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Basic Processes and Individual Differences in Understanding and Using Instructions

Final Report

Edward E. Smith and Kathryn T. Spoehr

October 1985

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This project dealt with how people understand and use written instructions in operating a device or assembling an object. In Experiment 1, subjects read and then executed single-step instructions for operating a simple device (e.g., "Turn the right knob so that the gamma meter reads 20 if the sigma indicator light is on"). Each instruction contained three topics - an antecedent (e.g., "sigma indicator on"), an action (e.g., "turn the right knob"), and a consequence (e.g., "gamma meter reads 20") - and the

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order in which the topics were mentioned varied across instructions. Generally, an instruction was read faster if its topics were mentioned in the order in which they would be executed. This effect, taken together with results due to individual differences in working memory, suggested that understanding an instruction involves instantiating a step schema, i.e., an abstract representation of an instructional step that contains slots for antecedent, action, and consequence information.

Experiment 2 used the same materials as the first study, but now the subject's task was simply to memorize each instruction. The time spent reading each word was measured. There was only limited evidence for use of a step schema, likely because the memory requirement fostered a task-specific strategy.

In Experiment 3, we switched to an assembly task. Subjects had to assemble a model helicopter from instructions that included 72 steps. Each step was presented one at a time (e.g., "Slide another joint onto the block so that the narrow end faces upward"). Again we varied the order in which the various topics in a step were mentioned (where now topics include agent, action, object, location, etc.); in addition, we varied the number of topics in a step (which we assumed corresponded to the number of slots in a step schema that need to be filled). Instructions were read faster when they contained fewer topics (or schema slots), and when their topics were mentioned in the order they would be executed. Moreover, these effects were more pronounced for readers who had smaller working-memory spans. These results were consistent with the idea that instruction understanding involves schema instantiation.

In Experiment 4, we returned to a device-operation task, but used a more complex device than that used in the earlier studies. Now, we focused on information other than that in the instructions, as the major variable was whether or not subjects had learned a mental model of the device they had to operate. Having a mental model facilitated memory of the components of the device, as well as the time to read an instruction about operating the device, as well as ability to reason about the device.

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BASIC PROCESSES AND INDIVIDUAL DIFFERENCES IN UNDERSTANDING AND USING INSTRUCTIONS*

Edward E. Smith and Kathryn T. Spoehr

Bolt Beranek and Newman Inc.

Final Report

October 1985

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Abstract

This project dealt with how people understand and use written instructions in operating a device or assembling an object. In Experiment 1, subjects read and then executed single-step instructions for operating a simple device (e.g., "Turn the right knob so that the gamma meter reads 20 if the sigma indicator light is on"). Each instruction contained three topics -- an antecedent (e.g., "sigma indicator on"), an action (e.g., "turn the right knob"), and a consequence (e.g., "gamme meter reads 20") -- and the order in which the topics were mentioned varied across instructions. Generally, an instruction was read faster if its topics were mentioned in the order in which they would be executed. This effect, taken together with results due to individual differences in working memory, suggested that understanding an instruction involves instantiating a step schema, i.e., an abstract representation of an instructional step that contains slots for antecedent, action, and consequence information.

Experiment 2 used the same materials as the first study, but now the subject's task was simply to memorize each instruction. The time spent reading each word was measured. There was only limited evidence for use of a step schema, likely because the memory requirement fostered a task-specific strategy.

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In Experiment 4, we returned to a device-operation task, but used a more complex device than that used in the earlier studies. Now, we focused on information other than that in the instructions, as the major variable was whether or not subjects had learned a mental model of the device they had to operate. Having a mental model facilitated memory of the components of the device, as well as the time to read an instruction about operating the device, as well as ability to reason about the device.

1. BACKGROUND

1.1 Major Goals

The overall goal of our project was to understand the cognitive processes operative when people use written instructions as an aid to assembling an object or operating a device. By understanding such processes, we hoped to contribute to a general theory of instruction as well as to understand the sources of individual differences in peoples' abilities to comprehend instructions.

In addition to the above basic-research goals, there were also practical goals of our work. One was to provide a scientific basis for making guidelines for the construction of real-world instructions, such as training manuals and job aides. Another practical goal concerned individual differences: by relating differences in how well different people coped with written instructions to measurable differences in their information processing capacities, we hoped to make it possible to screen individuals more effectively for different kinds of training materials.

1.2 Two Foci of Instructions Research

Since the inception of our work on instructions, there have been two distinct foci of our research. One focus is on the

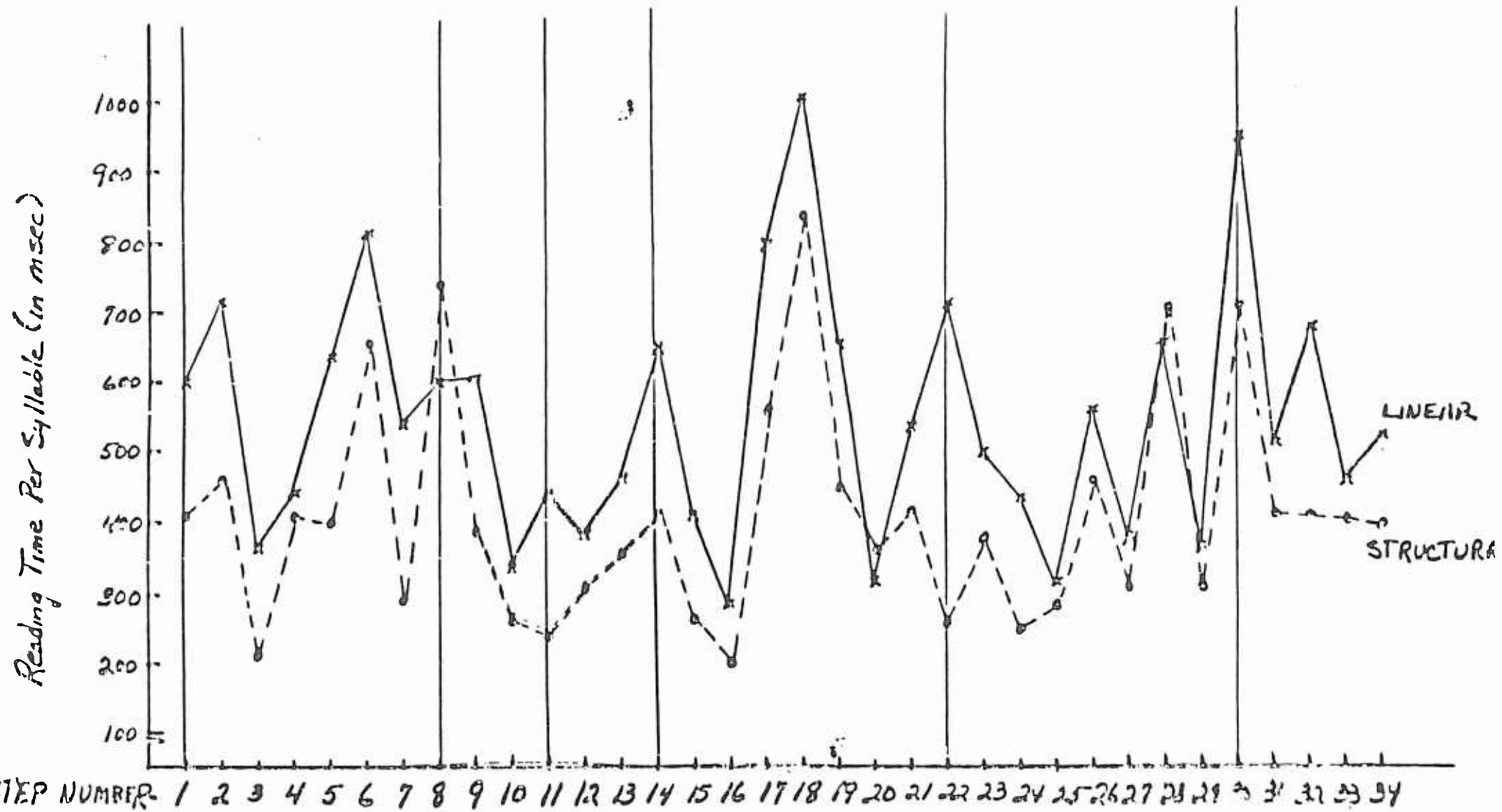
instructions themselves; the second is on knowledge other than the instructions that individuals bring to bear in assembling an object or operating a device. We can make this contrast clearer by considering a case where one is assembling a model helicopter: one may try to do this solely by following the instructions that accompany the kit; alternatively, one may try to assemble the model without ever consulting the accompanying instructions, relying instead on what the model is supposed to look like when completed, and on one's past experience in assembling models. Another way to highlight the difference between our two research foci is to note the different general research areas that they are related to: when we focus on the instructions per se, our work seems most related to text processing; when we focus on other knowledge about the task, our work seems more related to procedural learning and problem solving.

Over the course of our work on instructions, we have shifted from one focus to another. Our earlier work (summarized in Smith & Goodman, 1984) dealt with the assembly of electrical circuits. Our major concern then was how explanatory material about circuits in general affected one's ability to understand and use instructions to assemble a specific circuit; this was a clear-cut case of focusing on knowledge other than the instructions themselves. We found that providing subjects with an explanation of either the structure or function of circuits decreased the time needed to read each step. These results are illustrated in

Figure 1. Note that while explanatory material partly determines the time to read a step, there are other determinants of reading time that are intrinsic to the step; i.e., the reading time curves rise and fall for different steps in the same way for all groups. This led us to look at the intrinsic determinants of step difficulty, which is an instance of focusing on the instructions themselves. We found that the time to read a step increased with the number of propositions it contained. Further analysis suggested that some propositions were more important than others; two propositions that dealt with different topics (e.g., wires, dry cells) contributed more to reading time than two that described a single topic (e.g., the color and size of a wire). Thus, something like the notion of topics seemed to be a proper unit for studying step difficulty.

In the first phase of the present project (e.g., Spoehr, Smith, & Morris, 1983; 1984), we shifted our focus entirely to the instructions themselves, and to the determinants of step difficulty. Now we used an operation task (originated by Dixon, 1982), in which subjects read and executed instructions about how to operate a simple device. Each instruction mentioned three topics (an antecedent, action, and consequence) and we were interested in the effects on reading time of presenting these topics in various orders. We found that reading time was fastest when the topics were mentioned in the order in which they would be executed (antecedent, action, consequence).

Reading Time Per Syllable



In the last year of the present project, both foci of research have been well represented. We have studied two tasks, assembly of a model helicopter and operation of a control panel. The assembly task focused almost exclusively on the instructions per se, while the operation task was primarily concerned with the effects of knowledge other than the instructions. These tasks again showed that the time to read and understand instructions is determined both by factors intrinsic to the steps themselves, such as the number and order of topics, as well as by explanatory material. Virtually all of the remainder of this report is devoted to a detailed review of the research conducted in the past two years.

1.3 A Comment on Individual Differences

Before beginning our review, a word is in order about the role that individual differences plays in our experiments. In all our studies, we obtained measures of subjects' memory abilities; we did this because the relation between (i) individual differences in memory and (ii) performance on an instructions task provides important clues about the basic processes operative in the instructions task. The individual-difference data also have their applied value, in that they can be used to assess what kinds of abilities are needed for success in different kinds of tasks.

2. SCHEMAS AND A SIMPLE OPERATIONS TASK

2.1 Rationale

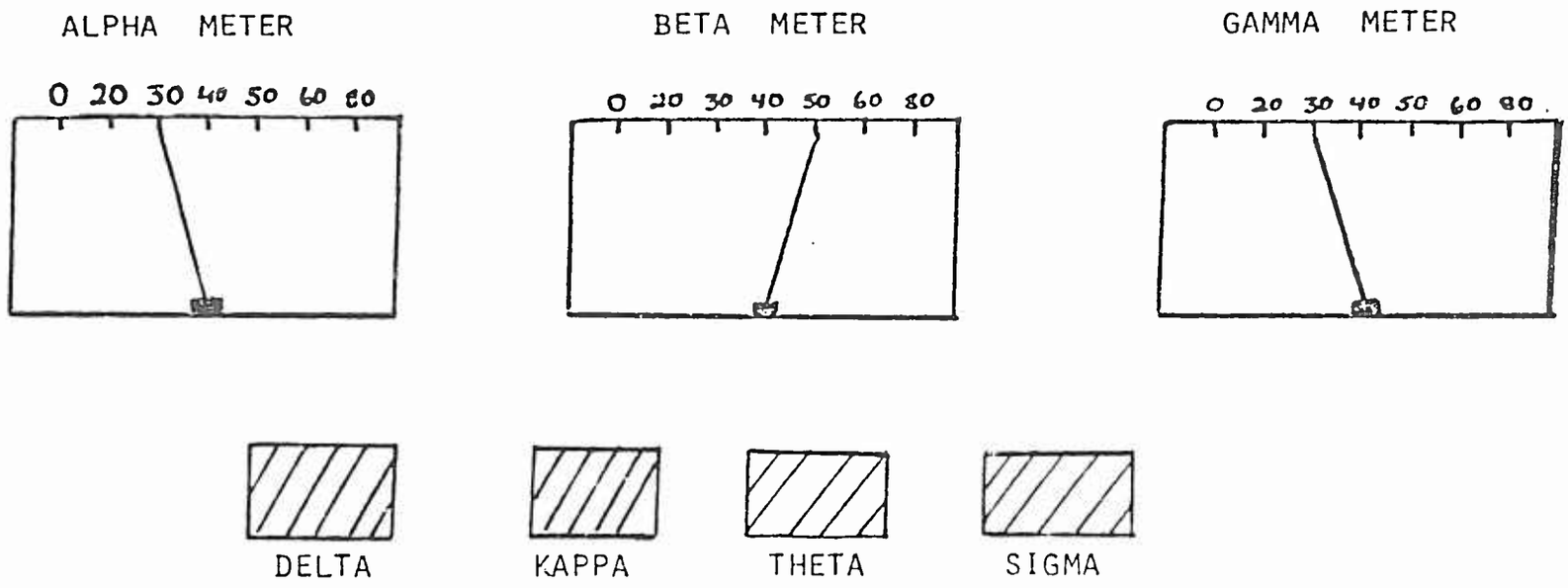
Our first year of work on the current project focused on the comprehension of simple written instructions like "If the sigma indicator light is on, turn the right knob in order to make the gamma meter read 20". We hypothesized that comprehension of such an instrucitonal step could be viewed as instantiating a step-schema, where the step-schema of interest has three major slots corresponding to the action, the antecedent (the circumstances under which the action is to be performed), and the consequence (the end result of the action). Understanding the preceding sentence, then, amounts to filling the step-schema's action slot with "turn right knob", its antecedent slot with "sigma indicator light on", and its consequence slot with "gamma meter read 20". The question of major interest was, How should the information (topics) in an instruction be ordered so as to facilitate the process of instantiating a step-schema?

