Efficient Processing Activities in Reading

RICHARD F. WEST
James Madison University

Reading is a composite of many subskills and therefore requires the coordination of numerous component processes. Proficient readers find reading a relatively easy activity. They are able to process written information smoothly and rapidly, with little or no conscious awareness of the mental activities that take place while they read. In other words, proficient readers carry out many of reading's component processes automatically and efficiently. As long as the written information is not too abstruse, this efficiency facilitates comprehension because these readers can concentrate their mental efforts on the meaning of the material.

In contrast, nonproficient readers frequently find reading a difficult activity. These individuals cannot process written material smoothly and rapidly; they must expend considerable mental effort in the execution of individual component processes. As a result, the comprehension of even relatively simple text may be beyond the reach of nonproficient readers. The proportion of their mental faculties that must be directed to decoding activities is so large that the meaning of the written material is ignored to a considerable extent. Although nonproficient readers may be able to carry out some of reading's component processes, their executions of these processes are inefficient. This inefficiency may result in a deterioration in the functioning of the process when it is exercised concurrently with other processes. Thus, the performance of a component process interferes with the concurrent performances of other component processes more for beginning readers than for skilled readers.

Psychologists long ago recognized that with practice the execution of a skill tended to become easier, more efficient, and in need of less conscious effort (James, 1890; Lashley, 1951; Woodworth, 1938). Indeed, Huey (1908), a pioneering reading

researcher and psychologist, made precisely this point when he stated that "To perceive an entire new word or other combination of strokes requires considerable time, close attention, and is likely to be imperfectly done.... [Practice, however,] progressively frees the mind from attention to details, and makes facile the total act, shortens the time, and reduces the extent to which consciousness must concern itself with the process" (p. 104).

One approach frequently used to study the acquisition of reading skills is to examine the repertoire of subskills possessed by individuals of different reading abilities. However, readers differ, not only in the particular subskills they possess, but also in the extent to which they are able to exercise their subskills efficiently.

In this paper, the acquisition of reading skills is explored by concentrating on various ways of conceptualizing and empirically elaborating processing efficiency per se. In pursuit of this goal, a general discussion of the notion of processing efficiency is first presented. Next, a model that deals explicitly with automatic information processing in reading (LaBerge & Samuels, 1974) is reviewed. Following this review, there is a methodologically oriented discussion of relevant research. Finally, additional procedures for studying the efficiency of reading skills are discussed.

Capacity Limitations and Processing Efficiency

Data- and Resource-Limited Processing Activities

NORMAN AND BOBROW'S MODEL

An information processing model that is relevant to our discussion of processing efficiency was presented by Norman and Bobrow (1975), who argued that the performance of a process can vary with both the nature of the input data and the amount of processing resources allocated to the process. Information processing systems possess a limited amount of processing resources (memory, processing effort, communication channels). As a result, different processes may have to compete for and share portions of these limited resources. So long as the amount of resources that processes jointly require does not exceed the total amount available, the operation of one process does not interfere with that of another. However, if the joint requirements of processes exceeds the amount of resources available, selective resource allocation must take place. When this occurs, the performance of at least one of these processes will deteriorate.

The allocation of additional processing resources to a task often results in improved performance on the task. Whenever performance on a task can be improved by an increase in the amount of processing resources, the performance is considered to be "resource-limited." However, if additional resources continue to be allocated to the task, a point may be reached where such increases have no additional influence on performance. In other words, a point may be reached where all the processing that can be done has been done. In this case, all variation in performance on this task now depends solely on the nature of the data received. Whenever this point is reached, performance on the task is considered to be "data-limited."

On most tasks, performance can be considered either resource- or data-limited depending on whether or not the allocation of additional processing resources has an influence on performance (Norman & Bobrow, 1975). While allocating additional resources to a task that is data-limited does not alter performance, changing the nature of the data presented can alter performance. Additionally, the imposition of conditions that place increased demands upon a system's limited processing resources can result in performance on a task shifting from data limitations to resource limitations, because the increased demands can result in insufficient resources remaining available for maximum performance. Such a shift is most likely for those data-limited tasks for which maximum performance initially required a large portion of the available processing resources. Tasks for which data-limited performance requires only a small portion of the processing resources would be less likely to undergo this shift. Presumably, the processes involved in the performance on these latter tasks are highly efficient, requiring only a small allocation of processing resources.

READING EFFICIENCY AND NORMAN AND BOBROW'S MODEL

A considerable amount of conscious effort is often required to perform an unfamiliar task. However, when the task is repeatedly practiced, performance becomes increasingly automatic, and less conscious effort is required. Thus practice can result in increased processing efficiency, that is, increased performance with no extra allocation of resources. Reading processes can be characterized as being efficient for skilled readers and inefficient for beginning readers. In terms of Norman and Bobrow's model, these characterizations mean that processes are less likely to be resource limited for skilled readers than for beginning readers.

Thus the demands which component reading processes make on processing resources are not likely to exceed the total amount of resources available when the reader is proficient. For good readers, the lower-order processes involved in decoding a written message do not normally interfere with the concurrent performance of the higher-order processes involved in semantic comprehension, even when these two levels of processes share the same limited resources. However, these lower-order and higher-order processes may often interfere with each other in unskilled readers. The inefficiency of these readers' processes increases the probability that the total amount of available resources will be exceeded.

When a written passage is relatively easy to comprehend, the amount of limited processing resources that must be allocated to higher-order processes is presumably small. A relatively large surplus of resources is then available for allocation to lower-order processes. Thus for easily comprehended passages, the total amount of available resources is likely to be sufficient to allow both skilled and less skilled readers to read the passage. In contrast, when a written passage is relatively difficult to comprehend, a large amount of processing resources must be allocated to higher-order processes. In this case the remaining amount of resources available for allocation to lower-order processes is small. Since lower-order processes are efficient for skilled readers, the small amount of remaining resources is likely to be sufficient for these readers to read the passage. However, this same small amount of remaining resources may not be sufficient for the inefficient low-level processes of less skilled readers. As a result, these readers may not be able to read this difficult passage. If an extremely difficult written passage is encountered, the resource demands of the higher-order processes may be extremely high. In this case the lower-order processes of even skilled readers may receive an insufficient allocation of resources. Therefore, the reading of the proficient reader may be halting and slow for difficult passages.

