Perception & Psychophysics
1993, 53 (4), 372-380

Saccadic overhead: Information-processing time with and without saccades

ETHEL MATIN and K. C. SHAO
Long Island University, Brookville, New York

and

KENNETH R. BOFF
Human Engineering, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio

Information-processing time was compared for serial and spatially distributed visual presentations with performance measures that permit the separation of total time into its during-display and post-display components. For all subjects, there was a significant saccadic overhead, that is, less time was required with the serial format, which allowed data access without eye movements. However, the magnitude of the overhead decreased as task complexity increased. All subjects were able to exercise some control over the distribution of total processing time, trading off short during-display times with longer post-display times and vice versa.

The purpose of the present research was to measure the "cost" of a saccadic eye movement. Our strategy was to measure information-processing time under two conditions, serial and spatially distributed. The former allowed information access without eye movements and the latter required them. However, all other aspects of the experimental procedures were strictly identical. The serial/spatial processing time difference is operationally defined here as the *saccadic overhead.*

The questions we are addressing have a rich background in basic as well as applied psychological research. Indeed, almost since the inception of psychology as an experimental discipline, researchers have studied the role of saccadic eye movements in visual cognition, particularly in reading (Dodge, 1900). The pace of these studies was accelerated with the development of modern digital computers, which allowed new and highly sophisticated methodologies (Just & Carpenter, 1987; Lévy-Schoen & O'Regan, 1979; McConkie, 1983; Rayner, 1978). In addition, a line of research arose that examined the role of saccades by seeing what happens when they are eliminated with a serial presentation format (Forster, 1970; Sperling, Budiansky, Spivak, & Johnson, 1971). Although such a format does not imply high presentation rates per se, the method is usually called *rapid serial visual presentation* (RSVP) (see Potter, 1984, for a review with extensive references to the literature).

This work was supported by the Research Committee of the Post Campus of Long Island University, by a grant from the Air Force Office of Scientific Research to Long Island University, and by a grant to the first author through the AFOSR Faculty Research program. The two AFOSR grants were administered by Universal Energy Systems, Dayton, Ohio. We also acknowledge the loyal commitment of our subjects, Bill McGovern, Dave Roberts, Greg Viscovitch, and Tara Zampardi. Requests for reprints should be sent to E. Matin, Department of Psychology, Post Campus, Long Island University, Brookville, NY 11548.

The present report, like most of the literature on the serial format, describes basic research motivated by an interest in exploring visual cognition with experimental control over stimulus timing and retinal image. (In contrast, when eye movements are used to access information, both the rate of stimulus presentation to the fovea and the moment-to-moment retinal image are usually under the subject's control, not the experimenter's.) However, we note in passing that a lively interest in the application possibilities has also been developing. Some of this work is relevant to the design of reading machines for persons with normal vision (e.g., Arditi, Knoblauch, & Grunwald, 1990; Chen, 1986; Juola, 1988) and some of it pertains to machines for people with visual impairments (Rubin & Turano, 1992). Other studies are concerned with the serial format as a visual display technology (Matin, Boff, & Donovan, 1987; Osgood, Boff, & Donovan, 1988).

The present experiments grew out of earlier research comparing serial and spatially distributed presentations in studies using a performance measure called the *frame duration threshold* (Matin & Boff, 1988). Briefly, this is the length of time a frame must be exposed for a given performance level (e.g., 90% correct). By computing the difference between the thresholds with spatially distributed and serial formats and dividing by the number of saccades, we obtained a measure of the saccadic overhead.

The results of this early research showed a large overhead (approximately 100 msec per saccade) with a simple digit recall task. However, it seemed possible that the threshold measure only tapped the early information-processing stages while the rest of the work continued after the last data frame disappeared. In effect, we could not rule out the possibility that more processing occurs in the post-display period in the serial condition than in the spatially distributed condition and that the overhead would disappear if this fact were taken into account. We addressed this problem in Experiment 1 by measuring total processing time (onset of display to response) at the duration threshold. In Experiment 2, we extended the scope of the findings by studying the effect of frame duration for a large range of experimenter-controlled durations.