2.2 Experiment 1: Operating a Simple Device

2.2.1 Method

Subjects were asked to read and execute instructions in order to operate the controls of the simple panel shown in Figure 2. All instructions contained three slot-fillers, or components

DISPLAY PANEL



IF THE SIGMA INDICATOR LIGHT IS ON TURN THE RIGHT KNOB SO THAT THE GAMMA METER READS 20

~~Figure 2.1 Diagram of Display Used In Our Experiment~~

of information: antecedent, action, and consequence. Each instruction was one of three possible orders of the three components, chosen so that we could experimentally test three different accounts of what ordering would yield the best performance. According to the first account, information within a step schema is organized with the action being primary and the other slot information being secondary to it (Dixon, 1982); therefore an action-consequence-antecedent order (e.g., "Turn the right knob in order to make the gamma meter read 20 if the sigma indicator light is on.") should be the easiest to read. According to the second account, the slots in a step schema should be filled in the order in which they are needed when the step is executed; therefore, the antecedent-action-consequence order (e.g., "If the sigma indicator light is on turn the right knob in order to make the gamma meter read 20.") should yield the best performance. Finally, the third account has it that schema slots are organized by goals, as it is in many production-system based expert systems; hence the consequence-action-antecedent order (e.g., "In order to make the gamma meter read 20 turn the right knob if the sigma indicator light is on") should be best.

We were not only interested in finding out how information in step schemas is structured but also in examining how the comprehension process is affected by different methods of presentation. Our subjects therefore read and executed a series of these individual steps under both simultaneous conditions,

where the instruction and device display appeared at the same time, and under sequential conditions, where the instruction was read and disappeared before the device display appeared.

2.2.2 Results

2.2.2.1 Basic results

Although the order in which the components appeared had no effect on execution times under either presentation method, the component order did affect the reading times. Under simultaneous display conditions, the antecedent-action- consequence order was read most quickly, followed by the action- consequence-antecedent order, and finally by the consequence-action- antecedent order. This suggested that components were being filled into the slots of the step schema in the same order they were needed during the execution of the step. In the sequential condition, less substantial effects of slot-filler ordering were found. The consequence-action- antecedent form still took the longest to read, but there were no significant differences between the other two orders. Subjects therefore appeared to be processing the instructions in an entirely different manner when they had to read in order to execute a step from memory.

2.2.2.2 Individual differences

The reasons for the different pattern of results under the two presentation conditions become apparent when one considers the working-memory capacity of the subjects. We consider

working-memory a critical factor in a reader's ability to comprehend instructions because of its involvement in just about every aspect of the task. At the simplest level, working-memory is used as a temporary store for individual words and phrases while the relevant schema is being operated on. Working-memory must also serve as a store for the reader's currently active set of goals and plans during both reading and execution, and may also maintain a subset of the reader's permanent knowledge store that is immediately relevant to the task.

We measured working-memory capacity in two ways. First we administered a relatively standard memory-span test: we determined the maximum list length of digits that the subject could reliably recall in reverse order immediately after hearing the list. We will refer to this measure as the "backward digit" span. Unfortunately, the psychological literature does not lend much support to the notion that a standard memory-span measure such as backward-digit span is at all predictive of reading comprehension performance. (see, e.g., Crowder, 1982). We therefore also used another measure, devised by Daneman and Carpenter (1980), and shown to correlate well with performance on reading tasks. Daneman and Carpenter required subjects to read aloud sentences of 14-16 words, and to remember the final word in each of a series of such sentences. The working memory span is the longest number of sentences that the subject can read in succession and still reliably recall the final words in the

correct order. We will refer to this capacity measure as the "working memory" span. The subjects in our experiment had working-memory spans ranging from 2 to 6, and their working-memory spans correlated only slightly with their backward-digit spans.

When the reading times for steps with different component orderings are considered separately for subjects with different working-memory spans, an interesting pattern emerges. Under the simultaneous presentation condition, all types of subjects read the antecedent-action-consequence version fastest, the action-consequence-antecedent version next fastest, and the consequence-action-antecedent version slowest. The higher the working-memory span, the faster the reading times overall, but there was no interaction between working-memory span and ordering of components. The pattern was quite different in the sequential condition. Here, although the subject's with the higher working-memory spans were faster overall, there was an interaction between component order and working-memory span. Subjects with good capacity read all types of instructions approximately equally fast, but subjects with poor working-memory spans showed the same pattern of increasing reading times over instruction types that they displayed in the simultaneous condition.

We interpret these results to mean that the simultaneous

presentation of instruction and display allows the reader to scan the instruction for the component that is to be executed first (in this case, the antecedent), and to actually carry it out (evaluate the antecedent). The reader can then scan and locate the second component (the action), and "anticipatorily execute" it in the sense that he or she can place one hand on the proper control. Finally the last (consequence) component is located and read prior to the subject signalling the completion of reading and starting to actually manipulate the controls. The net result is that simultaneous presentation places very little burden on a subject's working memory, making it possible for even the poorer capacity subjects to use the same strategy that the better subjects use.

When a step must be read and remembered in the sequential condition, subjects must instantiate a schema while they are reading each instruction, and then maintain then instantiated schema in memory when the instruction has been removed. The poorer working-memory subjects appear to be processing component by component, scanning for the slot-fillers in the order in which they are to be executed in much the same way as they did under simultaneous conditions (though in this case there can be no anticipatory executions). The subjects with better working-memories appear to be able to take the components in any order in which they are presented in the written instruction and fit them into the step schema. Thus the two types of subjects are doing qualitatively different things in the sequential condition.

2.2.3 Summary

To summarize our findings, working-memory limitations appear to force subjects into using different reading processes when the nature of the task creates an overload on working-memory. The best presentation method is to have the instruction and the display coincide in time. The best way to present the components within a single step is to put them in the order in which they will be needed when the step is executed. Subjects with good working-memory capacity are affected little by deviations from these principles, but subjects with poor capacity are impeded to a progressively greater extent the more conditions deviate from the optimal.

2.3 Experiment 2: On-Line Measures of Device Operation

2.3.1 Rationale

In this experiment we used the same materials as the preceding study, but now we measured the reading time for each word in an instructional step as our goal was to obtain an on-line analysis of how a step is understood. Our expectations about the patterns of reading times were guided by our schema account of understanding instructions. Specifically, we assumed that understanding a simple operation instruction amounts to instantiating a schema with slots for the antecedent, action, and consequence, and that these slots need to be filled in the order

just specified. Given this view, and the assumption that filling a schema slot takes measurable time, it follows that:

(1) When the order of components is antecedent-action-consequence, reading times should increase at words that end components, because the reader should be filling the relevant schema slots at these points.

(2) With other orders of components, readers may not pause at the end of a slot-filler if it does not correspond to the schema slot that the reader is searching for; in these cases, though, the reader may spend a relatively long duration on each word because he is holding a relatively large amount of information in working memory.

In addition to the above, we explored a third hypothesis, which was not tied to our schema account:

(3) For any order of components, reading times should be relatively long for the "informative" words, i.e., words that change from instruction to instruction; there were five such words in each instruction, including the name of the relevant indicator light (e.g., "theta", "sigma"), whether it was "on" or "off", whether the knob to be turned was "left" or "right", the name of the relevant meter (e.g., "alpha", "beta"), and that meter's reading.

2.3.2 Method

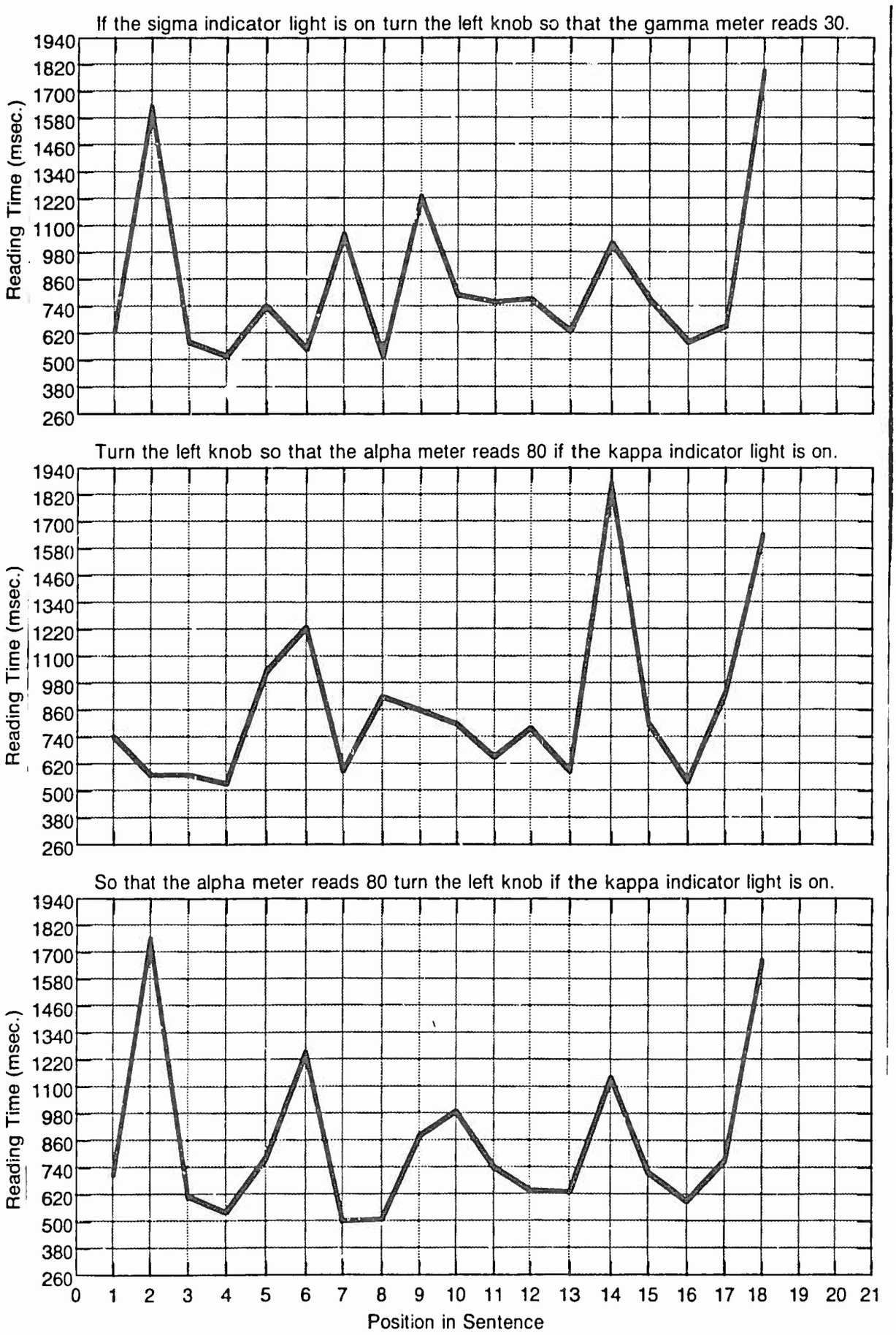
Since this study was an exploratory one, we decided to expedite matters by using a simple recall task rather than our device-operation task. Subjects read for understanding each instructional step, and then tried to recall it verbatim. In previous research (Spoehr et al., 1983), we found that this recall task reveals the same effect of order of components as does the device-operation task, presumably because the same schema is employed in both tasks.

Thirty different instructions were used. In 10 of them, the order of components was antecedent-action-consequence (the "antecedent-first" condition); in another 10, the order was action-consequence-antecedent ("action-first"); and in the remaining 10, the order was consequence-action-antecedent ("consequence-first"). The three types of instructions were randomly intermixed. On each trial, an instruction was presented on a microprocessor display one word at a time, and subjects pressed a space bar as soon as they understood the current word and its relation to the previous ones. Depression of the space bar immediately triggered presentation of the next word. After the last word of the sentence went off, subjects attempted to recall the sentence in correct order.