The Concept of Attention

The information processing model proposed by Norman and Bobrow is very general and does not require the identification of the specific sets of factors that constitute limited processing resources. Undoubtedly there are numerous factors that set limits to human information processing capacity (cf. West, 1975). Perhaps no concept has been more frequently associated with capacity limitation than attention. Because the remaining discussion of processing efficiency makes frequent use of this concept of attention, a brief consideration of this notion is in order. William James (1890) described attention in *The Principles of Psychology* in the following manner:

> Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seems several simultaneously possible objects or trains of thought.... It implies withdrawal from some things in order to deal effectively with others (p. 403).

At a later point in the book, James elaborated the notion of attention as follows:

> How many ideas or things can we attend to at once.... Not easily more than one, unless the processes are very habitual.... Where however, the processes are less automatic...there must be a rapid oscillation of the mind from one to the next, and no consequent gain in time (p. 407).

Thus James identified the properties of selectivity and capacity limitations as important characteristics of attention. With respect to the property of capacity limitation, he noted that we are able to process only one thing at a time, except when the processes involved have been so well learned that they can be carried out automatically. James also suggested that processes that are not automatic may appear to be carried out simultaneously when the focus of attention rapidly oscillates from one activity to another. In terms of Norman and Bobrow's model, this rapid oscillation of attention is analogous to sharing this limited processing resource. Presumably if attention is not focused for a sufficient duration on a nonautomated activity, performance on this activity will be poor.

The Mechanisms of Processing Efficiency

When the total amount of resources (e.g., attention) required by reading processes exceeds the total amount available, performance is likely to deteriorate. Since the amount of resources that must be allocated to a particular process is generally greater for the beginning reader than for the skilled reader, the component processes of the beginning reader are more likely to make demands on resources that exceed their availability. Assuming that the total amount of resources normally cannot be increased, the beginning reader must learn to carry out various processing activities with less consumption of resources.

Information processing efficiency is presumably acquired largely as a result of practice. What are the changes in the reader's processes that allow more efficient processing of written messages? To the extent that insufficient attentional resources are a cause of poor reading performance, the particular changes in the processes, and the forms of perceptual learning that result in lowered demands for attentional resources, must be identified.

At least two types of changes in processing activities can reduce the demands for attentional resources. First, the amount of information that is actually allocated to resources can be reduced. A written passage contains far more information than the reader can attend to at one time. Much of this information is either irrelevant to the meaning of the passage or redundant with other information contained in the passage. Therefore, the efficiency with which attentional (or other) resources are used can be increased by selectively allocating these resources to only those aspects of the written message that are most relevant for comprehension. In this case, economy in the use of attentional resources is achieved by avoiding the consumption of these resources on redundant and irrelevant information. A number of more detailed discussions of the role of selectivity in reading are available elsewhere

(Gibson, 1969; Gibson & Levin, 1975; E. Smith & Spoehr, 1974; F. Smith, 1971).

A second type of change in processing activities that can reduce demands for attentional resources occurs when processes have been so thoroughly practiced and learned that they can take place even when they are allocated minimal resources. In this case, the same amount of information receives processing for both efficient and less efficient readers. However, the processes of the efficient readers require a smaller amount of attentional resources, because they are carried out automatically. This automatic source of processing efficiency is investigated in detail in the remaining sections of this paper. In passing, it should be noted that there is no reason why the two general sources of processing efficiency cannot be involved in the same reader.

Automatic Information Processing in Reading

LaBerge and Samuels' Reading Model

AN OVERVIEW

LaBerge and Samuels (1974) recently presented an information processing model that deals explicitly with the acquisition of automated processing skills in reading. These authors argue that before the information in written material can be comprehended, it must undergo processing in a series of component processing stages involving internal representations, or codes, stored in visual, phonological, episodic, and semantic memory systems. Each level in this processing system need not be involved in all acts of processing written material, for there are several alternative routes that information may take as it is transformed through various stages. However, the general flow of information in this model is hierarchically organized, with the initiation of higher-level processes contingent upon adequate informational input supplied by lower-level processes. In this respect, LaBerge and Samuels' model is similar to other pattern recognition schemes (Lindsay & Norman, 1972; Selfridge & Neisser, 1960).

The skill with which processing takes place at each level in the processing hierarchy is assumed to be acquired through an associative learning process. During early stages of the

development of skills, the codes at any given level in the processing system can be activated only with assistance from a limited capacity attentional mechanism. Later, after the processing skill has become well learned, attentional assistance is no longer requisite and codes can be activated solely on the basis of input stimulation. The degree of skill acquisition can be evaluated with respect to both the accuracy with which processing takes place with attentional assistance and the extent to which processing is able to progress automatically, or without use of attentional resources. LaBerge and Samuels consider a skill to be automatic when "it can complete its processing while attention is directed elsewhere" (LaBerge & Samuels, 1974: 295).

The view that familiar material may be processed into internal codes without use of attentional resources is consistent with a number of other attentional models (Deutsch & Deutsch, 1963; Norman, 1968). LaBerge and Samuels emphasize that the attentional mechanism retains the ability to selectively activate codes even after automation has been achieved.

INFORMATION PROCESSING IN THE VISUAL MEMORY SYSTEM

In the first stage of LaBerge and Samuels' model, written information is transformed through a hierarchically organized series of codes in the long term visual memory system. At the bottom of this hierarchy are feature detectors which analyze the various lines, angles, and curves that make up written text. Through a perceptual learning process that is likened to the first stage in concept learning (Trabasso & Bower, 1968; Zeaman & House, 1963), the reader learns which subsets of features are relevant for making discriminations between letters. Once appropriate features have been identified, the learner can begin the construction of letter codes with the aid of attention, by rapidly scanning each letter's constituent features. However, "every time the subject organized the features into a particular letter code, some trace of this organization between features and letter code is laid down" (LaBerge & Samuels, 1974: 299). Eventually, the association between the new letter code and its corresponding features becomes strong, and attentional resources are no longer required for letter-code activation. At this point, features can be processed into the letter code automatically.