EXPERIMENT 1

The purpose of Experiment 1 was to measure the saccadic overhead by comparing serial and spatially distributed processing times at the duration threshold. The subjects made a two-choice speeded response, which could only be correct at above-chance levels if each of the three data frames presented on a trial was viewed and processed correctly.

Before proceeding to the description of the method, we comment briefly on two further aspects of the procedure that are not obviously motivated by the prior introduction. The first is the role of a variable that we call the *subject operating mode*, and the second is our use of two windows, not three, for presenting the three data frames in the spatially distributed condition.

The existence of an operating mode factor came to our attention when pilot work showed an unusually high variability in the duration thresholds in comparison with the variability in our earlier studies, which involved no concomitant measures of reaction time (RT). A possible explanation for this increased variability was suggested by the comments of 1 of the subjects, who reported that she could generate two different thresholds by operating in one of two different modes: emphasis on making the during-display time short with a correspondingly longer post-display time, or emphasis on a minimal post-display time, with a longer during-display time (and therefore a longer threshold). To clarify the effect of this variable, we incorporated the operating mode into the design of the experiment.

The use of a two-window spatially distributed condition regardless of the number of data frames was a departure from our earlier work, for which we used a set of *n* windows, one for each of the frames, with the data available in all the windows throughout the trial. For at least two reasons, the latter procedure was not optimal for measuring the saccadic overhead. First, the serial and spatially distributed conditions were not comparable because the possibility of simultaneous access to information in more than one window through peripheral vision existed in the spatial condition, but not in the serial condition. Second, the two conditions were not comparable because the serial format imposed a rigid frame duration structure (each frame was presented for the same length of time) whereas the subjects in the spatial condition were free to vary the time allotted to the various frames provided that all the frames were viewed before the display was removed.

Freedom in varying the fixation time is an important part of normal viewing in reading and other scanning tasks and needs to be studied in its own right (Carpenter & Just, 1983; Lévy-Schoen & O'Regan, 1979; McConkie, 1979). With respect to our current objective, however, allowing free viewing in the spatially distributed condition raises the possibility that the serial format's elimination of costs due to planning and executing eye movements is counteracted by costs due to rigid temporal structuring, with the result that a "pure" saccadic cost cannot be calculated (see Cocklin, Ward, Chen, & Juola, 1984, p. 435, for related comments). This important issue will come up again in the General Discussion.

The problems of peripheral access and rigid temporal structuring were addressed in the present experiments by presenting the data frames for the spatially distributed condition in two widely separated windows. The subject accessed the information by saccading from the first (left) window to the second (right) window, and back again to the first (two saccades for the three data frames that were presented on each trial, because the subject was already fixating in the center of the left window where the first data frame appeared at the beginning of the trial). As in the serial condition, each frame's duration was fixed by the experimenter and only one data frame was available at any time. In effect, the stimulus presentation method was identical for the serial and the spatially distributed conditions, except for the use of two windows instead of one in the latter.

Method

Subjects. There were 4 subjects, 2 of whom (Subjects 1A and 1B) were authors of the present study. All the subjects practiced the procedures extensively (10–15 h) before the formal data collection began.

Apparatus. The experiment was run with an IBM XT microcomputer equipped with an enhanced graphics adapter (EGA) card, an EGA monitor, an IBM data acquisition card, and a standard IBM keyboard for response entry. Assembly language routines were used for stimulus timing, measurement of post-display times with the data acquisition card, and synchronization with the 60-Hz display raster (see Dlhopolsky, 1982, for a discussion of raster synchronization).

Subject's task. On each trial, the subject viewed three data frames, each containing one digit in the range 2–9 and flanked on both sides by two "#" characters (see Figure 1a). The task was to count the number of odd digits and to respond "odd" if this count was odd, and "even" otherwise. The "V" and "M" keys were used to enter the even and odd responses, respectively. The stimuli were white digits (33 cd/m²) on a dark background (3 cd/m²). The width of the characters with intercharacter space was .25° at a viewing distance of 63.5 cm. The flanking characters were used for comparability with the visual conditions in Experiment 2, for which more than one digit per frame was used in some runs.