2.3.3 Results

While our primary interest is in the reading times, we also analyzed the recall data. Only the five informative words in each sentence were scored for accuracy. The percentage of words recalled in correct order was 95.2 for the antecedent-first condition, 91.4 for the consequence-first condition, and 85.0 for the action-first condition. These results reveal another performance advantage of the antecedent-action-consequence order.

Let us move on to the reading times. As in our previous recall study (Spoehr et al., 1983), instructions in the antecedent-first order were read faster than those in the action-first order. In the present study, however, there was no real difference between the antecedent-first and the consequence-first orders. More detailed analyses are in Figure 3, which presents the reading times (measured in milliseconds) for each word of an instruction, separately for the three orders. (Note that the words in the sample instruction given at the top of each panel are not always perfectly alligned with their position in the sentence as given on the x-axis.) Consider how these results line up with our hypotheses about increased processing at the end of components or slot fillers. For the antecedent-first condition (top panel of Figure 3), reading times are relatively long at the words ending the antecedent and consequence components, but not for the word ending the action component.



~~Figure 2.2~~ -- Reading Times For Each Word Of An Instruction

For the action-first and consequence-first orders (the middle and bottom panels of Figure 3), reading times are elevated only for words ending the antecedent component. Though this latter outcome is consistent with our second hypothesis (the reader is presumably searching for the antecedent slot-filler), there is reason for caution. Specifically, in the action-first and consequence-first orders, the last word of the antecedent is also the last word of the sentence, so the pause at the end of these antecedents may reflect some end-of-sentence process that occurs in all conditions.

Our third hypothesis was that of elevated reading times at the five informative words. As an indication of this, we expect longer times for informative words than for the words adjacent to them. In the antecedent-first condition, this criterion was met only for the two informative words that ended components; in the action-first and consequence-first conditions, the criterion was met for 3 of the 5 informative words. Thus, there is at best limited support for this hypothesis.

2.3.4 Interpretation

It appears that end-of-component words and informative words are responsible for only part of the variation in reading times. Another factor that seems to be involved is serial position in the instruction: subjects tend to pause at certain points when reading the instruction regardless of what word occurs at that

position. As evidence for this, there are positive correlations between the reading times for any two of our conditions over the positions of the sentence, e.g., it takes longer to read the tenth than the eleventh word in the sentence, regardless of what exact words fill those positions. This position effect likely reflects a rehearsal process: because they must recall the instruction verbatim, subjects pause at various points to rehearse what they have read thus far, and these rehearsal points are determined by how much is in memory not by what the current word is.

3. SCHEMAS AND A COMPLEX ASSEMBLY TASK

3.1 Rationale

Experiment 1 showed that when subjects had to understand an instruction, reading time was fastest when the topics were mentioned in the order they needed to be executed. To extend the generality of this finding and to provide some further tests of our schema account of it, we decided to switch from an operation to an assembly task, and to use a task where the steps differed appreciably in the number of topics or slot-fillers they contcined.

The task we used involved assebling a model helicopter from Fischer-Technik parts. The written instructions to do this contained 72 steps of the form "Slide another slanted joint onto the block so that the narrow end faces up". Within any step, the slot-fillers might include an action (e.g., "slide"), and actor (e.g., "joint"), and object (e.g., "block"), a location (e.g., "knob of the block"), a modality (e.g., "so that narrow end faces up"), and an orientation (e.g., "lengthwise"). To assess our order-of-mention effect, we varied whether the action, actor and object appeared in the early or latter part of the step; since these three slot-fillers are needed early in execution, we expected faster reading times when they occurred early in the step. To further evaluate our schema hypothesis, we varied the

number of slot-fillers in a step; the more slots to be instantiated, the longer it should take to read the step.

3.2 Experiment 3: Assembling a Helicopter

3.2.1 Method

3.2.1.1 Overview

The experiment included three stages. In the first, we measured individual differences in memory. The second stage was devoted to familiarizing the subjects with the various components of the assembly. The third stage consisted of the main task--construction of the helicopter. We discuss these stages in sequence.

3.2.1.2 Individual differences

Again we assessed two different measures of working-memory, backward-digit span and working-memory span.

3.2.1.3 Familiarization with components

All told, 54 parts were used in the assembly, which were of 24 different types. The names of these 24 types were quite transparent (e.g., "small block", "small plate", "slanted joint"). They had been taken from Baggett's (e.g., 1985) work with the same helicopter assembly; she had devised the names by first having subjects generate candidate names, then using these names in an identification task, and then refining the names

further. Transparent though the names were, they and their referents were still somewhat unfamiliar to our subjects, and so we included familiarization training with the parts and their names.

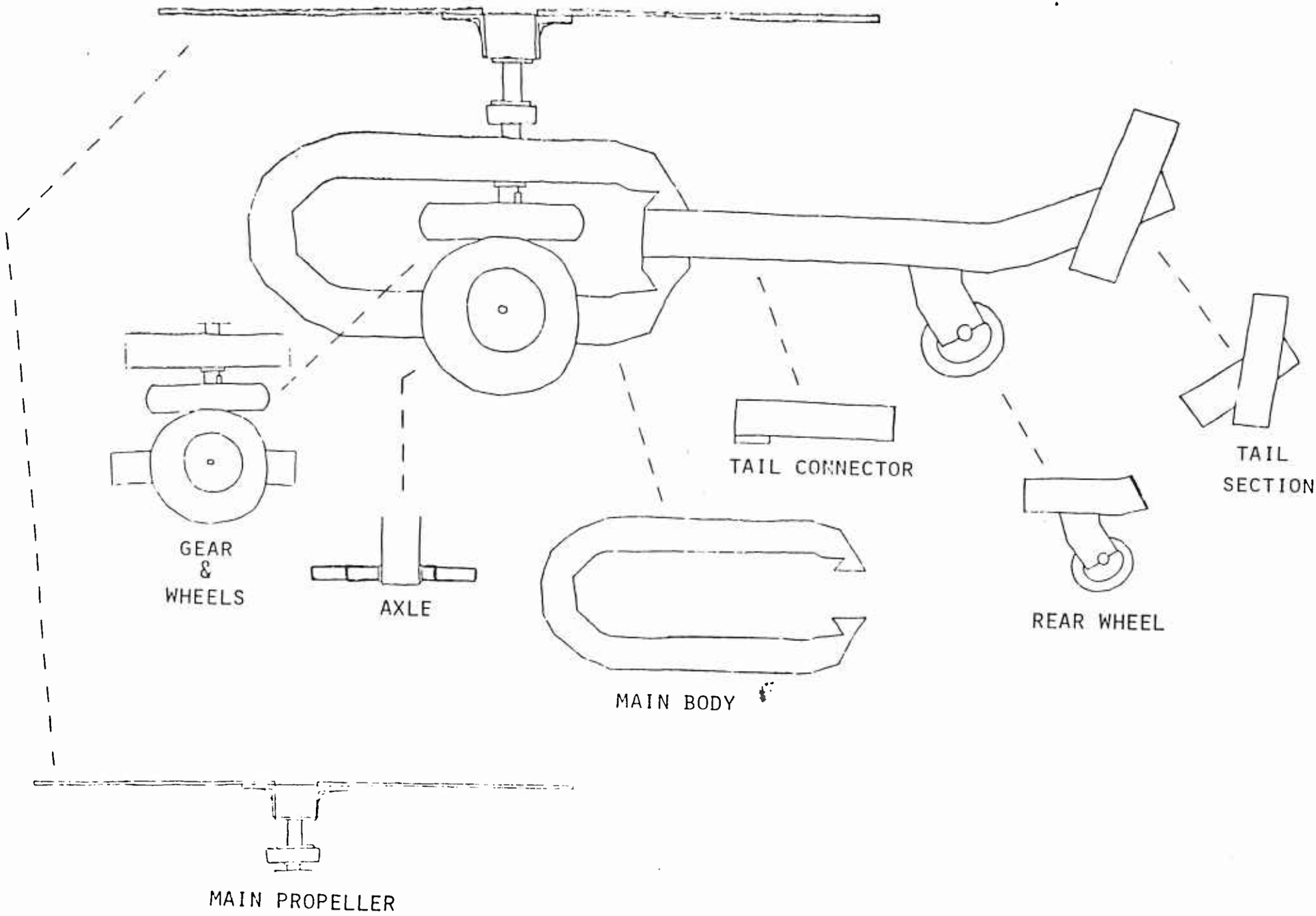
Instances of the 24 different types and their names were arrayed on a large piece of cardboard. The array consisted of 2 columns, each containing 12 slots, where a slot contained an actual part and the name of that part. Subjects studied the array at their own rate (usually on the order of 3-5 minutes), starting with the left column and going from top-to-bottom within a column. Typically, they picked up each piece and examined it. To insure that they had learned the parts, the array was removed from view and subjects were given a quiz. The quiz consisted of thirteen questions (only half the parts were queried), where the typical question first asked the subject to find a part with a particular property or name, and then to state how this part differed from similar ones. A few of the questions also required a minor assembly operation (e.g., putting together a tire and wheel). If subjects made a mistake, they were informed of their error and told to try again. Subjects typically made few errors.

3.2.1.4 Assembly task

The heart of the experiment required assembling the helicopter from written instructions. A diagram of the helicopter, which gives its major subassemblies, is presented in

Figure 4. There were 72 steps, which had the subjects build the copter from the tail section to the main propeller. For half the subjects, the steps were such that the action, actor, and object were mentioned first, while information about location, modality, and orientation were mentioned in the second part of the step; this is referred to as the "basic" order. For the other half of the subjects, the order of mention was reversed so that information about location, modality, and orientation came first; this is referred to as the "modified" order. For both orders, some of the steps mentioned 3 slot-fillers, others mentioned 4, and the rest mentioned 5. The steps therefore represented the orthogonal combination of order of slot-fillers (basic vs. modified) and number of slot-fillers (3 vs. 4 vs. 5). Examples of all six kinds of steps are shown in Figure 5. However, the set did not contain an equal number of each type.

In addition to these steps, we also included in the instructions statements that introduced each subassembly of the helicopter (e.g., "First you will assemble the tail section of the helicopter. This section includes the rear propeller".), as well as statements that signalled completion of a subassembly (e.g., "Make sure the rear propeller turns. If it does – congratulations!! – you have successfully completed the tail section.") These statements provide knowledge about the assembly other than that contained in the steps <u>per se</u>, but there was no variation in this other knowledge. Similarly, in addition to the


GEAR
&
WHEELS
AXLE
MAIN BODY
TAIL CONNECTOR
REAR WHEEL
TAIL
SECTION
MAIN PROPELLER

Illustrations of Materials in Helicopter Assembly Task

# Topics	Basic Instructions
3	Tighten the handle by turning it clockwise.
4	Slide another slanted joint onto the block so that the narrow end faces upward.
5	Lay a large block lengthwise on the table so that the knob faces to the right and the slot on the end of the block is vertical.

# Topics	Modified Instructions
3	By turning clockwise, tighten the handle.
4	With the narrow end facing upward, slide another slanted joint onto the block's knob.
5	With the knob facing right and the slot on the end of the block vertically, lay a large block lengthwise on the table.

instructions we also provided subjects a diagram of two views of the completed helicopter (see Figure 6), which remains in view throughout the task. This diagram also provides assembly knowledge additional to the instructions, but again we did not experimentally manipulate any aspect of this additional knowledge.

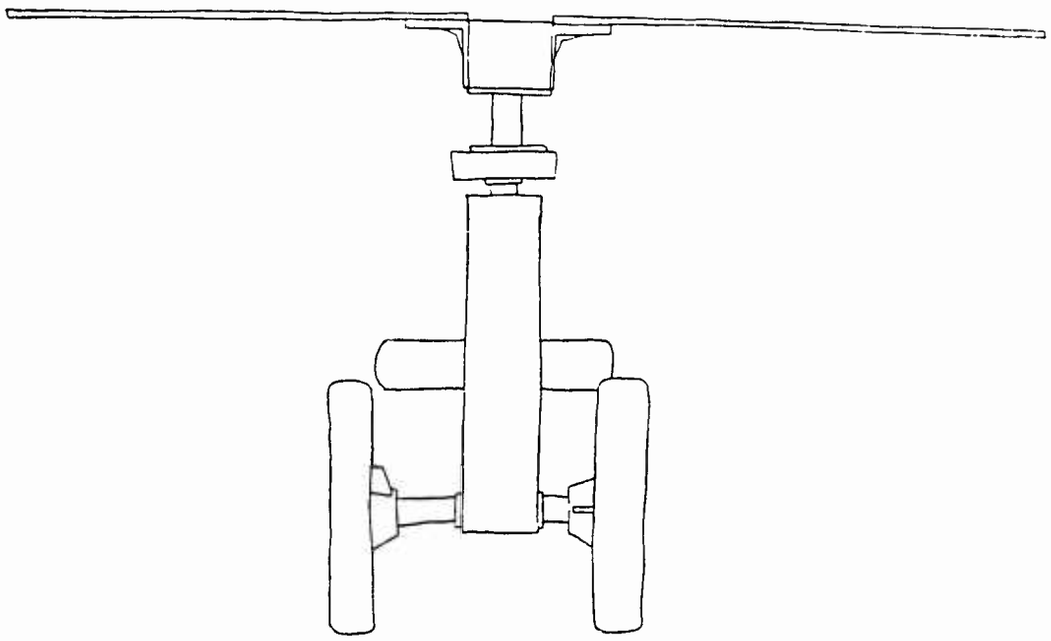
The details of the procedure are as follows. Instructions appeared one step at a time on a microprocessor display. The name of the current subassembly appeared in the lower right of the screen; we did this because often we had to use the name of the subassembly in the step, and also because Baggett suggests that this makes things easier for the subjects. Subjects read each instruction, pressed a space bar when they thought they understood it, and tried to execute the instruction after it disappeared from view (the assembly kit was adjacent to the display). Both reading time and execution time were recorded for each step.