The activation of letter codes results in a flow of information through the visual memory coding hierarchy to spelling-pattern codes, which in turn feed into visual-word and, possibly, even visual-word-group codes. As was the case for letter codes, these higher-level codes are constructed with the aid of attention and initially can be activated only with attentional assistance. With repeated activation, the associations between these higher-level codes and their corresponding subordinate codes gradually become so strong that the activation of subordinate codes can result in the activation of the higher-level codes without attention. While the flow of information through the visual memory system is from lower-level to higher-level codes, each level within the system need not always be involved. For example, LaBerge and Samuels suggest that features might directly activate spelling-pattern or word codes without the intervening activation of letter codes (E. Smith & Spoehr, 1974; F. Smith, 1971).

INFORMATION PROCESSING AND THE VISUAL, PHONOLOGICAL, AND SEMANTIC MEMORY SYSTEMS

After information has been processed in the visual memory system, codes in the phonological memory system are activated. These codes feed into codes in the semantic memory system. LaBerge and Samuels suggest that spelling-pattern, word, and word-group codes are activated in the phonological system, while word-meaning and word-group-meaning codes are activated in the semantic system. Attention is required during the code construction and the initial stages of skill acquisition. However, some connections between phonological-word and semantic-word codes may be fairly automatic by the time reading instruction commences, as most children become well-practiced oral language users at a young age. The flow of information between memory systems at very early stages in code acquisition may be mediated by a memory for contextual events. LaBerge and Samuels liken this memory to Tulving's "episodic" memory (1972).

Just as the flow of information through the visual memory system has alternative routes, the flow of information

through the phonological and semantic memory systems also may follow alternative routes. When the entire processing system is considered, the number of possible alternative routes is quite large. Indeed, most of the inward-flowing processing routes postulated in reading by researchers can be encompassed by one or another of these alternative paths. For example, a visual-word code may activate a phonological-word code, which in turn may activate a word-meaning code. Alternatively, a visual-word code may directly activate a corresponding semantic-meaning code without any phonological code involvement (Bower, 1970; Goodman, 1972; Kolers, 1970; F. Smith, 1971). LaBerge and Samuels point out that our quick recognition of homonyms such as "two" and "too" lend credence to this latter option.

The particular selection of codes and routes postulated by LaBerge and Samuels are not essential to their general reading model. However, the role attention plays in the initial code construction, and attention's slowly increasing expendability with skill development, are critical.

Comprehension takes place in LaBerge and Samuels' model when the reader organizes word-meaning and word-group-meaning codes in the semantic system by rapidly shifting his attention among these meaning codes. This rapid shifting is made difficult when attention must allocate a large portion of its limited resources to nonsemantic levels of processing. Thus a goal of fluent reading is to automate most of the processing at levels below the semantic level, so that attentional resources can be allocated largely to processing in the semantic system.

Discussion of LaBerge and Samuels' Reading Model

HIGHER-ORDER LINGUISTIC PROCESSES AND READING

The reading model proposed by LaBerge and Samuels (1974) cannot be considered comprehensive because the roles played by higher-level linguistic processes have received little elaboration. With the stipulation that the mental activities that take place at low levels in the processing system function relatively independently of higher-level activities, there are few reasons why this particular model cannot be highly useful.

However, to the extent that the fundamental nature of lower-level processing activities is modified by the functioning of higher-level processing activities, allowance must be made for the influence which higher levels have on lower-level functioning.

The general flow of information through LaBerge and Samuels' reading model is from lower-level to higher-level processing stages. No provision is made in the model for the reverse flow of information. That is, there is no specified mechanism by which information at a higher stage can influence some of the processing activities in a lower stage. In this respect, the model can be contrasted with other models that emphasize the interactions between component processes (Goodman, 1972; Mackworth, 1972).

There are a number of factors which suggest that the activities of higher-level processing components exert an influence on the activities of lower-level processing components. The rapidity with which information must be interpreted by low-level processes makes it likely that input data are at times erroneously encoded. Consider the influence which an error in encoding material at a low level would have on the activities of higher-level components, if the sole source of information for processing at the higher level was the erroneously encoded information received from below. Presumably, there are mechanisms which monitor and correct the accuracy of information received from below. Such mechanisms, which are assumed to involve relatively high-level processing components, make extensive use of contextual constraints and the redundant nature of the information contained in a written message.

"Pandemonium," a pattern recognition scheme proposed by Selfridge and Neisser (1960), provides for the elimination of low-level errors in a manner that could probably be incorporated into LaBerge and Samuels' model. The pandemonium scheme consists of a hierarchical arrangement of devices (not unlike the codes described by LaBerge and Samuels) that are activated when the presence of a particular pattern of encoded information is detected in a number of lower-level devices. When one of these detection devices is activated, it emits signals which feed into corresponding higher-level devices. The strength of these signals varies as a

function of the number and/or intensity of relevant signals received from lower-level devices. Since the extent to which the higher-level devices are activated depends upon the combined intensity of signals received from numerous lower-level devices, the impact of any given erroneous signal from a low-level device tends to be progressively diluted as information undergoes continually higher levels of processing. In other words, high-level processing components make use of information that has been gleaned from several redundant sources of information.

A number of processing schemes have been devised which assign a far more active role to high-level linguistic processing components (Cooper, 1972; Halle & Stevens, 1962: Neisser, 1967). Often referred to as analysis-by-synthesis models, these schemes propose that language analysis proceeds in a manner that is similar to Bruner's "hypothesis testing." For example, Halle and Stevens suggested that the analysis of speech proceeds by matching an internally recreated version of the sensory signal with the actual stored input. A hypothesized version is accepted as true when it closely matches the stored input. The low-level processing components in such schemes must initially analyze only the amount of information needed to generate reasonable hypotheses. Unlike the pandemonium scheme, the analysis-by-synthesis schemes reflect a view that is not consonant with LaBerge and Samuels' model.

Study of the types of errors readers make lends credence to the view that higher-level linguistic processes are actively involved in some fairly low-level processing activities. For example, Goodman (1969, 1970, 1972) has observed that oral reading errors, or miscues often can be predicted more accurately from higher-level factors (e.g., contextual relevance) than from lower-level factors (e.g., spelling anomalies). Kolers (1970) reported that an analysis of errors made by subjects reading distorted texts suggests that these readers were quite sensitive to syntactic constraints. The word substitution errors which occurred were likely to have been syntactically acceptable with the preceding text. Indeed, syntactic sensitivity is apparent even in the reading errors of young children (Weber, 1970). In each of these cases, the reader appears to make use of his linguistic knowledge in an attempt to make sense of written material. Perhaps low-level visual processing activities are executed less carefully when contextual constraints have made a particular meaning relatively certain. Elaboration of LaBerge and Samuels' model is needed before it can adequately account for reading errors whose presence is attributable to higher-level processes.