Trial procedure. The subject initiated a trial by fixating in the center of a 1.25° × .75° window on the monitor, entering a ready signal, and then holding the index fingers on the response keys, ready for the binary odd/even response at the end of the trial. For the serial condition, which eliminated the need for saccadic movements, the three digits were then presented in temporal succession as individual frames for the frame duration selected for the trial. The last frame was followed immediately by a mask (#####). As soon as the subject responded, the response (O or E), the correct response (also O or E), and the trial number were presented as feed-

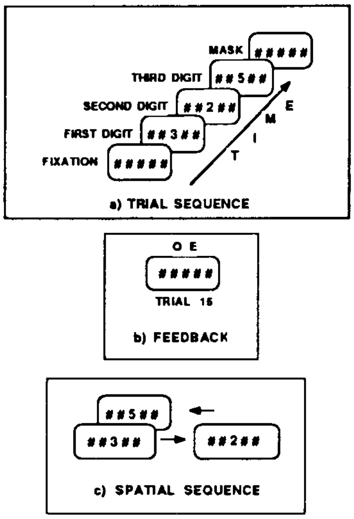

Figure 1. An example of the frame sequence (a) and the feedback at the end of the trial (b). In this example, the subject made an error on Trial 15 by responding "odd" when the correct answer was "even." For the serial condition, the digits and all the other frames were presented sequentially in one window in the center of the screen. For the spatially distributed condition (c), they appeared in two windows (left window, right window, back to left window), while all other frames appeared in the left window.

back for 800 msec. When the feedback was removed, the mask fixation frame reappeared and the subject was free to initiate the next trial (see Figures 1a and 1b).

For the spatially distributed condition, there were two 1.25°×.75° windows centered on the middle of the screen and separated horizontally by 11°. The first data frame was presented in the left (fixation) window. The subject then made a saccade to the right window to get the second digit, and a second saccade to the left window to get the third digit (see Figure 1c). Except for the use of two windows instead of one, the trial sequence was identical to the sequence for the serial condition.

Session procedure. Experimental sessions were divided into four blocks of trials. At the beginning of each block, the subject was informed whether the serial or spatially distributed condition was in effect, and whether the operating mode was the short display time or the short postdisplay time. In the first half of the block, the computer measured the frame duration required for 85% correct responding, using a variant of the up-down procedure modified for use with a 60-Hz raster scan display (see Matin & Boff, 1990, for details). This usually required 50-60 trials. Immediately thereafter, the computer presented another 40 trials, for all of which the frame duration was fixed at the previously determined threshold. In short, for the purposes of this analysis, each block of trials yielded three numbers: the duration threshold obtained in the first part of the run, the mean postdisplay time for the 40 trials at the threshold in the second part of the run, and the percent-correct responses for the 40 trials.

The subjects were encouraged to look at their results, which were printed at the end of each run, in order to learn to discriminate between the two operating modes (short display time or short post-display time). They were frequently reminded of the overall objective: keep the total time as short as possible. Each block of trials took approximately 5-7 min; the subjects relaxed between the four blocks in the session.

Design. Each subject participated in a completely balanced 2×2 factorially designed experiment. Factor 1 was the presentation format (serial or spatially distributed) and Factor 2 was the operating mode (emphasis on short display time or emphasis on short post-display time). Each of the four experimental treatments was run as a block in every experimental session to control for possible improvements in performance as the experiment progressed. In addition, the position of a given treatment within the four-block session was counterbalanced across sessions to control for possible performance differences within a session.