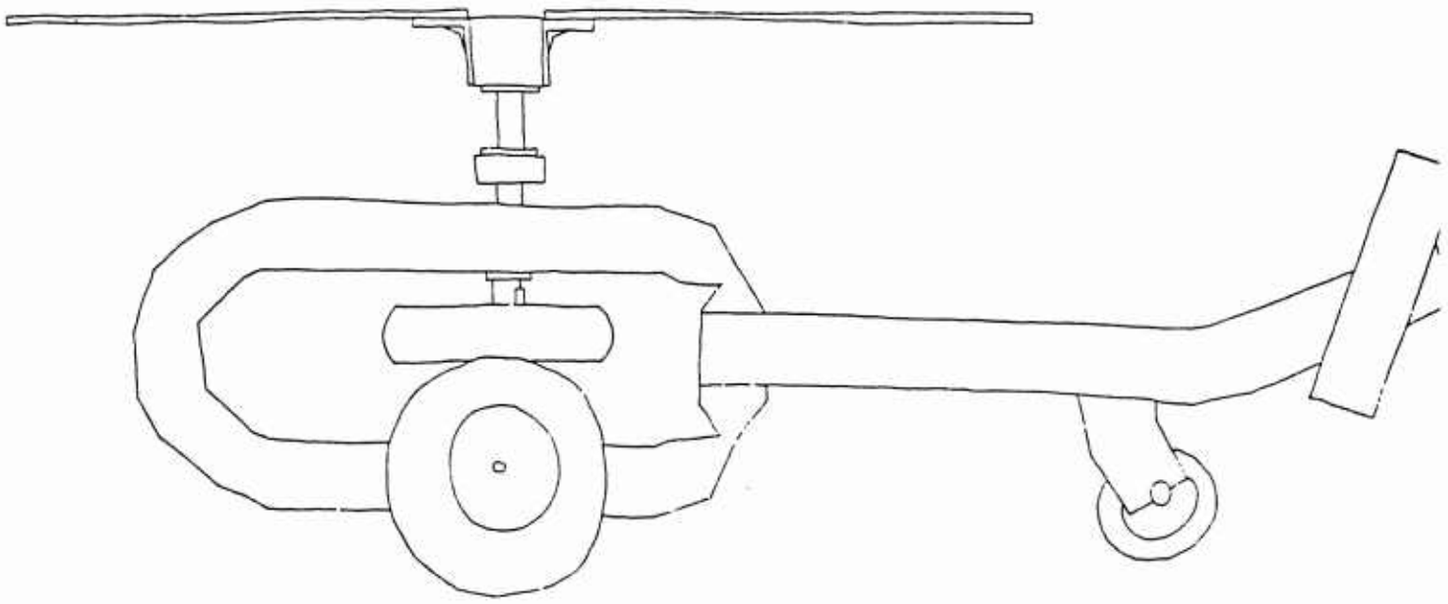
3.2.2 Results

The results of interest are all from the assembly task.

3.2.2.1 Major results

Raw reading times varied from about 5 to 25 seconds. Since the number of syllables in a step covaried with the number of topics or slot-fillers, we converted each raw reading-time to a



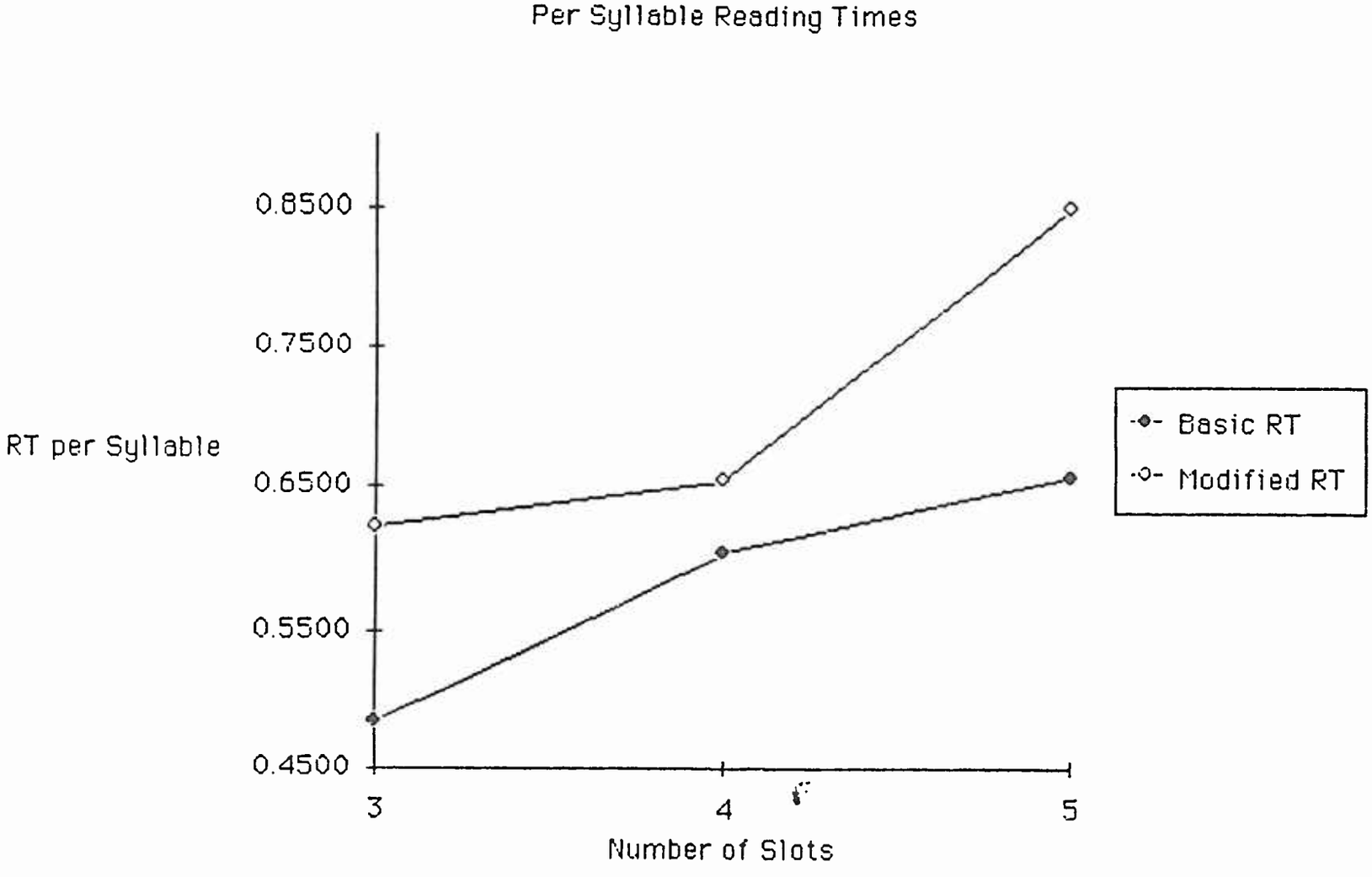


reading time per-syllable. These normalized scores are the referents of "reading times" in what follows.

Figure 7 presents reading times, as a function of number of slot-fillers, separately for basic and modified instructions. Steps are read faster with basic than modified instructions, which extends our earlier finding that reading is facilitated when the order of mention mirrors the order of execution. Moreover, for both sets of instructions, reading times increase monotonically with the number of slot-fillers in the step. This result provides an added reason for construing the process of understanding a step as instantiating the slots of a step schema. Furthermore, there is an interaction between order and number of slot-fillers, such that the number has a more deleterious effect with a non-optimal ordering than an optimal ordering of slot-fillers.

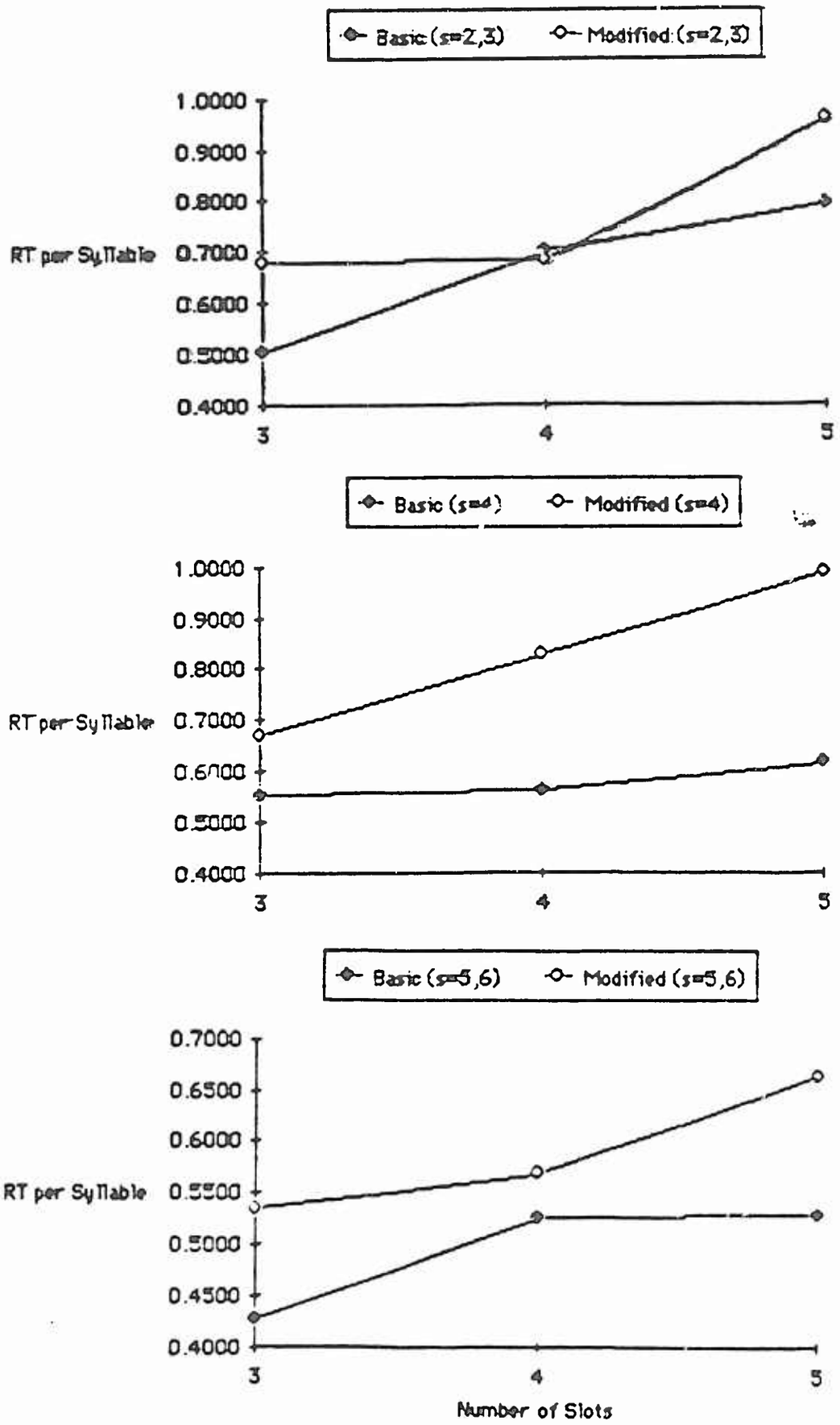
Figure 8 depicts the same results as above, but presented separately for subjects with different working-memory spans (as estimated by the Daneman and Carpenter, 1980, technique). Note that the time scale is expanded for the subjects with the largest spans. In general, the higher their span, the faster the subjects read the steps. More interestingly, high-span subjects showed less effect of the number of slot-fillers than did subjects with lower spans.

