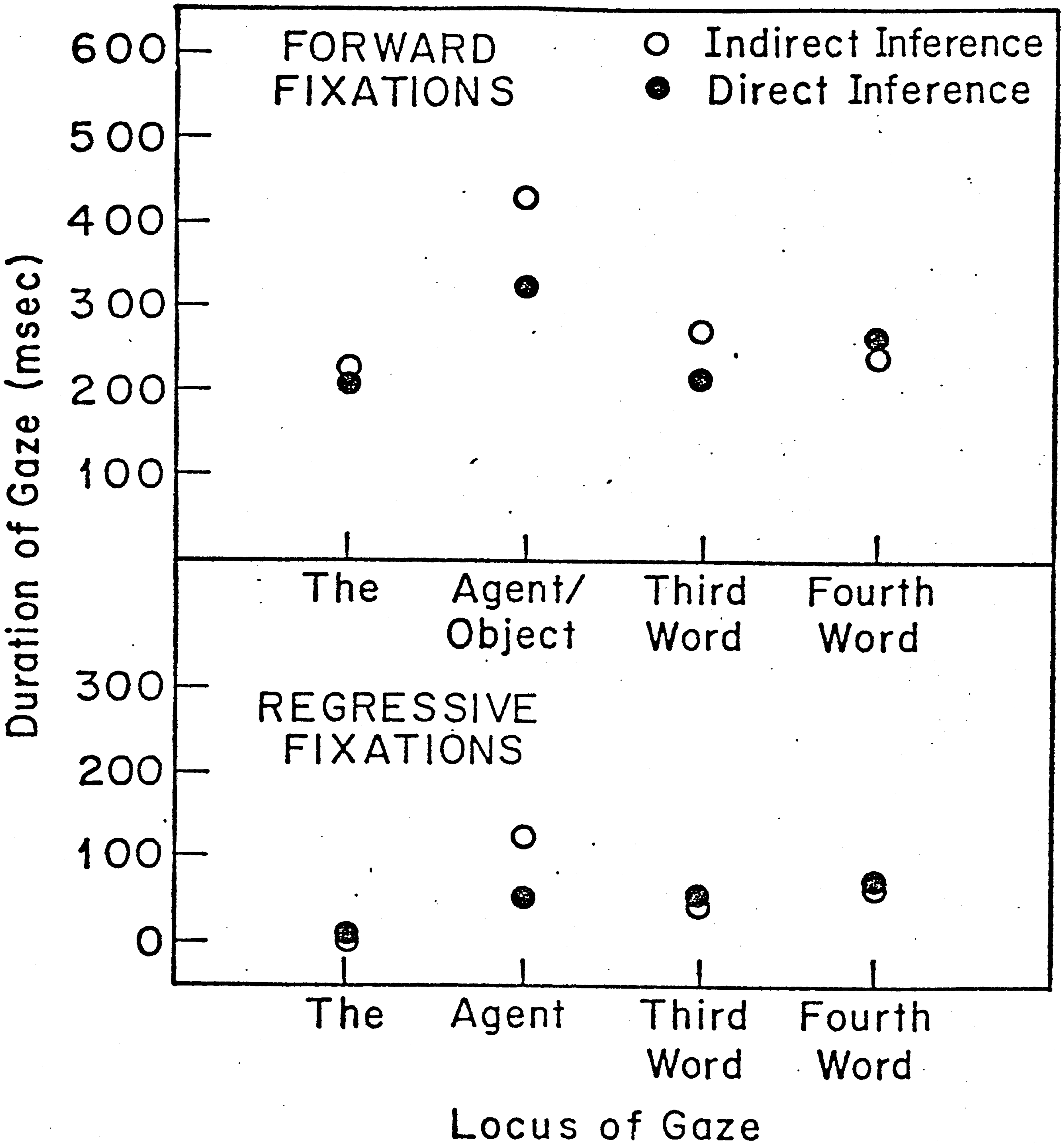

Fig. 4. The gaze duration averaged across subjects. The top panel shows the gaze duration computed from forward fixations. The bottom panel shows the gaze duration computed from regressive fixations.

the definite article. The regressive fixations occurred on the agent word and to the subsequent words. Second, the duration of regressive gazes was 71 msec longer on the agent word in the indirect inference condition. Thus, both the duration of forward and regressive gazes demonstrates the increased difficulty of the indirect inference condition.