Results and Discussion

The main findings are presented in Figure 2, which shows the effect of the two experimental factors—display method (serial or spatial) and operating mode (emphasis on short during-display time, or emphasis on short post-display time). The height of a bar represents the total processing time (display onset to response). In addition, each bar shows the processing time's breakdown into two components: display duration for the three frames (the duration threshold times 3), and the length of time from the end of the display to the response. For example, for Subject 1A, serial format, short display mode, the mean duration threshold was 164.6 msec, the during-display time was 493.8 msec (dark bottom of the bar), and the post-display time was 550.0 msec (white top of the bar). Across experimental conditions, the mean deviation from the 85% correct level was −.007%, +.004%, +.003%, and +.017%, for Subjects 1A, 1B, 1C, and 1D, respectively. Moreover, the size of the error was not systematically related to the experimental conditions. Depending on the subject and the operating mode, the mean duration thresholds ranged from 81.4 msec to 322.9 msec for the serial condition, and from 188.9 msec to 420.8 msec for the spatial condition.

From the results shown in Figure 2, the main experimental findings can be summarized as follows:

1. The serial method resulted in a faster total processing time for both operating modes and all the subjects. Averaged across subjects and treatments, 194 msec were saved, for an overhead of 97 msec per saccade (194/2—note again that the three frames in the spatial condition were accessed with two, not three, saccades).

2. All the subjects were able to exert some control over the distribution of the processing time: In the short during-display time mode, the duration threshold was short and the post-display time was correspondingly long. The converse was true in the short post-display mode. However, for 3 of the subjects (1D is the exception), total time was significantly less for one of the two modes for both presentation formats.

EXPERIMENT 2

Experiment 1 showed a pronounced saccadic overhead and a tradeoff between the during-display and post-display processing time components. Further evidence on these issues was obtained in Experiment 2, for which we measured the processing time at the 85% level for a wide range