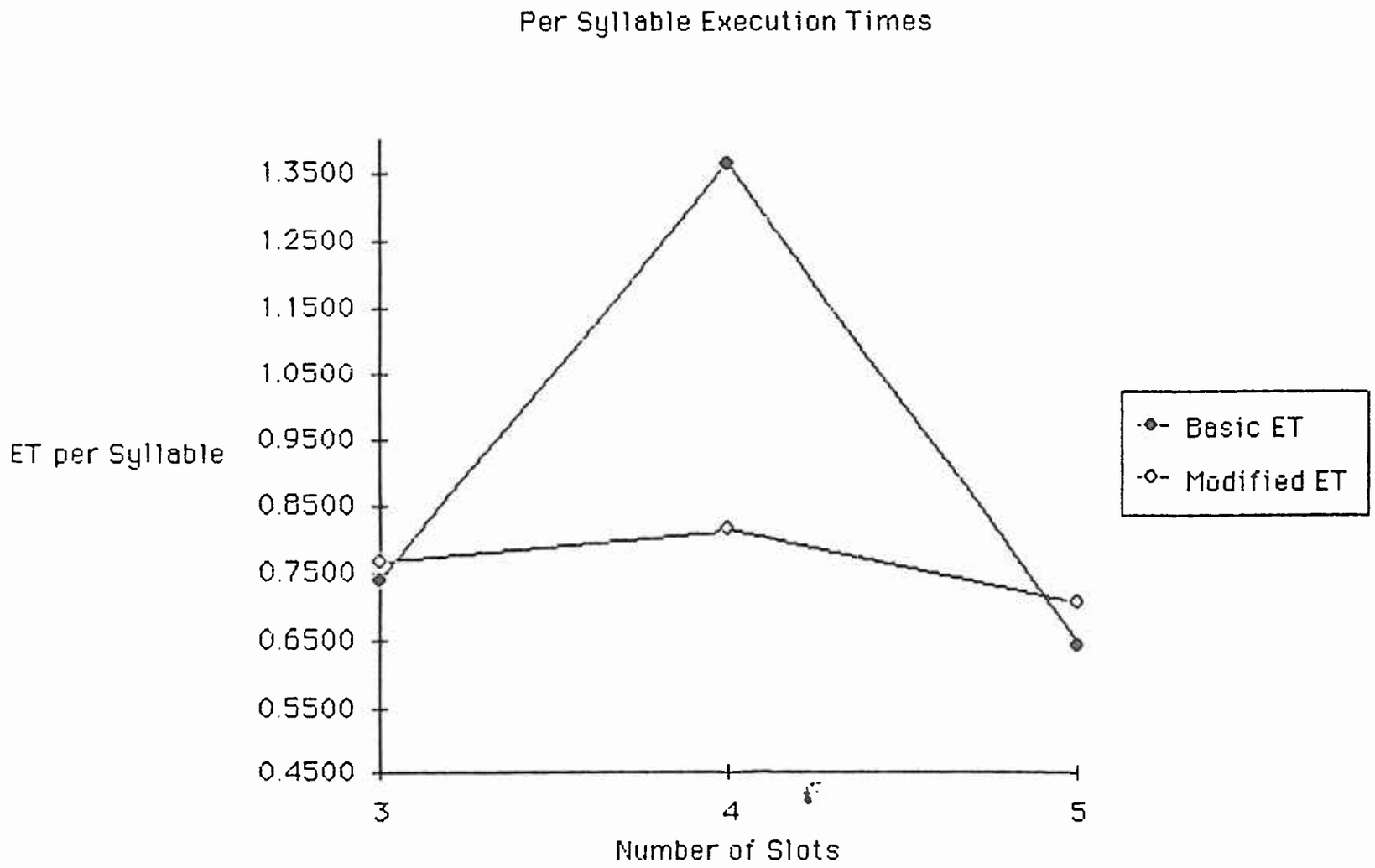
Figures 9 and 10 present the comparable analyses of


Per Syllable Reading Times
RT per Syllable
0.8500
0.7500
0.6500
0.5500
0.4500
3
4
5
Number of Slots
Basic RT
Modified RT

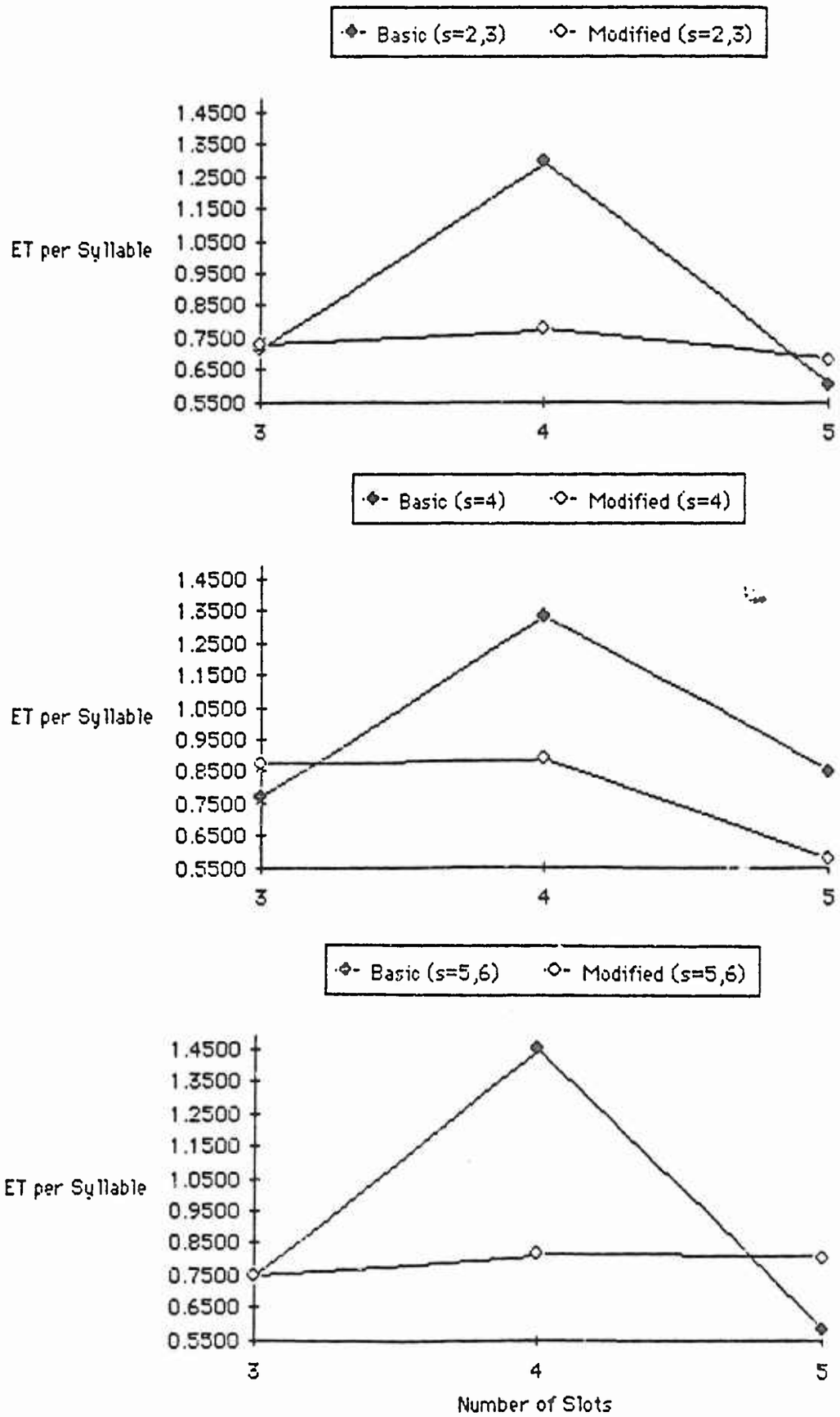
24a

Per Syllable Reading Times




Per Syllable Execution Times
ET per Syllable
1.3500
1.2500
1.1500
1.0500
0.9500
0.8500
0.7500
0.6500
0.5500
0.4500
3
4
5
Number of Slots
Basic ET
Modified ET

Per Syllable Execution Times



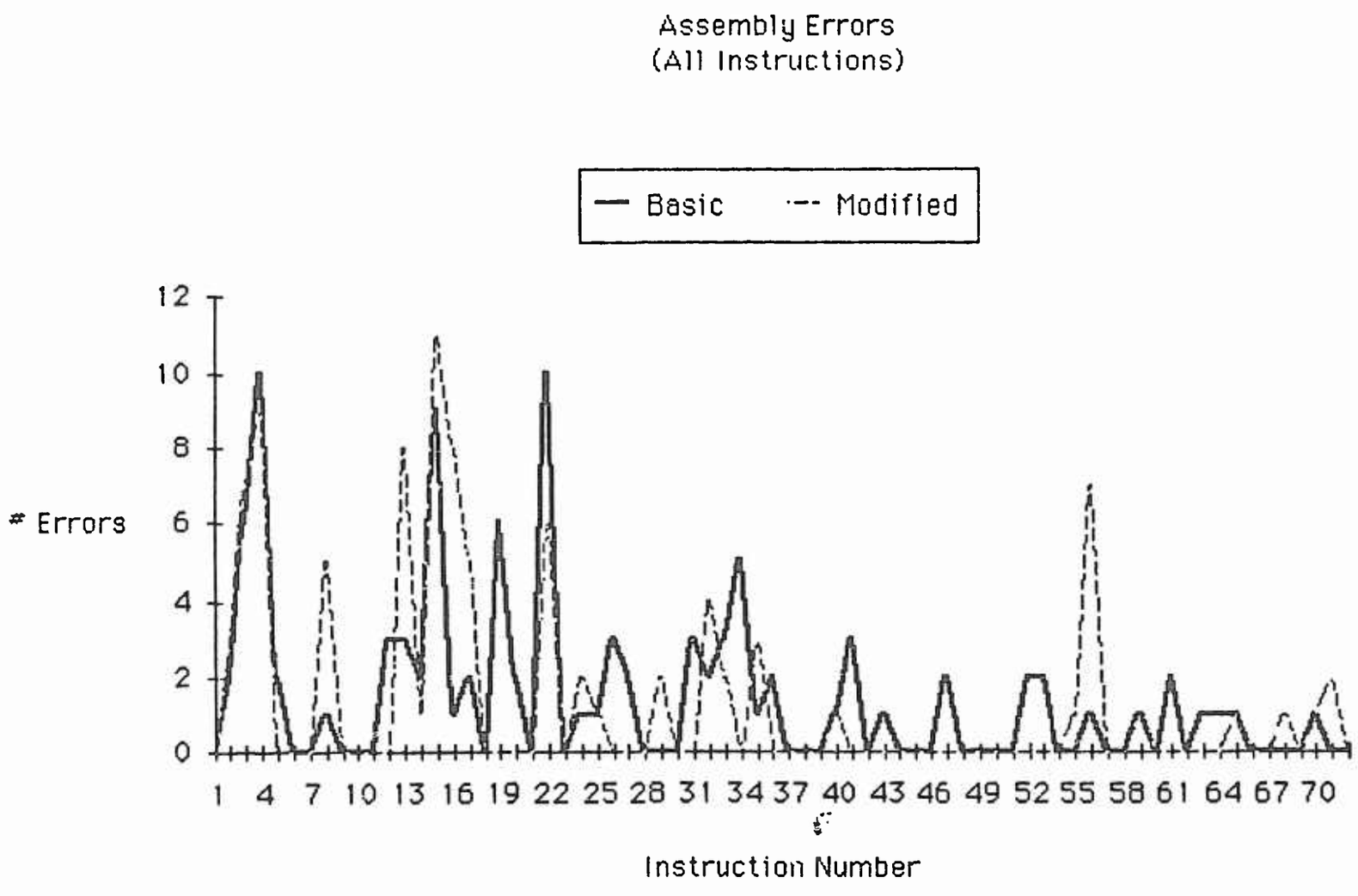
execution times. Since the number of syllables in a step was related to the number of actions (including checking actions) needed to execute the step, we again normalized each score by the number of syllables in the step. With regard to the data in Figure 9, there was no overall effect of either number of slot-fillers or basic vs. modified instruction; but there was an interaction between the two variables such that the basic instructions took longer than the modified ones only when the step contained four slot-fillers. This anomalous result occurred at all sizes of working-memory span (see Figure 10).

3.2.2.2 Other results

Three other findings are worth briefly noting. First, when backward-digit span is used as the measure of working memory, the regularities between working-memory and RT disappear. That is, in contrast to the Daneman and Carpenter measure, there is no relation between backward-digit span and the comprehension of instructions.

Second, there were relatively few errors of execution; indeed, for many of the steps, no subject ever made an error. The errors that did occur seemed tied to the specifics of the step, and there was no difference in the distribution of errors between the basic and modified instructions -- see Figure 11.

Third and finally, an analysis of subjects' inspections of the available diagram showed that there was no relation between


Assembly Errors
(All Instructions)
Basic
Modified
Errors
12
10
8
6
4
2
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70
Instruction Number

the number of times a subject checked the diagram and how quickly that subject read or executed the steps. However, all subjects did check the diagrams more on steps that were error prone; this is indicated in Figure 12, which shows similar patterns to those observed in our analysis of errors. Figure 12 also indicates that there was no difference in the distribution of diagram checks between the basic and modified instructions.