There was one final aspect of interest in the pattern of gazes on the target sentence. Very often, the final forward fixation on the sentence was extremely long. To quantify this effect, we measured the duration of the last forward fixation in the sentence plus any other consecutive fixations on the same word. The duration of this gaze averaged 462 msec in the direct condition and 538 msec in the indirect condition. These gazes are certainly longer than the last gaze observed in the previous experiment (352 msec for the indirect condition and 368 msec for the direct condition). One explanation is that the long gazes occurred during or at the end of the sentence because subjects were rehearsing the sentence, perhaps in preparation for recall. These long gazes also support the view that the duration of gazes may be sensitive to the duration of underlying cognitive processes. Rehearsing an entire sentence or even simply its major constituents requires more time than encoding and comprehending a word or phrase.

Discussion

Temporal aspects of inference making. In both experiments, there was an increase in gaze duration around the agent word. This result suggests that at least in some paragraphs, the reader made an inference relating the agent word to the preceding information immediately upon encountering the agent word itself. Since this inference was more difficult in the indirect inference condition, it manifested itself as an increased gaze duration on the agent word. However, the extra time on the agent was not equal to the total response difference between the indirect and direct inference conditions. Thus, the readers did not always make the linking inference immediately upon encountering the agent word.

The distribution of regressive fixations suggests that sometimes the inference-making process was accompanied by regressive fixations. The reader fixated more than the agent word, perhaps the entire subject-verb phrase or the sentence, before linking information in the previous sentence to the currently-read sentence. The linking inference is accompanied by a regression to the agent word or to the previous sentence. Regressions to the previous sentence generally occurred after the entire agent sentence was read. Thus, these experiments suggest that inferences that relate two sentences may be made at various times. The two best candidates may be when the related lexical item is first encountered or at the end of the clause or sentence.

The mechanism of inference making. The current experiments also suggest that semantic distance may not completely account for lexically-based inference making. Both experiments showed an asymmetry in the effects of the order of the agent and verb sentences. A verb that is related to a subsequent agent facilitated comprehension of that sentence. However, the converse did not occur. When the agent was read first, both direct and indirect verbs were equally easy to link. Thus, the information value of the second sentence was important. When the second sentence was deducible from the first, comprehension was not more difficult even if the two concepts were in some sense semantically more distant.

There are two main ways that the verb-based inference could be made. One possibility is that when a verb like murder is encountered in a text, the verb and all of its associated cases (like a killer, a victim, an instrument, and a manner) are explicitly represented, even if the cases are not explicitly mentioned in the sentence (cf. Fillmore,1968; Schank, 1973). This will be called a forward inference, because the cases are represented before they are required (Clark, 1975). If a later lexical item refers to a previously unspecified case, the item can be integrated easily because the case is already in the representation. Thus, after reading a sentence with _murder_, it would be easy to integrate _killer_ because the representation of _murder_ already contains the concept of a killer. By contrast, if the verb were _die_, then an additional inferential step would be necessary to integrate _killer_, consuming extra time, as the results showed. Consequently, _murder_ (with its entailed extra cases) might be expected to take longer to represent than _die_, according to this formulation. However, the reading times were close for _die_ and _murder_ sentences in the opening position. If anything, verbs like _murder_ took less time.

An alternative possibility is that case relations are not represented until they are required (Clark, 1975). In the current experiment, no agent would be represented on encountering either _murder_ or _die_, so reading time for the sentences with the verb in the opening sentence should be equal, as they were. When the agent sentence is read, only then would the agent (or other case) be represented and an inference would be made relating that representation to the representation of the sentence with the verb. This will be called a backward inference. Presumably, the inference would be easier when the verb and agent were semantically more related, that is, in the direct inference condition. Thus, this approach explains the pattern of reading times in both the opening sentences and the agent sentences.

Semantic control of reading fixations. The selectivity of the eye fixations demonstrates that gaze location and duration is sensitive to underlying semantic processes. When the individual word is adopted as the unit of analysis, there is no lag between the inference process and its manifestation in gaze duration. The reader spends longer on the agent word itself.