THE HEURISTIC VALUE OF READING MODELS

The fact that LaBerge and Samuels' model cannot account for the influence which high-level linguistic processes have on reading does not necessarily mitigate the usefulness of this model. Comprehensive reading models, which attempt to make a relatively complete description of the reading process, are generally unable to generate specific hypotheses that can be subjected to empirical verification. Indeed, the dismal performance of comprehensive models in this respect led Calfee (1974) to refer to such models as "Jello" models (see Marsh, this volume). In contrast to the more comprehensive reading models are models which attempt to elaborate a more restricted set of phenomena. While these partial models fail to account for the complexities of reading processes, they can serve the valuable heuristic role of generating hypotheses that are specific enough to be empirically investigated. The final assessment of LaBerge and Samuels' model will largely depend on its ability to play this heuristic role, by generating experimentally verifiable predictions about the automatic performance of particular component processes.

Research on Processing Efficiency in Reading

Methodological Considerations

As was demonstrated earlier in this paper, the notion that the cognitive processes involved in reading become automated with practice has a long history in psychology. LaBerge and Samuels' model of reading adds to the earlier notions on how processes become automated. They argue that when a process is practiced, associative learning takes place that decreases the amount of attentional resources required for the process to function.

CONVERGING OPERATIONS

Research efforts directed toward elucidating mental processes must deal with a question that is familiar to

cognitive psychologists. Can valid inferences be made about the characteristics of processes that are not directly observable? In an affirmative answer to this question, Garner, Hake, and Eriksen (1956) suggested that the properties of mental events may be delimited by experimental designs that employ converging operations, which they define as follows:

> Converging operations are any set of experimental operations which eliminate alternative hypotheses and which can lead to a concept which is not uniquely identified with any one of the original operations, but is defined by the results of all operations performed (p. 158).

THE SUBTRACTION METHOD

The Subtraction Method, first used by Donders over one hundred years ago, is one set of converging operations which has become very popular in the past fifteen years. Recent studies have employed a version of the Subtraction Method in an attempt to measure the extent to which automatic processing takes place under a variety of experimental conditions (LaBerge, 1973a; LaBerge & Samuels, 1973). Although the mental processes of interest in cognitive research cannot be directly observed, they are assumed to take place in real time. For this reason, the duration that a process takes to complete its processing has become one of the most frequently used dependent variables in psychology. Reaction time, normally measured from the onset of the stimulus presentation to the elicitation of the subject's response, is assumed to represent the minimum duration required by the subject to correctly respond to a stimulus (Pachella, 1974).

One of the goals of cognitive research is to be able to attribute the effects of particular experimental manipulations to a mental operation that intervenes between the stimulus and the response. Because the reaction time interval is filled with more than one process, a procedure is needed for isolating an intervening process and measuring its duration. The Subtraction Method is a set of converging operations that provides a procedure for doing this.

The Subtraction Method "is applicable when the performance of an experimental task involves the sequential action of a series of mental events" (Pachella, 1974: 46). To measure the duration of an isolated process the reaction time of an experimental task that contains the process of interest is compared to the reaction time of a comparison task that is identical to the experimental task, except for the deletion of the process of interest. The difference between the two reaction times is assumed to represent the length of time required to execute the deleted process.

To study the effects that certain experimental manipulations have on the length of time required to carry out a particular mental process (i.e., the isolated process), the difference between the reaction times obtained under the experimental- and comparison-task conditions are compared as a function of the experimental manipulations (Pachella, 1974). When experimental manipulations do not affect a particular process, the duration of this process, as measured by the above procedure, should not be influenced by the experimental manipulations. In this case, differences in reaction times obtained as a function of the experimental manipulations must be attributed to changes in the durations of one or more of the other intervening processes.

Automatic Perceptual Processing

LaBerge and Samuels (1974) account for increased reading efficiency in terms of the gradual automation of processes. At the lowest level in their model, visual information is analyzed by feature detectors. The outputs of these feature detectors activate letter codes stored in visual memory. While proficiency in attentively processing features into letter codes is rapidly achieved, proficiency in automatically carrying out these same activities is acquired only gradually.

For this reason individuals may be able to identify unfamiliar letters as rapidly as familiar letters when their attention is focused on the letters. However, they may not be able to identify the unfamiliar letters as rapidly as the familiar letters when the letters are encountered while their attention is focused elsewhere. Although both types of letters can be processed with assistance from attention, only the processing of the familiar letters can take place without assistance from attention (automatically). The processing of the unfamiliar letters can begin only after attention has had time to switch its focus to these letters. Thus, if the unfamiliar letters are

encountered at a time when they are not expected, they may be processed more slowly than the familiar letters by the duration required for attention to switch its focus to the letters. Such attention switching has been estimated to require as long as 80 msec. (LaBerge, 1973b).

A STUDY OF AUTOMATIC LETTER RECOGNITION

LaBerge (1973a) examined three predictions based on the above argument. First, he predicted that recognition time would be greater for unfamiliar letters than for familiar letters when the letters were encountered under conditions of nonattention (i.e., conditions where attention switching was required). Second, he predicted that the differences between the recognition times found under conditions of nonattention would gradually decrease as practice was obtained on the unfamiliar letters. Third, he predicted that the recognition times for two types of letters would not differ when the letters were presented under conditions of attention. This latter prediction was based on the assumption that any difference in response times under conditions of nonattention would be due to the fact that only the familiar letters could be processed automatically (i.e., while attention was switching to the task).

The measurement of letter recognition latencies. LaBerge used letter-matching latencies to assess relative letter-recognition speeds. Although these latencies contain time-consuming activities in addition to those involved with letter recognition, the differences between these latencies provide useful estimates of relative recognition speeds (cf. Posner, Lewis, and Conrad, 1972). The subjects in this study were presented both familiar and unfamiliar letters. The familiar letters were the letters *b d p q*. Presumably these letters were at an asymptote of familiarity and could be processed both with and without assistance from attention. The unfamiliar letters were the arrow-like shapes . Presumably these letters could be processed only with the aid of attention. In other words, the unfamiliar letters could be processed under conditions of nonattention only after an attentional switch was made.