3.2.3 Interpretation of Major Results

With regard to the reading-time results, we suspect that the effects of order of topics or slot-fillers, number of slot-fillers, and working-memory span all have the same theoretical locus, namely instantiating a step schema. Assume that understanding a step involves assigning each topic in the step to a slot in a step-schema, where these slots include actor, action, object, orientation, location, and modality. Assume further that this instantiation process takes place in working memory, which is very limited with respect to how much material can be kept active at any point in time (e.g., Anderson, 1976). The more schema slots to be filled in a step, the less activation there will be for any slot filler, and the longer it will take to understand the step. Hence reading time should increase with the number of slot-fillers. Moreover, the smaller one's working-memory span, presumably the less activation one has, and the more deleterious the effect of extra slot-fillers. Hence the

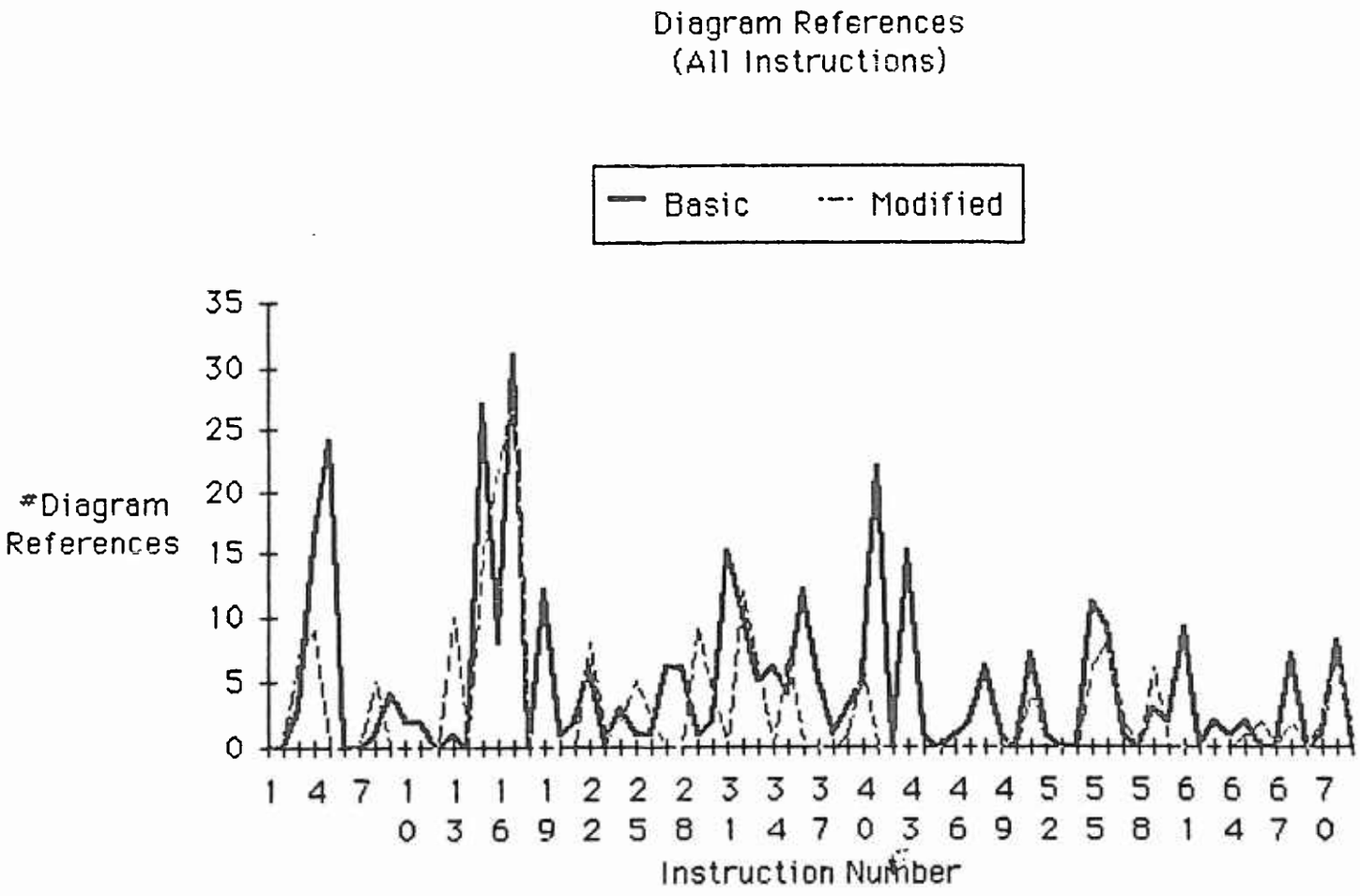


Diagram References
(All Instructions)
Basic
Modified
#Diagram References
35
30
25
20
15
10
5
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70
Instruction Number

interaction we observed between working-memory span and number of slot-fillers. Finally, if fillers must be assigned to slots in a particular order -- namely, actor, action, and object first, because they are the top-level slots -- then when the fillers are mentioned in some other order, some of them may have to be temporarily stored rather than instantiated, and this should thin the activation still further. This should lead to order-of-fillers interacting with both and (1) the number of fillers and (2) working-memory span; we observed the first of these interactions, but not the second.

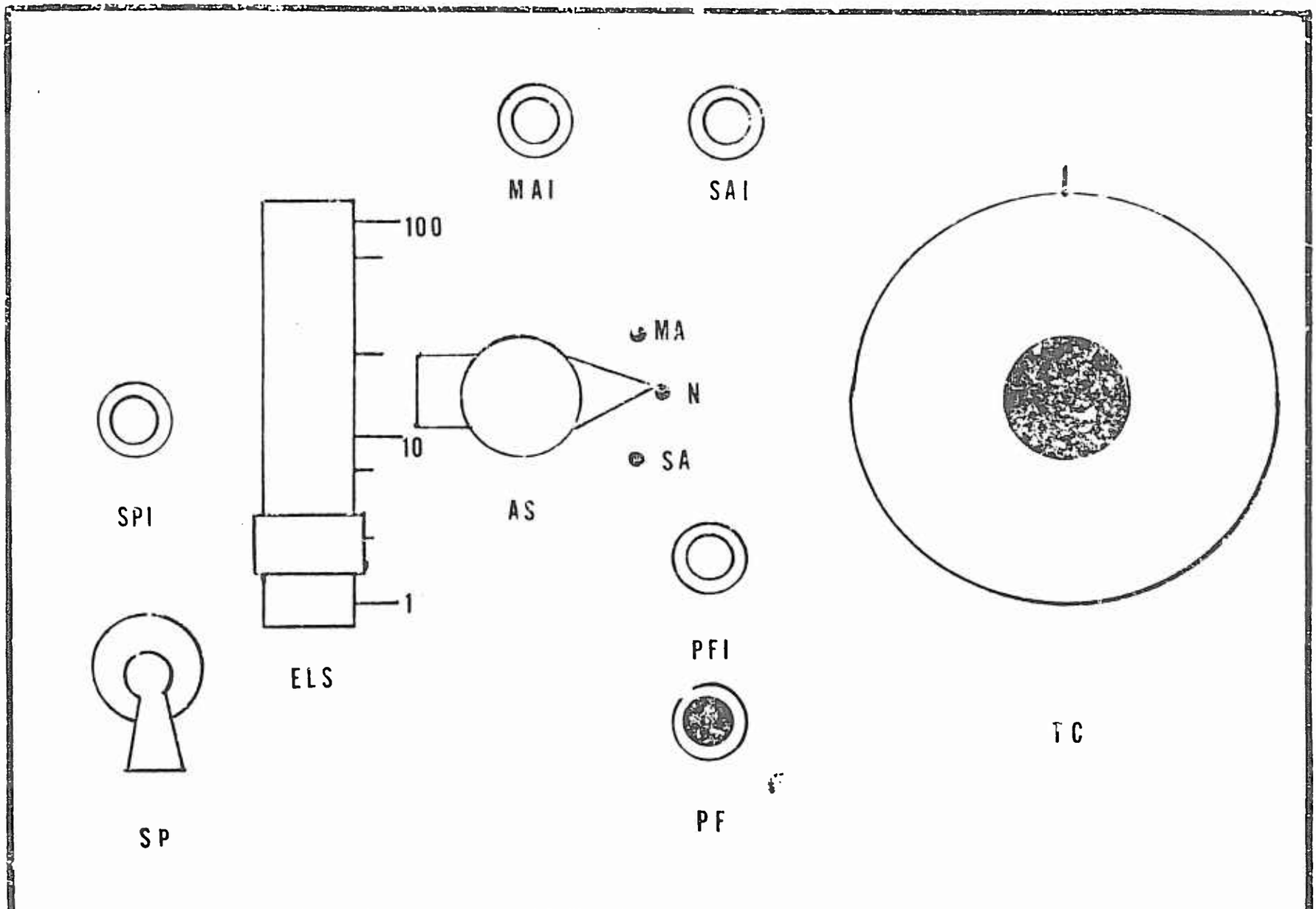
Finally, some comment should be made about the fact that variables that affected reading times had little or no influence on execution times. This pattern has emerged before in our work; e.g., in Experiment 1, which dealt with operating a simple device, the order of slot-fillers affected reading time but not execution time. We take this pattern to mean that the variables of interest primarily affect the understanding process, which is what the reading-time measure reflects.

4. MENTAL MODELS AND AN OPERATIONS TASK

4.1 Rationale

We now shift our focus to knowledge other than that contained in the instructions. In our previous studies with this focus (Smith & Goodman, 1984), we used an assembly task, and the additional knowledge was such that it would presumably be represented as a schema (the information rarely referred to change and was easily represented propositionality). In the current study, in contrast, we used a device-operation task, and the additional knowledge was such that it presumably was represented as a mental model of the device (the information encompassed dynamic and changing properties of a system).

The task required using multi-step procedures to operate the display illustrated in Figure 13. This task is an elaboration of one developed by Kieras and Bovair (1984), and our work rests on theirs in a number of respects. Kieras and Bovair have shown that providing subjects a mental model of the device shortened the number of trials that subjects needed to learn procedures for operating the device. Our concerns were somewhat different. First, we wanted to determine whether having a model of the device facilitates the comprehension of each instructional step in a multi-step procedure, as reflected in the time to read each step. Thus, we were interested in the comprehension of each step


MAI
SAI
100
MA
N
SA
10
SPI
AS
1
PFI
ELS
TC
SP
PF

rather than the learning of the entire procedure. Second, we wanted to extend the generality of our previous findings and show that the order in which the topics were mentioned affected performance in the current task; hence there was some concern with the instructions per se as well as with other knowledge in the current study. Third and finally, we were interested in how knowledge in the form of a model affected reasoning about the device.

4.2 Experiment 4: Operating a Device via Multi-Step Procedures

4.2.1 Method

4.2.1.1 Overview

The experiment included four stages. The first three were similar to those of the previous study. Thus, stage 1 measured individual differences, stage 2 familiarized subjects with the components or their task, as well as introduced the model, and stage 3 consisted of the main task of operating the device. In stage 4, subjects were given the equivalent of a couple of steps and asked to generate the rest of the procedure. This stage was included so as to provide another opportunity to observe the effects of mental model on the use of instructions.

4.2.1.2 Individual differences

Again, we used two different measures of working memory, backward-digit span and Daneman and Carpenter's (1980) working-memory span.

4.2.1.3 Familiarization with components and presentation of the model

With the display in front of them, subjects were told about the various components of the display. Exactly what they were told depended on whether subjects were given a model of the device (hereafter, the "model" group), or not (the "control" group). Subjects in the control group were told the following:

"Before explaining the components of the system, I want to tell you that your goal when operating the device is to get the PFI light to flash four times, which will enable you to push the PF button. Now we can go on to the components of the device.

The first component is the SP switch. It has two positions. When the SP switch is flipped up, the SPI is illuminated. The device will not work unless the SP is flipped up. Thus, the neutral position for the SP switch is the down position. The second component is the ELS control. It is a sliding selector on a logarithmic scale that ranges from 0 to 100. The third component is the AS control It has three positions - MA, SA, and N. When the AS is turned to MA, the MAI is illuminated. When the AS is turned to SA, the SAI is illuminated. When the AS is turned to neither control (N), then neither the MAI nor the SAI will be illuminated. The AS is important because the PFI will not flash unless the MA or SA setting is selected. The neutral position for the AS is the N position. The setting of the AS selector is related to that of the ELS control, in that settings of the ELS above 50 require selection of the MA position in order for the device to work.

The fourth component is the TC dial. It is a circular control and has a range from 0 to 360. A TC setting of more than 180 is compatible only with the AS control being at MA; if the TC setting is 180 or less, then the AS control can be at either MA or SA. The TC is important because the PFI will not flash until this dial is set correctly. The fifth and sixth components are the PFI and the PF button, respectively. The PFI will flash four times. This means that you can push the PF button and reach your goal. After you have done so, the controls should be placed in the neutral position, that is, the SP switch should be flipped down and the AS should be set to N."

In contrast, the model group's familiarization with the components included a description of a device model

"The device you will operate is the phaser control panel of the starship Enterprise. The phaser bank firing system can be divided into three subsystems: Power Booster, Power Accumulator and Phaser Firing. The functions of the system components will be explained in terms of these three sub-systems.

The Power Booster subsystem consists of three components, the Shipboard Power Switch (SP), the Shipboard Power Indicator (SPI), and the Energy Booster (EB). When the SP switch is flipped up, the SPI is illuminated. Energy flows from the shipboard engines to the Energy Booster (EB). The EB boosts the power from the ship's engines to a higher level. Power will not be accumulated in the accumulators if the EB malfunctions.