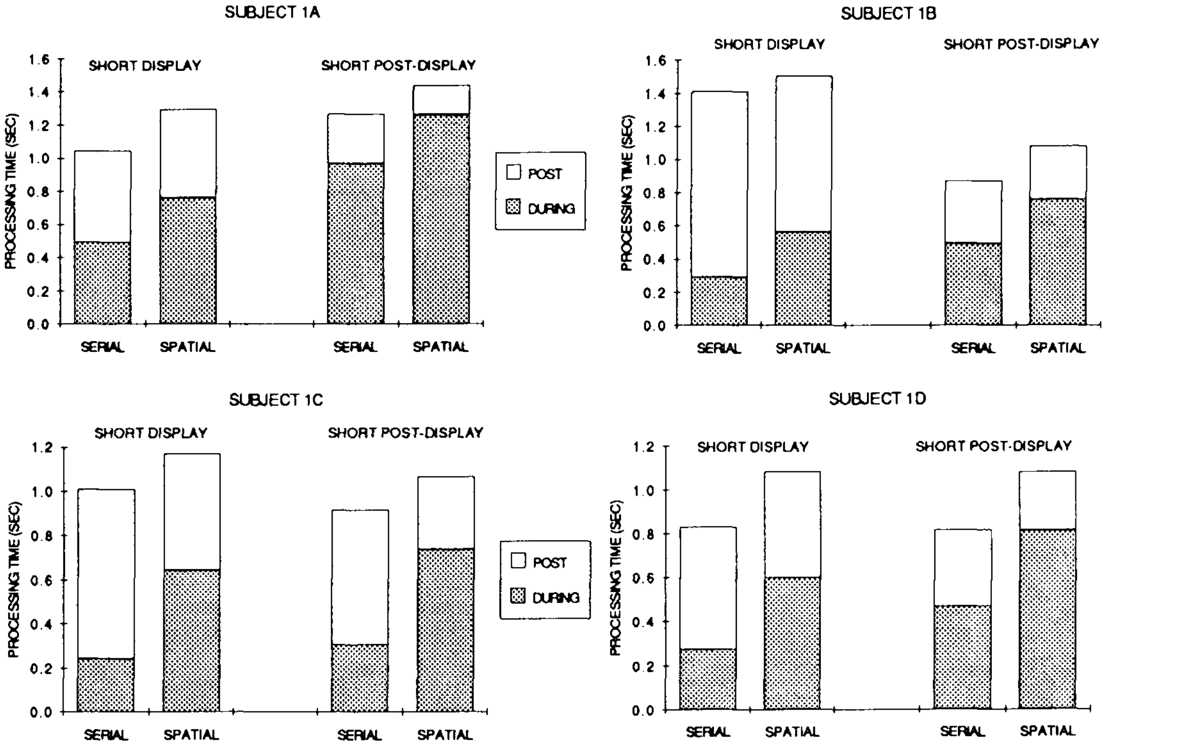

Figure 2. The results of Experiment 1. The information-processing times for serial and spatially distributed formats are shown in adjacent columns. The results are shown separately for the short during-display and short post-display operating modes. Total processing time (onset of the three-frame display to the response) is divided into during-display and post-display components. The during-display component (3 times the threshold frame duration) is the dark area at the bottom of the bar; the post-display component (end of the last frame to the response) is the white area at the top.

of experimenter-controlled frame durations. Our purpose was to study the frame duration's effect on the saccadic overhead and to find the range of durations for which tradeoffs could occur. In addition, we wanted to see if there was an optimal duration for minimizing total time and to see whether this minimum, if any, was affected by the presentation format.

Initially, we did not know whether the subjects could learn to respond at the 85% level, regardless of frame duration. To explore the possibilities, we ran pilot studies with blocks of 20 trials and a single, experimenter-selected frame duration for an entire block. We asked the subjects to respond at the 85% level for each block, noting that this implied three errors in the course of the 20 trials. Hoping to counteract the normal tendency for improved performance with increased duration, we suggested that they decrease their post-display times for blocks with longer frame durations.

Contrary to our a priori expectations, this task was surprisingly "doable" over a wide range of durations. The subjects quickly learned to respond at the 85% level for all durations greater than some minimal value that depended on the specific condition. The durations used in the study ranged from this pilot-determined minimum to durations that were just long enough to produce negative post-display times (i.e., the subject responded before the last frame was removed). Task difficulty was varied by using one, two, or three digits per frame, with three frames per trial in all cases.

Method

Subjects. Two subjects were run. One of them (Subject 2A) was an author and also served as Subject 1A in the first experiment. Subject 2B had not previously served in any experiment of this kind. Both of them practiced extensively (10–15 h) before the formal data collection began.

Apparatus. The apparatus was identical to that used for Experiment 1.

Subject's task. As in Experiment 1, the subject counted the number of odd digits and responded on the "odd" key if this count was odd, and "even" otherwise. Note that this task required the processing of *all* digits in each frame (simply counting the number of odd numbers by checking the last digit in each frame would not yield above-chance performance when there was more than one digit in a frame). For the three-digit-per-frame condition, for example, the count could range from zero (none of the nine digits was odd) to nine (all of them were odd).

Trial procedure. The trial procedure was identical to the procedure for the fixed duration trials in the second part of the run in Experiment 1.

Design. Each subject participated for 18 days in a completely balanced design with three factors. Factor 1 was the display format (serial or spatially distributed), Factor 2 was the task difficulty (one, two, or three digits per frame), and Factor 3 was the frame duration.

Two sessions were run on each experimental day, one serial and one spatially distributed. The serial session was run first on odd days, and the spatial session was first on even days. One level of task difficulty was used for both sessions, and a 3-day cycle was used for this factor to control for possible performance improvements as the experiment progressed.

Sessions were divided into blocks of 20 trials, with one block for each of the frame durations selected for the session's particular combination of the display format and task difficulty factors. The number of blocks ranged from 11 to 18, depending on the subject and the other two factors (format and task difficulty). The frame duration values were chosen on the basis of pilot work, and ranged from the shortest possible duration for 85% correct performance to durations just long enough to create "negative" post-display times (subjects responded before the last frame disappeared). The frame duration blocks were presented in ascending order. If the percentage of correct responses for a block was greater than 90% or less than 80%, the block was repeated. This happened in about 10% of the blocks; it was not systematically related to the experimental condition. Figures 3 and 4 show the specific values used for the 2 subjects and the six combinations of the format and task difficulty factors.

One complete replication of the experiment required 3 experimental days. In all, six replications were run.