The momentary control of attention's focus. To obtain letter-matching latencies for the familiar and unfamiliar letters under conditions of nonattention, a cueing technique (LaBerge, Van Gelder, & Yellott, 1970) was used to induce the subject to focus his attention momentarily on a particular letter. A single letter was briefly presented at the beginning of each trial. This letter served as a cue which informed the subject that a single target letter identical to the cue was likely to appear after a short interval. When the target letter was identical to the cue, the subject was to press a button as rapidly as possible. When this target letter did not match the cue, the subject was to do nothing. Since the proportion of positive responses on this successive matching task was always greater than 50 percent, the presentation of the cue was assumed to create a strong expectation that the target would be identical to the cue. This expectation presumably resulted in the subject's focussing his attention on the expected letter.

On occasional trials the presentation of the cue was followed, not by a single letter, but by an unexpected pair of letters that had been selected from the set of familiar and unfamiliar letters described above. The subject was instructed to press the button if the pair of letters matched and to do nothing if they did not match.

The trials with the unexpected pairs of letters provided the data on letter recognition under conditions of nonattention (the nonattention task). On the first day of testing, the results from these simultaneous-letter matching trials indicated that the unfamiliar-letter pairs took 48 msec. longer to respond to than the familiar-letter pairs. The size of this difference decreased as the subjects practiced on the matching task. Indeed, by the fourth day of practice the letter matching latencies for the two types of letters were indistinguishable.

By themselves, these findings do not strongly support the idea that the familiar letters were processed more automatically than the unfamiliar letters. Any one of a number of processes may have been responsible for the differing response times. For example, it is possible that the response latencies were shorter for the familiar letters simply because they underwent more rapid attentive processing.

Application of the Subtraction Method. The Subtraction Method was employed to demonstrate that the differences between the two letter-matching latencies was due to differences in automatic perceptual processing. A separate group of subjects was tested on a comparison task. For the comparison task, the familiar and unfamiliar letters were used

as both cues and single-letter targets in a successive-letter matching task. This procedure allowed letter-matching latencies to be gathered for the two types of letters under conditions when they were expected (the attention task). The resulting latencies were assumed to involve all of the processes involved in the nonattention task except for those processes that functioned automatically (i.e., before attention had time to switch its focus to the target letters). No significant differences (9 msec.) were found between the familiar and unfamiliar letter-matching latencies in the attention task, and LaBerge concluded that the inequalities found in the nonattention task were due to differences in automatic perceptual processing.

Conclusions and implications. The recognition time for familiar letters was shorter than that for unfamiliar letters in the nonattention task, but not in the attention task. Therefore, the familiar letters appeared able to undergo more automatic processing than the unfamiliar letters. However, the difference between these two types of letters vanished when the unfamiliar letters were sufficiently practiced to be themselves automatically processed.

These results are consistent with LaBerge and Samuels' reading model (1974) and the predictions discussed above. Unlike many reading models (see Marsh, this volume), LaBerge and Samuels' model would seem to serve a heuristic purpose. It can be used to generate hypotheses that are relatively specific and testable. In addition, the findings support the view that perceptual learning continues well after a high level of performance is achieved in an attention condition. This view has pedagogical significance, for it implies that proficiency in recognizing letters encountered at moments when attention is focused upon the letter-recognition activity does not guarantee comparable proficiency in a situation where attention is not continually focused upon the letter-recognition activity. The fact that a beginning reader may be able to identify the unfamiliar letters of the alphabet rapidly does not necessarily mean that he will be able to carry out this processing concurrently with the other processes involved in reading.

Children who frequently make letter reversal errors when reading have been found to make few such errors when letters are individually presented (Liberman, Shankweiler, Orlando, Harris, & Berti, 1971). Perhaps the attentional requirements of reading are such that only a small amount of attention can be allocated to the process of letter identification. Therefore, frequent letter reversal errors may indicate that a child's proficiency in letter recognition is not yet sufficient to allow accurate automatic processing.

In assessing a child's letter-identification skills, it may be important to take into account the effort that goes into letter recognition. For if the recognition can be carried out only by consuming large amounts of limited attentional resources, the child may be unable to allocate sufficient processing resources to other vital processes. Perhaps the procedures used in LaBerge's study will prove useful in assessing the efficiency of reading skills in problem readers.

CRITICISM OF THE LABERGE STUDY

Applicability of the Subtraction Method. There are a number of criticisms that can be made of LaBerge's study (1973a). The most fundamental of these criticisms questions the conclusion that the difference between the recognition latencies obtained for familiar and unfamiliar letters on the experimental task is due to an automatic stage of processing. Since letter recognition involves numerous processing stages, the Subtraction Method was used to isolate the automatic stage of processing (i.e., the stage that preceded attention's focussing on the target letter in the nonattention task). Thus, the validity of the main conclusions drawn in this study depends on the applicability of the Subtraction Method. However, this method is applicable only when a number of assumptions (Pachella, 1974) are made. Unfortunately, some of these assumptions can be made only on tenuous grounds.

To begin with, it must be assumed that performance on the letter-matching tasks reflects the activities of a series of discrete mental processes. The various component processes that influence the response latencies must function independently of one another. For example, the processes involved in the execution of the button-pressing response cannot affect the manner in which information is processed by other component processes. No evidence was presented concerning this assumption. Sternberg's Additive Factor Method (1969) might provide means of testing assumptions about the discreteness of the mental processes involved in LaBerge's tasks.

Another assumption that is critical to LaBerge's conclusion is the assumption of task comparability, which implies that the nonattention (experimental) and attention (comparison) tasks are comparable (i.e., both tasks are identical except for the deleted processes). In the nonattention task subjects pressed a button whenever a matching pair of letters simultaneously appeared, while in the attention task subjects pressed a button whenever a single letter matched a preceding letter cue. Thus the two tasks cannot, strictly speaking, be considered identical, unless it is assumed that simultaneous and successive letter-matching tasks involve identical processes. Interpretation of the difference between the nonattention and attention tasks would be less tenuous if an identical matching task had been used for both conditions.

Additional evidence pertaining to the validity of the assumption that the two tasks were identical can be acquired through inspection of the reaction time data. One relevant finding is that the response latencies observed in the nonattention task were considerably longer than those latencies observed in the attention task. Indeed, even the familiar letters required approximately 200 msec. longer to be responded to in the nonattention task.