The Power Accumulator subsystem consists of the Energy Level Selector (ELS), the Accumulator Selector (AS) and the latter's related components, the Main Accumulator (MA), the Secondary Accumulator (SA), the Main Accumulator Indicator (MAI), and the Secondary Accumulator Indicator (SAI). The Energy Level Selector (ELS), a sliding selector on a logarithmic scale that ranges from 0 to 100, determines the amount of power that will be stored in one of the accumulators. The Accumulator Selector (AS) allows one to choose which accumulator will receive and store the power. The Main Accumulator (MA) collects 10 Universal Power Units (UPU's) per second while the Secondary Accumulator (SA) collects 5 UPU's per second. When the MA is selected, the Main Accumulator Indicator (MAI) is illuminated. When the SA is selected, the Secondary Accumulator Indicator (SAI) will be illuminated. If Neither (N) accumulator is selected (neutral position), both indicators will be off. Energy will not be stored in the accumulators when the AS is in the N position. The phasers cannot be fired unless an accumulator (MA or SA) is selected. The setting of the Energy Level Selector and the accumulator selected depend on the distance between the Enterprise and the target. For distant targets, the ELS must be set above 50; since the amount of power that must be stored is large, the Accumulator Selector must be set at the MA position.

The third subsystem, Phaser Firing, consists of the Target Coordinator (TC), the Phaser Firing Button (PF), the Phaser Firing Indicator (PFI), and the Phaser BAnk (PB). The Target Coordinator, a circular control, specifies the angular direction of the target from the Enterprise in degrees, ranging from 0 to 360. For targets between 0 to 180 degrees, only limited power is needed so either the Secondary or Main Accumulator can be used; for targets at an angular direction of greater than 180, more power is needed, so the Accumulator Selector must be set at the MA position. When enough power has been stored in an appropriate accumulator, the PFI will flash four times if the TC is set

correctly. After the PFI light flashes four times, the PF button should be pushed. This releases power from the Accumulator to the Phaser Bank, firing the phasers in the direction specified by the Target Coordinator. After the phasers have been fired, the controls should be placed in the neutral position, that is the SP switch should be flipped down and the AS should be set to N.

After hearing one of the above explanations, the device was removed from view, and subjects in both the model and control groups were given a ten-question quiz about the components and their settings. The questions asked either for the name of a component that had a particular property, or for a property of a named component, or for both (e.g., "What's the name of the switch with two positions? What are the two positions?"). If subjects made any errors on the quiz, the entire explanation was repeated and they were retested on the items that they had missed.

4.2.1.4 Instructions task

The main part of the experiment involved following multi-step procedures for operating the device. Subjects worked with 4 basic 4-step procedures, and they saw each procedure 3 times. Two of the basic procedures are given in Figure 14. Note that in each procedure three of the steps are "simple", in that they specify a single action, while one step is "complex", in that it specifies three actions; this distribution of simple and complex steps held for all procedures. The reason for including the complex steps was to allow a variation in the ordering of topics or slots; e.g., in Figure 14, the topics are mentioned in

SAMPLE PROCEDURES FOR OPERATING CONTROL PANEL

1. FLIP THE SP UP
2. SET THE ELS TO 100
3. ADJUST THE AS TO MA
4. IN ORDER TO GET THE PFI TO FLASH FOUR TIMES SO THAT YOU CAN PUSH THE PF BUTTON -- ADJUST THE TC TO 260

1. FLIP THE SP ON AND ADJUST THE ELS TO 1 AND THEN TURN THE AS TO MA
2. SET THE TC TO 250
3. WAIT UNITL THE PFI FLASHES FOUR TIMES
4. PUSH THE PF BUTTON

the order of execution in the first procedure but not in the second.

The four basic procedures varied in several respects: (1) the complex step was either first or last; (2) the order of the topics in the complex step was either optimal or nonoptimal (i.e., order of mention either mirrors execution or not); and (3) the steps included either (a) the SA setting on the Accumulator Selector and compatible settings on the ELS (below 50) and the TC (below 180), or (b) the MA setting on the Accumulator Selector and arbitrary settings or the ELS and TC (this captures the constraints between the Accumulator Selector, ELS, and TC).

Each procedure was presented one step at a time on the display of microprocessor. Subjects read each step, pressed a space bar when they thought they understood it, and tried to execute the instruction after it disappeared from view (the device was adjacent to the display). Both reading time and execution time were recorded for each step.

4.2.1.5 Generation task

The purpose of this task was to explore how the model affected subjects' reasoning about the procedures. A total of 12 partial procedures were presented, each containing information about 1, 2, or 3 of the 6 acts needed to specify a complete procedure. Samples are presented in Figure 15. Subjects had to determine how to complete the procedure, and they were asked to

SAMPLE CONSTRAINTS IN GENERATING NEW PROCEDURES

GET THE PFI TO FLASH IN A SHORT AMOUNT OF TIME WHILE THE TC IS SET AT 35

THE ELS SHOULD BE ADJUSTED TO A HIGH VALUE AND THE TC TURNED TO 310

CHOOSE COMPATIBLE SETTINGS FOR ALL OF THE CONTROLS IF THE TC IS SET AT 220

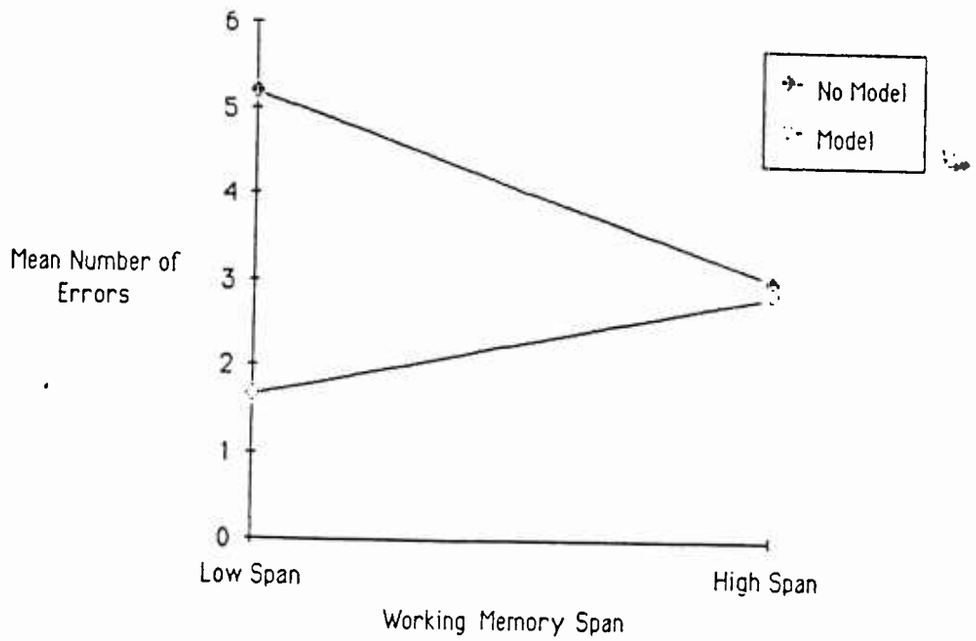
think aloud while they did this. Then they tried to execute their planned procedure. The partial procedures always specified the TC setting, but never gave all three of the settings that had constraints between them.

4.2.2 Results

Three different stages yielded results of interest, including component familiarization, the instructions task, and the generation task. We consider them in turn.

4.2.2.1 Component familarization

Recall that this stage involved a ten-question quiz on the names and properties of the components. Figure 16 presents the average number of errors subjects made as a function of their working-memory span and whether they were in the model or control group. Among high-span subjects, there is no difference between the number of errors in the model and control groups; among low-span subjects, there is a very substantial difference, with model subjects making many fewer errors. This boost for the low-span subjects is consistent with meaningfulness increasing memory. Thus, the names of components are essentially nonsense syllables to the control subjects but acronyms of meaningful units to the model subjects, and the addition of "meaning" to a nonsense syllable boosts its memoralibility (e.g., Crowder, 1976), a boost that is sorely needed by subjects with low spans. While this result does not tell us much about the effects of


6
5
4
3
2
1
0
Mean Number of Errors
No Model
Model
Low Span
High Span
Working Memory Span

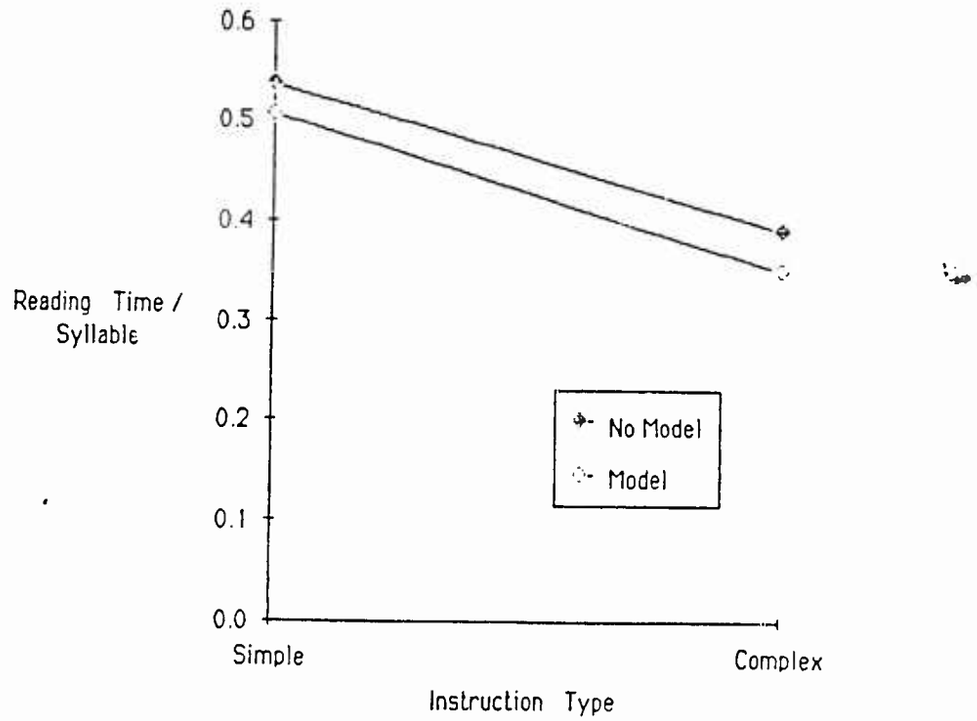
mental models on comprehension, its impact ought not to be minimized -- learning the names and properties of task-relevant components can be a major source of difficulty, and if a mental model reduces this difficulty then this is an important aspect of a model.

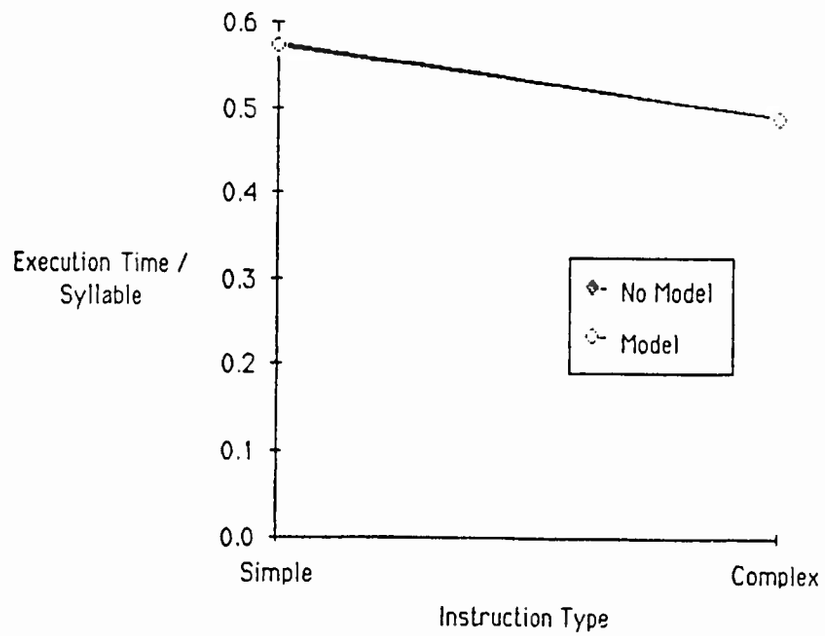
4.2.2.2 Instructions task

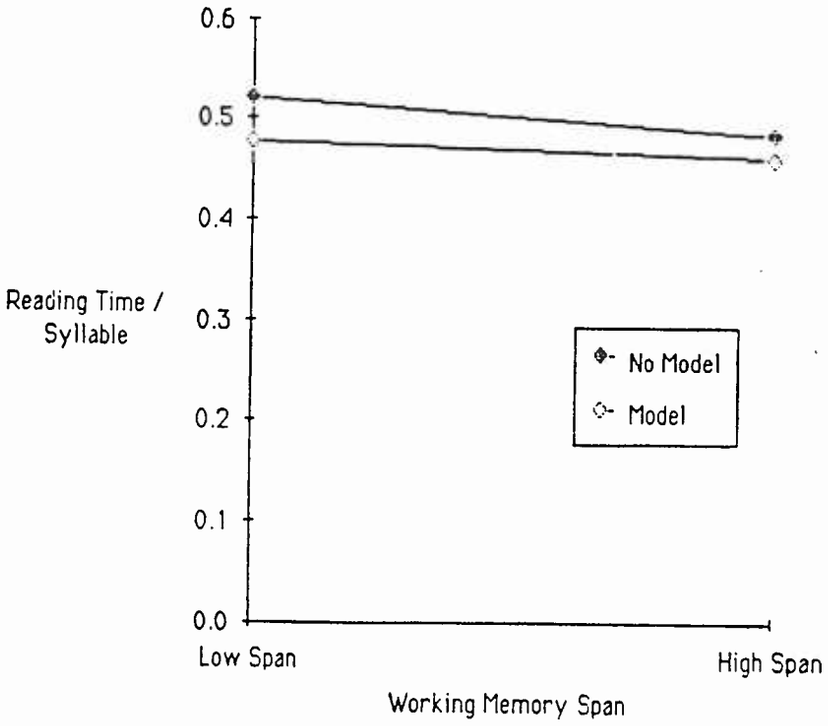
The major result to emerge from this experiment is that having a model facilitated the reading of steps.