Results and Discussion

Figures 3 and 4 show the results for the serial and spatially distributed runs, respectively. In all cases, the independent variable is the frame duration and the dependent variable is the mean total processing time (onset of display to response) across the six replications. For the two or three points at the longest frame durations on each curve, the post-display times are negative. For both display formats, the minimal frame duration for 85% correct performance increases with the number of digits per frame. The average percent correct over the six samples at each point was within .02% of the 85% criterion for Subject 2A and within .01% for Subject 2B. Moreover, the errors did not vary systematically with the experimental condition.

The purpose of the lines that are superimposed over the data will be clarified in the following text; the serial/spatial differences will be discussed as well.

Tradeoffs. With the plotting method used in Figures 3 and 4, a perfect tradeoff between the during-display and post-display processing time components would yield a linear function with slope 0, that is, a processing time that is independent of frame duration.

For the 12 functions in Figures 3 and 4, perfect tradeoffs occur at low values of the frame duration for a short range of durations, whose values depend on the experimental condition and the subject. They are shown as line segments with slope 0. For longer frame durations, the total processing time increased in all cases. For 7 of the 12, it also increased at the shortest durations.

At the longest frame durations, each of the 12 curves is fitted with a line segment with slope 2. The latter fits are remarkably good, and they lend themselves to the following very simple interpretation: When the frame duration exceeds a critical value (the time needed to access the data in the frame and process it completely), the subject is forced to waste time for the first two frames of the three-frame sequence. Specifically, the subject wastes 1 msec for every millisecond beyond the critical value waiting for the first frame to disappear so that the second frame can be accessed. Similarly, the subject wastes 1 msec waiting for the second frame to disappear. Because the response could be made as soon as the subject was ready, there was no forced waste of time with the third frame.

In effect, a 2-msec increase in the total processing time occurred for every additional millisecond of frame duration beyond the critical value. Although space does not permit a full discussion, we note in passing that the critical values could be used as a measure of the time required

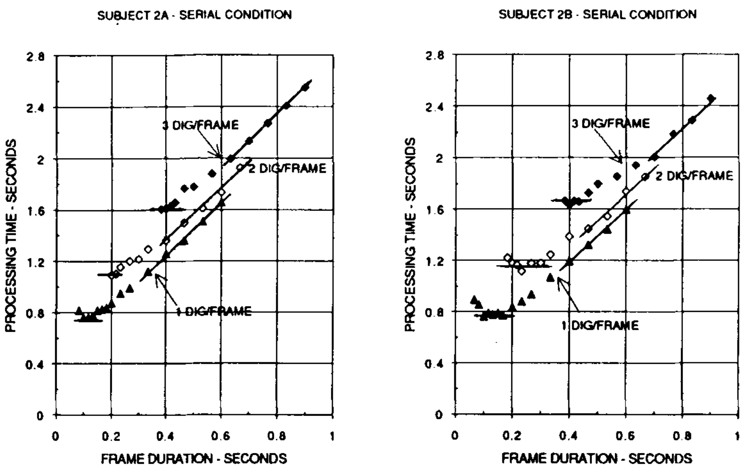

Figure 3. The results of Experiment 2, serial condition. Total processing time (onset of the three-frame display to the response) is shown as a function of frame duration. See the text for an explanation of the lines with slopes 0 and 2.

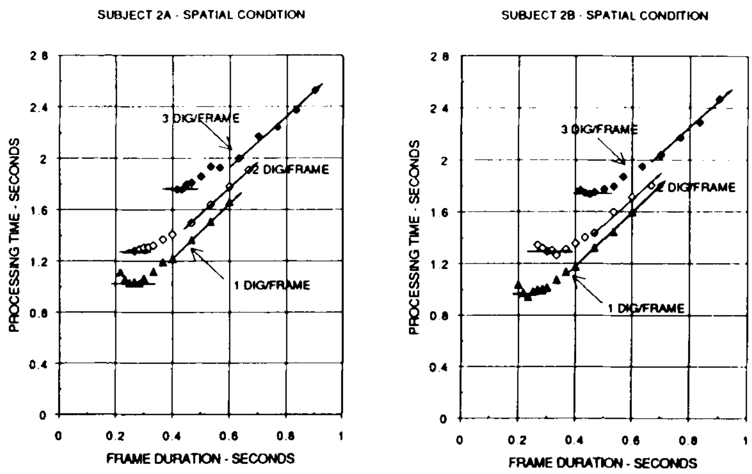

Figure 4. The results of Experiment 2, spatially distributed condition. Plotting method is identical to the method used in Figure 3.