Since the familiar letters are presumed to be automatically processed during the attention switching interval of the nonattention task, the reasons for this 200 msec. difference are not immediately clear. Certainly, it seems unlikely that the attention switching interval requires 200 msec. Thus the processes that take place in the two tasks seem to differ by more than the presence or absence of attention. Possibly a portion of this 200 msec. difference can be attributed to an attentional priming or heightening of the excitability of processing components in the attention task. Unfortunately, this suggestion does not resolve the problem, for the deletion of the attention switching interval would then have to be viewed as influencing the speed of the functioning of the remaining processes. Thus the requirements for the construction of an appropriate comparison task, as discussed above, would again seem not to have been strictly met.

The speed-accuracy problem. Before taking a further look at the relevant experimental data, it will be useful to consider what has come to be known as the speed-accuracy problem. Reaction time is normally assumed to represent the minimum duration required to produce an accurate response. However, when subjects are induced to either lengthen or shorten their response latencies, the number of errors they make changes systematically. Likewise, inducing subjects to vary the accuracy of their performance results in systematic changes in response time. The typical finding obtained in studies which explore this speed-accuracy problem is that as the speed of responding increases, the accuracy of responding decreases (Pachella, 1974; Pew, 1969).

Normally, the information-processing tasks on which response times are used as the dependent variable are so simple that subjects would probably make no errors if they were not rushing their response (Pachella, 1974). Certainly, the subjects in LaBerge's study would have made no errors on the simple letter-matching tasks if they had not been trying to minimize their response times. Thus the average response time obtained on a task might be considered to be the minimum duration required to perform the task, given a specific error rate.

Small variations in accuracy performance can result in relatively large changes in response latencies, particularly on tasks, such as those used in LaBerge (1973a), where the average level of performance is high. This is because subjects may not use the same accuracy criterion on different tasks. Consideration of the speed-accuracy problem can be critical when attempts are made to compare response latencies obtained under different conditions. This, for example, means that findings concerning the response latencies of two tasks that are not performed equally as accurately will be difficult to compare meaningfully.

Thus consideration of both LaBerge's reaction time and performance accuracy data (1973a) is in order. On the first day of testing in the nonattention task, the unfamiliar letters were found to require an average of 48 msec. longer to respond to than the familiar letters. This 48 msec. difference formed one critical part of the data supporting the study's conclusion that only the familiar letters underwent significant automatic processing while attention was switching its focus to the target

letters. Inspection of the performance accuracy data obtained in the nonattention task indicates that a nearly identical, low percentage of errors was made for each type of letter presentation. In light of the above discussion of the speed-accuracy problem, the similarity between these error rates is one important precondition to a meaningful comparison of the two sets of reaction time data.

The finding that the response latencies for the two types of letters were almost equal on the first day of testing in the attention task was critical to the study's conclusion that the unfamiliar letters required an average of only 9 msec. longer to respond to than the familiar letters. However, inspection of the performance accuracy data in the attention task suggests that it may be difficult to make a meaningful comparison between the two types of letter's response latencies. Although the percentage of errors was low on trials where the familiar letters were presented, a considerably higher percentage of errors was made on trials where the unfamiliar letters were presented. Indeed, based on data graphically presented in LaBerge (1973a, Figure 4, p. 27), the present author estimates that the unfamiliar letters resulted in more than twice as many errors as the familiar letters in the attention task.

One interpretation of this difference in accuracy performance is that subjects adopted a different accuracy criterion for each type of letter. If this were the case, it would have grave consequences for LaBerge's conclusions, because the following question would then have to be asked: How large would the difference have been between the average response latencies for the unfamiliar and the familiar letters if the subjects had adopted the same accuracy criterion for both types of letters?

While this question can only be answered in a definitive manner when appropriate empirical data are collected, a prediction can be made based on the speed-accuracy findings reported in other studies (Pachella, 1974; Pew, 1969). The prediction is simply that, if the accuracy criterion for the unfamiliar letters had been as high as the criterion for the familiar letters, the difference between the response latencies of the two types of letters would have been greater. It follows from this prediction that the durations required to process the unfamiliar letters might have been significantly longer than the durations required to process the familiar letters.

Fortunately, there are experimental procedures that have been used successfully in inducing subjects to adopt specified accuracy criteria (Pachella, Fisher, & Karsh, 1968). These procedures could be used to eliminate the potentially contaminating influence of unequal error rates, should they be found on future studies using LaBerge's general paradigm.

Concluding remarks. A number of useful purposes have been served by the above critical discussion of LaBerge's study. The most apparent purpose was to point out the problematical nature of a few of the central assumptions which must be made before the conclusions of this study can be accepted without qualification. In spite of the above criticism, this study should be considered a valuable initial attempt at elaborating some of the mental processes which seem germane to the acquisition of reading skill. The design of this study was well thought out. Its results were obtained with a commendable precision that is all too often lacking in research on reading processes. Still more importantly, LaBerge's general paradigm appears to provide a flexible model capable of suggesting procedures for studying a number of problems related to the acquisition of efficient reading processes. This latter point will be taken up in more detail below.

A more general purpose also has been served by the above critical discussion. Many of the assumptions that were identified as fundamental to the logic of LaBerge's study must also be made for most cognitively oriented reading research. Use of some form of converging operations seems necessary to study mental events. The general criticism that LaBerge's tasks were not comparable can be directed at most experiments employing converging operations:

> Converging operations, by definition, involve several tasks or conditions that differ from each other in certain systematic ways. They must do this; otherwise they wouldn't converge on some theoretical construct. The argument can thus be made that the converging tasks may involve fundamentally different mediational components (Pachella, 1974: 51).

The perennial nature of criticism concerning the comparability of tasks should not disparage the use of designs using converging operations. Where possible, however, these designs should contain provisions for obtaining data relevant

to the assumptions of comparability. Because it may be impossible to prove that tasks are comparable, all relevant experimental findings must be thoroughly scrutinized for evidence that is inconsistent with critical assumptions. In the case of LaBerge's study, a careful inspection of the data resulted in the identification of findings which appear somewhat incongruous with assumptions of task comparability. However, these incongruities do not provide definitive evidence that the basic assumptions do not hold up. Rather, they provide indications of places where careful scrutiny will be called for in future studies. Additional research using the experimental design used in LaBerge's study should provide evidence needed to clarify questions which are at present ambiguous.