The duration of gaze on the words around the critical word also showed some selective increase in the indirect inference condition, particularly the word(s) following the agent word. There are at least two interpretations of this effect. One possibility is that sometimes the reader makes the inference after encoding more than just the agent word itself. For example, perhaps the inference is made after the verb is encoded. Thus, the increased duration on the verb would reflect the fact that the reader is making the inference somewhat later in the sentence. This is a reasonable interpretation of the effect, since the evidence from the regressive fixations indicate that sometimes the linking inference is not made until much or all of the sentence is read.

A second possibility is that the increased gaze duration reflects a "smearing" of duration of the main inference. The duration of the inference might be manifested over a number of fixations. With this interpretation, the longer gaze duration on the verb would reflect an inference process initiated when the agent was fixated but which was longer than a single gaze. (See Russo, this volume, for a more detailed discussion of this hypothesis.) Of course, both interpretations could be correct also.

Regressive fixations are fairly prominent in the current experiments for both their frequency and regularity. Their prominence raises the question of the functional role of regressions during reading. Why do good readers tend to make regressions within and between sentences? The traditional interpretation was that regressions are "holding patterns" that allow the reader to maintain an optimal temporal relation between what is fixated and what is processed. If a reader has several processes to execute at one point, he might make a regression until the cognitive load is lightened. While this hypothesis might account for some regressions, it does not explain why the locus of the regressive fixation is so selective. Regressive fixations occurred on particular words that correlated with the inference that was being processed.

An alternative explanation is that the reader regresses to check some information. This explanation would account for the selectivity in the locus of a regressive fixation. However, the meaning and function of the "checking" process requires some clarification. Presumably, checking does not mean that the reader totally forgot some information. If he had, his regressions should be less selective since he would have to reread at least a couple of elements. A more likely interpretation is that the reader is confirming some interpretation of an element and regresses to check his interpretation.

A third possibility is that regressive fixations play a place-keeping role. The reader may fixate a particular word to keep track of the inference he is executing. For example, if he were making an inference about the killer, he would look at that word. Then, when the inference was complete, he would continue reading new textual elements. A closely related version of this hypothesis is that regressive fixations are a collorary of certain semantic processes. In reading, as in many other cognitive domains, there may be a tendency to fixate the referent of the concept being processed. In this view, such regressions may not be functional. The reader may not be encoding information from the text. Rather, the fixation may occur because there is a spatial index to a particular concept that he is thinking about. (These hypotheses are outlined in the domain of spatial information processing in the chapter by Carpenter and Just in this volume.) Of course, there may be many kinds of regressions so that several of these alternative explanations may be necessary to account for regressions. In any case, the data suggests that regressions are an index of semantic processes such as inference making.

The results of these experiments show that reading eye fixations are sensitive to semantic processes during comprehension. This does not mean that semantic processes are the only factors that influence reading eye fixations. Visual processes certainly play a role and perhaps even oculomotor processes. For example, there might be a general scanning rule to fixate the next word or phrase that is out of the area of clear vision. However, this general scanning rule can receive interrupts from semantic and visual processes. These interrupts could increase the duration of a fixation, cause a refixation, or even a regression. The current data argue very strongly for at least some semantic control of reading fixations. For this reason, eye fixations may be a valuable tool for examining substantive issues about the nature of the underlying semantic processes.

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Footnotes

[1]This research was a collaborative effort; the order of authorship is arbitrary. The research was supported in part by Grant NIMH-07722 from the National Institute of Mental Health and Grant NIE-77-0007 from the National Institute of Education.

[2]Some responses (less than 2%) were discarded because of an incorrect response or because the response time was over 10 sec. These trials were equally distributed between the direct and indirect inference conditions.

[3]The data was not analyzed for six subjects. Three subjects were not analyzed because their overall response times did not show the advantage for the direct inference condition. One subject could not be analyzed because of problems with tracking apparatus. Two other subjects were dropped in order to have an equal number of subjects from each version of the experiment. Eleven per cent of the agent sentences were not included in the analysis because of loss of eye spot or head movement. These trials were equally distributed between the direct and indirect inference conditions. The total response time for the scored subset of data was 3340 msec for the indirect inference condition and 2688 msec for the direct inference condition, $F'(1, 27) = 26.98$, $p < .01$.