to process the first two frames independently of the time needed for selecting and executing the response. In short, the procedure we devised to study the saccadic overhead and the during-display and post-display tradeoffs has interesting possibilities for mental chronometry studies.

Saccadic overhead. To show the saccadic overhead, we plotted Figures 5, 6, and 7, for which the serial and spatially distributed data are plotted together on the same graph for the one-, two-, and three-digits per frame cases, respectively. In addition, we obtained an overall quantitative measure of the overhead for each of the six serial/spatial comparisons by calculating the difference between the shortest times for the spatial and serial functions (using the intercepts of the slope 0 branches to estimate the minima).

The total times for the serial and spatially distributed functions, the difference between them, and the saccadic overhead (in msec/saccade) are shown in Table 1, which indicates a substantial overhead for all values of the digits-per-frame variable. However, its magnitude diminishes as the difficulty of the task increases. The significance of this diminishing return will be considered below.

GENERAL DISCUSSSION

Experiment 1 showed a statistically significant and very substantial saccadic overhead, and Experiment 2 showed that this overhead diminishes with task difficulty. Qualitatively, we expected the latter result. Indeed, we previously predicted that a saccadic overhead would only be found for tasks requiring information-processing times shorter than about 250 msec per frame (Matin et al., 1987). Nonetheless, the quantitative details of this diminishing return are contrary to our a priori expectations, which are summarized as the *saccadic bottleneck hypothesis* in the following paragraphs. Another equally simple and quantitatively specific *fixed overhead hypothesis* is also incompatible with the results. Although the data force their rejection, we describe these models in some detail to provide a concrete framework for discussing the results and for relating them to the literature.

Before proceeding, we need to clarify the term *saccadic overhead*. In the introduction, it was defined operationally as the difference between the processing time for the spatially distributed and serial conditions. In the theoretical discussion, however, the term refers to a cost that can be specifically attributed to the programming and/or execution of the eye movements.

Identification of the operationally defined measure with the theoretical saccadic overhead is only justified if the difference between the spatial and serial processing times cannot be attributed to factors other than the eye movements per se. As noted in the introduction to Experiment 1, our experimental procedures were specifically devised to eliminate two such confounding factors. First, we imposed the rigid temporal structuring that is normally only found with serial presentations on the spatially distributed condition. Second, we eliminated information access through peripheral vision in the spatial condition.

Despite the stimulus presentation methods that were introduced to address confounds in the previous literature, our identification of the operationally defined measure with the theoretical saccadic overhead continues to be tentative. Specifically, we call attention to the fact that our calculations assumed exactly two saccades on each trial in the spatially distributed condition and also assumed synchronization of the eye movements with the display changes. In addition, they assumed that no saccades were made in the serial condition. We think these assumptions are reasonable as a first approximation, given the stereotyped, extensively practiced task that our subjects performed. Nonetheless, further work with simultaneous eye movement measurements is needed.

The reader should also be aware of the possibility that the saccading eye in the spatial condition did not necessarily land in the optimal position for identifying the digits.