If the experimental paradigm used by LaBerge can be criticized because of its reliance on some rather questionable assumptions, this innovative research design can also be lauded for its potential value as a research tool. The properties of the mental activities which LaBerge examined could not be observed directly; his design seems to provide a means for obtaining relatively precise estimations of these activities. We will turn next to a study (LaBerge & Samuels, 1973) that employs the same general experimental design. A good portion of the criticism directed at LaBerge's study (1973a) could be directed at this new study. As little would be gained from repeating this same criticism, the following discussion will focus exclusively on the general design and positive findings of LaBerge and Samuels (1973).

Automatic Associative Processing

According to LaBerge and Samuels' model, automatic processing can take place at several levels in the processing hierarchy. LaBerge and Samuels (1973) used a design very similar to that used by LaBerge (1973a). A cueing technique similar to the one described above was used to induce the expectation that a particular target would appear. However, in this study, the cueing technique involved a successive word-matching task. The subject was instructed to respond by pressing a button whenever a target word matched the cue word. On occasional trials the presentation of the cue was followed, not by a word, but by either a familiar or unfamiliar letter. The subject was to name the letter aloud immediately upon its presentation (nonattention task). The letter-naming latency was measured from the onset of the letter to the vocal response which triggered a voice key.

The familiar and unfamiliar letters used in this study were the same ones used in LaBerge (1973a). The naming responses associated with the letters were bee, dee, pea, and cue, respectively, for the familiar letters (*b d p q*) and one, two, four, and five, respectively, for the unfamiliar letters (ᒪᒧ ᒥᒣ). Because the experimenters wanted response latencies to reflect differences in associative processing instead of letter recognition speeds, subjects were first trained on matching the unfamiliar letters to a point where they were matched as rapidly as the familiar letters under conditions of nonattention. Following this training, the subjects received the first of twenty days of testing in the nonattention task. The termination of each testing period was followed by a period of intensive letter-naming training.

During the first day of testing, the unfamiliar letters took considerably longer to name than the familiar letters in the nonattention task. The results obtained in a comparison task, where the targets were expected, resulted in no difference between the naming latencies for familiar and unfamiliar letters. With additional days of training, the unfamiliar-letter naming latencies gradually became shorter, while the latencies for the familiar letters remained fairly constant. Even after twenty days of training, however, the latencies for the unfamiliar letters remained considerably longer than those for the familiar letters. LaBerge and Samuels (1973) interpreted these findings as supporting the notion that the familiar letters could undergo automatic associative processing to a much greater extent than the unfamiliar letters. The finding that the unfamiliar letters could not be named as rapidly as the familiar letters after 20 days of training suggests that the automation of this form of associative processing occurs very gradually.

An implication of these findings is that beginning readers may be able to carry out associative processing activities only when a large proportion of their attentional resources are allocated to this task. In contrast, skilled readers may be able to carry out this same processing activity

efficiently and automatically. As a result, skilled readers need to allocate only a small portion of their attentional resources to associative processing activities. The attentional mechanism of skilled readers, thus, would be free to focus on other processes.

Additional Applications of LaBerge and Samuels' Research Paradigm

The general experimental design used in LaBerge (1973a) and in LaBerge and Samuels (1973) appears to have considerable value as a research tool. We have already seen how this experimental design has been used to test predictions about automatic processing in letter identification and naming. Numerous additional processing skills, subject variables, training procedures, and distracting task variables could possibly be investigated with this paradigm.

SUBJECT VARIABLES

A variety of subject variables might be investigated by use of LaBerge and Samuels' paradigm. Samples composed of subjects who differ in age, mental ability, or reading proficiency can be systematically manipulated to determine how these groups compare on various types of processing activities. Significant differences between groups may sometimes appear only under conditions of nonattention. Children who are poor readers may not have automated important processing skills to the same extent as their better-reading peers. Additionally, retarded children may generally require more extensive training before they are able to execute processing skills automatically.

The weakness of a skill may not be identified if the skill is assessed at a time when no other skills are simultaneously involved. For this reason, a method is needed to assess how a component skill functions when it is executed concurrently with other processing skills. LaBerge and Samuels' paradigm might be adapted for use in this assessment.

TRAINING PROCEDURES

The influence which various types of training procedures have on the acquisition of automated reading skills might be explored. For example, the effects of a few intensive practice sessions could be compared to the effects of several less intensive sessions. The influence that relaxing demands for accurate performance could be investigated. Many of the low-level processes involved in reading may not normally need to be carried out with extreme accuracy, for higher-levels receive considerable redundant information. Additionally, contextual constraints may help reduce the need for accurate low-level processing. Occasionally, when the reader detects a significant discrepancy between his predictions and the results of automatic processes, he might reexamine the visual information more carefully.

DISTRACTING TASK VARIABLES

LaBerge (1973a) and LaBerge and Samuels (1973) used relatively easy matching tasks to control the subject's expectations, thereby preventing him from attending to a particular stimulus. Use of a variety of more complex distracting tasks might provide additional insights. Since reading involves semantic processing, the use of a distraction task that focuses the subject's attention on an activity involving the semantic processing of words might provide results more readily generalizable to reading.

A process is considered to be automatic when its processing activities can be carried out while attention is focused elsewhere. This criterion for automatic processing fails to make differential predictions for the varying influences of different kinds of distracting tasks. Research suggests, however, that when performance decrements on one task result from the concurrent performance of a second task, the extent of the performance decrement is a function of the difficulty of the second task (Keele, 1967). For this reason, the complexity or difficulty of the distracting task per se should prove to be an interesting variable.

Processes that appear to be automated when the distracting task is relatively easy may not appear to be automated when the distracting task makes large demands on limited processing resources (Norman & Bobrow, 1975). When the processing activities involved with an attention distracting task require only a small allocation of limited resources, the remaining surplus of these resources might be sufficient to

allow the operation of a second process. In this situation the second process might appear to be automatic. Yet, when a distracting task involves activities that require a larger allocation of attentional resources, the remaining attentional resources might be insufficient for the operation of a second processing activity. The second process would not appear to be automatic in this case. Thus, a process may appear to require attention in one situation and not to require attention in another.