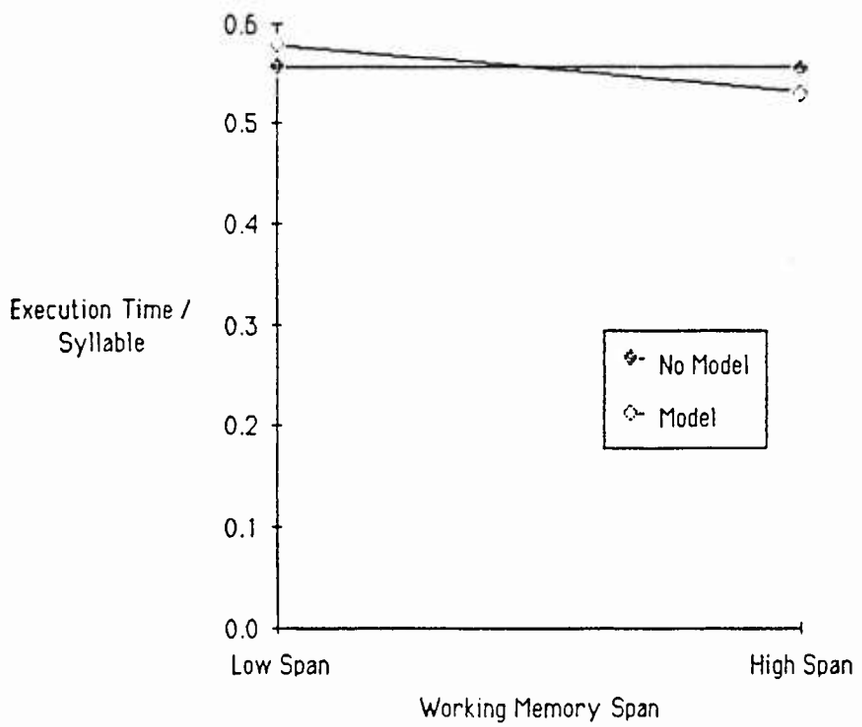
Figure 17 presents reading-time-per-syllable, in seconds, for simple and complex steps, separately for the model and control groups. After normalization by number of syllables, complex steps are read faster than simple ones, suggesting that subjects speed up as they go through the step, perhaps because they can infer some of the later information. There is also a beneficial effect of having a model, which is worth about 30 msec per syllable. Figure 18 presents the comparable data for execution time per-syllable. There is less effect of complexity on the normalized times, and no effect at all of having a model.

Figure 19 plots reading-time-per-syllable as a function of working-memory span, separately for the model and control groups. There is no effect of span, which is not surprising given that most of the steps were short and simple. As before, there is about a 30-40 msec benefit per syllable when subjects have a model. Figure 20 presents the comparable data for execution


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reading Time / Syllable
No Model
Model
Simple
Complex
Instruction Type


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Execution Time / Syllable
No Model
Model
Simple
Complex
Instruction Type


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Reading Time / Syllable
No Model
Model
Low Span
High Span
Working Memory Span

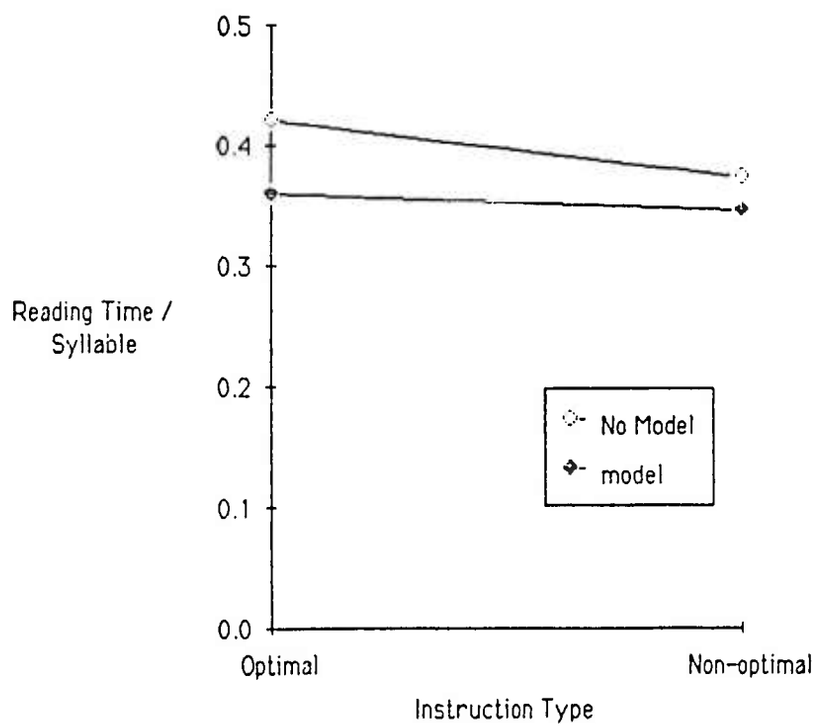

0.6
0.5
0.4
0.3
0.2
0.1
0.0
Execution Time / Syllable
No Model
Model
Low Span
High Span
Working Memory Span

times. There is no effect of span, nor is there any beneficial effect of the model.

Figures 21 and 22 consider only complex steps, and focus on the effects due to differential orderings of the topics or slots within a step. Figure 21 plots reading-time-per-syllable as a function of optimal vs. non-optimal orderings, separately for the model and control groups. Unlike the results in our previous experiments, there is no significant effect of order on reading time in the present case; having a model again facilitates reading, though, with the effect this time being about 50 msec per syllable. The comparable results for execution times are in Figure 22. Now, there is a substantial effect of the order of topics, with the optimal order resulting in a marked reduction in execution time, especially for the control group; while there is no overall effect of having a model, there is an interaction between presence of a model and type of instruction.

In addition to its effects on the speed of execution, having a model also improved the accuracy of execution. The average number of errors was 4.38 in the model group, compared to 5.85 errors in the control group.

To summarize the major results: there is a small but consistent effect of having a model on reading times, and a substantial effect of ordering on execution times. These results raise two questions of interpretation: Why does ordering affect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Reading Time / Syllable
No Model
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Optimal
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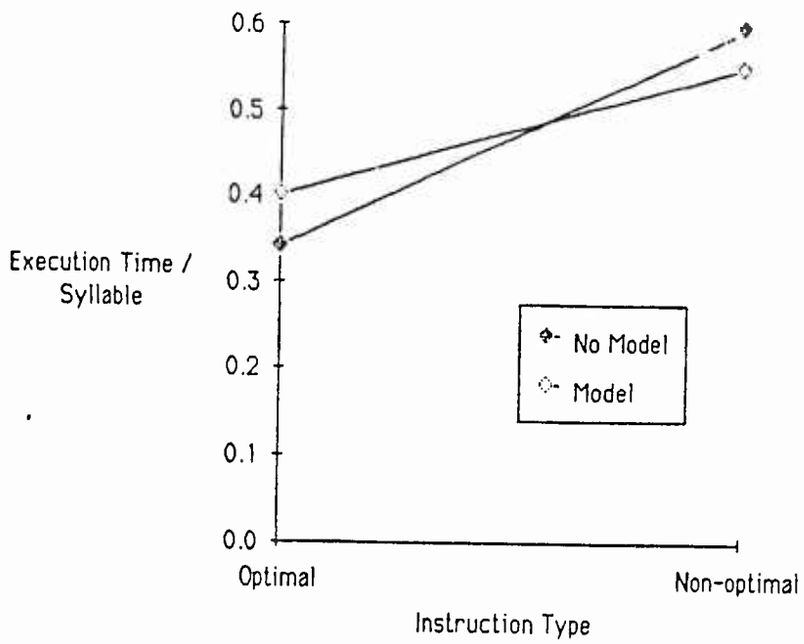
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Execution Time / Syllable
No Model
Model
Optimal
Non-optimal
Instruction Type

execution but not reading?, and How does having a model lead to improvements in reading?

With regard to the question about ordering, in our previous experiments using an operation task (Experiment 1) or an assembly task (Experiment 3), we found that the ordering of the topics or slot-fillers affected reading time but had no effect on execution time. In interpreting these findings, we assumed that: (1) the ordering effects reflects understanding processes (e.g., instantiating a step schema), and (2) these processes are completed before execution begins, i.e., subjects do not attempt to execute an action until their plan for that action is completed. We suspect that the present results -- that ordering affects execution times but not reading times -- reveal a failure of our second assumption. In the present study as in earlier ones, an optimal ordering of the topics or slot-fillers may have facilitated comprehension of the step, but this time subjects started to execute the actions before they fully understood them, and hence some comprehension effects spilled over into the execution phase.

Consider now the question of how a model leads to improvements in reading. One possibility is that model subjects were more familiar with the components than control subjects. However, we suspect this factor was of limited influence because even control subjects continued component familiarization until

they knew all the items. A more likely possibility is suggested by Kieras and Bovair (1984). They propose that a model facilitates the learning of procedures by encouraging inferences; more inferences may have played a role in our results too. Similarly, the model may have allowed subjects to see the relations between the steps in a procedure, and even though subjects did not need these relations to perform their task they may have tried to understand them. We found some evidence for this kind of mechanism in our earlier studies showing a beneficial effect of explanatory material (Smith & Goodman, 1984).

We can flesh out the last two proposals with an example. Suppose the second step of a procedure is "Set the ELS to 100". Subjects in the model group might refer this to the model, and realize that it suggests a distant target which necessitates a lot of power be stored. If the next step is "Adjust the AS to MA," our model subjects have already inferred it; if a subsequent step is, "Adjust the TC to 260," while model subjects may not have inferred it they at least see the relation between it and previous steps. Consider now subjects in the control group. When presented, "Set the ELS to 100," they too have information which permits them to infer that the AS will be set to MA, but this information is abstract and correlational, and hence less likely to be used. In short, model subjects may draw more inferences and construct more relations between steps because

they can use something like causal reasoning with concrete material.

4.2.2.3 Generation task

The primary measure of performance in this stage was the average number of generated procedures that contained an error: this number was marginally greater for the control than the model group -- 2.23 and 1.62, respectively -- suggesting that a model enhances one's ability to reason about possible procedures. Though the performance difference is marginal, it seems useful to ask how it might have arisen. This time the verbal protocols provide a clue. In reasoning about the procedures they had to generate, subjects in both the model and control groups typically mention the constraints between the settings on the Accumulator Selector, Energy Level Selector, and Target Coordinator; but most subjects in the model group, 11 of 13, expand on these constraints (they do this by bringing up considerations about energy flow), while few subjects in the control group, 4 of 13, engaged in such expansion. Perhaps the greater embellishment in the model group highlighted the importance of the constraints, which led to a greater use of them in the generation of procedures, and to fewer errors. This is roughly the same account we offered of why model subjects might make more inferences than control subjects.

4.2.3 A Final Comment

While our results are preliminary, they suggest that a model produces widespread effects. Having a model facilitated memory of the components, comprehension of instructional steps, execution (accuracy) of the steps, and, to some extent, reasoning about new procedures. While the effects were small, the model and task were quite simple, which no doubt limited the influence the model could have. More complex models, particularly causal ones, might produce far more striking effects.

Lastly, this study shows that the two foci of our research may be merged. We obtained effects of both the model and the ordering of topics within a step. Moreover, the ordering effect was less in the model group than in the control, which suggests that the more one relies on knowledge other than the instructions the less the efficacy of the instructions matters.

5. SUMMARY

The major findings of our research include:

(1) For both operations and assembly tasks, less time is needed to understand an instructional step if the topics are mentioned in the order in which they will be executed.

(2) The importance of order-of-mention is greater when the reader's working-memory is taxed; hence, order-of-mention matters more for reader's with smaller working-memory spans.

(3) To measure working-memory span in a way that is predictive of success with written instructions, one should not use standard memory-span tests; rather, one should use a test that involves processing as well as storage, like the Daneman-Carpenter (1980) measure.

(4) Although operations and assembly tasks may seem very different on the face of it, the two tasks are affected in the same way by the same variables (e.g., order of mention within an instructional step, role of explanatory material); this suggests that the same general theory of instructions may encompass both tasks.

(5) The notion of a schema can be successfully applied at the level of a single instructional step; in particular, understanding a step can be modelled as instantiating a step

schema, thereby accounting for why reading time increases with the number of topics mentioned in a step.

(6) Having a mental model of a device has a substantial benefit on memory of the device's components, and smaller benefits on (a) comprehension of instructions about using the device and (b) reasoning about new ways to use the device.

(7) The more knowledge other than the instructions that one has about a device, the less affected one will be by the goodness of the instructions.

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