Alternative Ways to Study Processing Efficiency

EVIDENCE OF AUTOMATIC SEMANTIC PROCESSING

While the experimental approach used by LaBerge and Samuels provides an important means of investigating automatic processing in reading, alternative means are available. One approach that seems likely to provide evidence on automatic processing explores the subject's ability to attend to a task while simultaneously ignoring potentially distracting or interfering semantic information.

Perhaps the best known examples of this type of research involve various forms of the Stroop test. In this test, subjects are instructed to name the colors of the ink in which strings of letters are printed. When the strings of letters spell the names of incongruous colors (e.g., the word "red" printed in blue ink), the color-naming times are slow, relative to the times when the letter-strings spell only nonwords. Since the subjects in this task are attempting to attend to the colors of the letter strings, not to their colors, this color-word interference seems to be due to the automatic reading of the letter strings. The subjects seem unable to avoid automatically processing the interfering words. Color-word interference is not restricted to adults, for it is found for even young children (Schiller, 1966). Apparently the automatic processing of familiar words is learned at an early age (Rosinski, Golinkoff, & Kukish, 1975).

Additional support for the notion that semantic processing can take place automatically is found in a recent study that investigated selective attention in good and poor readers (Willows, 1974). Subjects were instructed to read passages that were typed in black ink. Words that were typed in red ink, which appeared between the lines in black ink, were to be ignored. When the meanings of the words typed in red ink were congruous with the attended to passage (black ink), proficient readers were found to make more errors involving semantic intrusions of the nonattended words (red ink) than the unskilled readers. Presumably, the low-level reading skills of the proficient readers were highly automated. Their attentional efforts could be focused almost entirely on the meanings of the passage, rather than on the particular colors of the inks involved. As a result, the words printed in red ink, which were automatically identified along with the words printed in black ink, were often adopted as part of the passage when their meanings were consistent with the passage.

TIME SHARING RESEARCH AND THE MEASUREMENT OF EFFICIENT PROCESSING

In recent years, the influence that the performance of one task has on the concurrent performance of a second task (Keele, 1967) has been investigated. The information processing model of Norman and Bobrow (1975), described earlier in this paper, provides a useful theoretical framework for interpreting this research. When the performance of one task interferes with the concurrent performance of a second task, the performance of the second task is considered to be resource limited, i.e., the amount of processing resources allocated to the second task is insufficient for maximum performance. Presumably, performance on the second task decreases as a function of the amount of resources allocated to the first task. This functional relationship between the performances of two tasks can be used to measure the attentional requirements (Kerr, 1973) or processing efficiency of the timeshared tasks.

Therefore, the efficiency of various reading processes can be studied by investigating their influence on a second, concurrently performed task. To be meaningful, however, variations in the performance of the timeshared task must be attributable to variations in the availability of a processing resource of interest. This means, for example, that if we are interested in the extent to which attentional resources are consumed by various reading processes, performance variations on the timeshared task must be attributable to variations in the allocation of attention to this task.

It is assumed that nonproficient readers generally must allocate a larger portion of their attentional resources to reading processes than proficient readers. Thus, as compared to proficient readers, nonproficient readers should experience larger decrements in performance on an appropriate second task that is timeshared with reading processes. In addition, increasing the portion of attentional resources allocated to the reading processes by making the written material more difficult to comprehend, should result in lower performance on the timeshared task. Conversely, increasing the portion of attentional resources allocated to the timeshared task should retard the performance of the reading processes.

Summary and Concluding Remarks

As proficiency in reading is acquired, the numerous component processes involved in reading become increasingly efficient in their use of limited attentional resources. Thus skilled readers need to allocate only a minimal amount of attentional resources to lower-level processes as they read. As a result, their comprehension is normally high, because their attentional resources can be directed almost entirely to the meaning of written passages. In contrast, beginning readers must allocate a considerably larger amount of their attentional resources to lower-level processes. Indeed, for beginning readers the portion of their attentional resources consumed by lower-level activities may be so large that they often pay insufficient attention to the meanings of written passages. As a result, their reading is likely to be awkward and slow, and their comprehension is likely to be low.

The reading model proposed by LaBerge and Samuels (1974) accounts for increased processing efficiency in terms of the automation of various processes. Written information is assumed to undergo processing through a series of component processing stages that involves codes stored in the visual, phonological, episodic, and semantic memory systems. During early stages of skill acquisition, information can be processed through these codes only when assisted by attention. With practice, however, attention becomes dispensable, because much processing can take place automatically. The increasing automation of lower-level processes frees attention to focus on higher-level processes, such as those involved with comprehension.

Mental events cannot be directly observed. However, their properties can be investigated with experimental designs that employ converging operations. The Subtraction Method is a set of converging operations that has been used to elaborate the role that attention plays in the recognition (LaBerge, 1973a) and naming (LaBerge & Samuels, 1973) of familiar and unfamiliar letters. The conclusions drawn in these studies were as follows: Familiar letters can undergo processing both with and without assistance from attention, while unfamiliar letters can undergo processing only with assistance from attention. In addition, the processing of unfamiliar letters gradually appears to become automated with practice.

These conclusions are consistent with LaBerge and Samuel's reading model. The validity of these conclusions rests on the appropriateness of the Subtraction Method. This method is applicable only when a number of critical assumptions hold up. Unfortunately, empirical evidence for some of these assumptions (i.e., task comparability) is lacking, and LaBerge and Samuels' conclusions cannot be accepted without qualification. This criticism is by no means unique to LaBerge and Samuels' studies, for similar assumptions must be made for most research employing converging operations. Because converging operations of one form or another must be used to study mental activities, care must always be taken to minimize the chances that critical assumptions will be violated. With respect to LaBerge and Samuels' work, additional evidence is needed before their findings can be accepted with confidence. Research applying their paradigm, as well as research employing various Stroop and timesharing procedures, seems likely to yield findings that will help to elucidate the role of automatic processes in reading.

A large portion of the research conducted on reading processes attempts to elaborate the repertoire of subskills possessed by individuals of different reading abilities. However, skilled readers can differ from less skilled readers, not only in the size of their repertoire of subskills, but also in the efficiency and facility with which they are able to execute these subskills. Numerous subskills must be coordinated for reading to take place. Therefore, in addition to identifying the component processes involved in reading, it is necessary to explore the mental effort that goes into various processing activities.

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