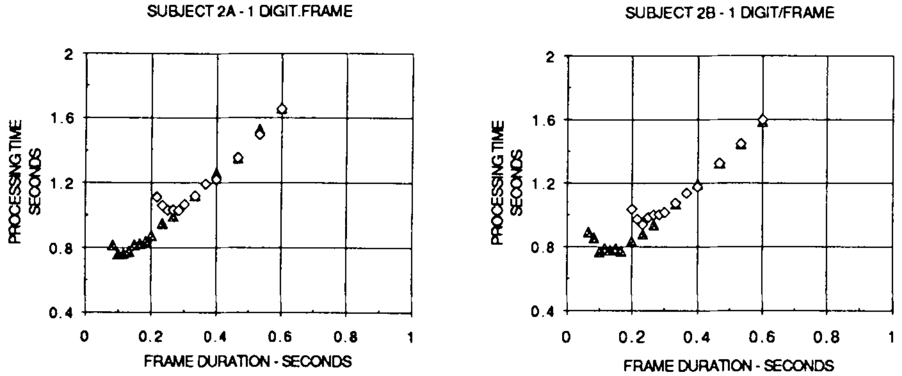

Figure 5. The results of Experiment 2, serial/spatial comparison for the one-digit-per-frame case. The total processing time (onset of the three-frame display to the response) is plotted as a function of frame duration for the serial condition (filled triangles) and for the spatially distributed condition (open diamonds).

If that were the case, some of the experimentally measured overhead would be due to this visual factor, rather than to the programming and execution of the eye movements per se. Again, further work with simultaneous eye movement measurements should be the next step in measuring a "pure" saccadic cost.

Fixed Overhead

As the name we chose implies, the fixed overhead hypothesis calls for a saccadic overhead that is independent of the cognitive processing time. We formulated this hypothesis as a quantitative statement of the results that would be expected if the information acquired during a fixation is processed to some criterion level before the oculomotor system is activated to move the eyes, provided that no further parallel cognitive processing can occur before the next fixation. In effect, the time to program and execute the eye movement is a constant that is added after the visual and cognitive processing is completed.

Although not a necessary requirement, a constant overhead would presumably be the optimal result from the viewpoint of models that treat the fixation duration as a measure of the information-processing time, that is, the eye-mind theory (Carpenter & Just, 1983; Just & Carpenter, 1987), and, more generally, the class of models that Rayner (1978) has called *process monitoring* theories (for careful analyses of the issues and for references, see Lévy-Schoen & O'Regan, 1979; McConkie, 1979, 1983; O'Regan & Lévy-Schoen, 1987; Rayner, 1978; Rayner & Pollatsek, 1989; Sanders & Houtmans, 1985). Such models assume that a precise correspondence exists between the duration of an individual fixation and the amount of time needed to process the information, with the result that the fixation duration can serve as a measure of the cognitive processing time.

The fixation duration measure could be interpreted most readily if the eyes fixate until the stimulus is processed completely and then move to the next location, generating a constant saccadic overhead that is easily separable from the cognitive processing time. However, if further processing occurs during the programming and execution of the eye movements, the process monitoring approach would not require a constant overhead (or indeed, any overhead at all).

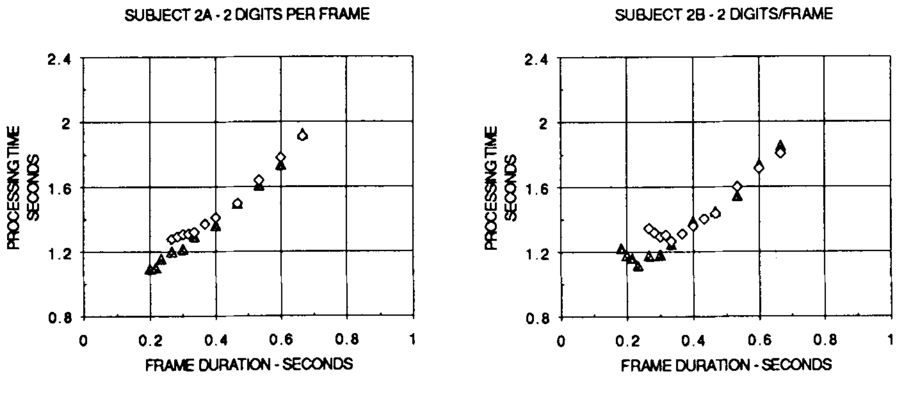

Figure 6. The results of Experiment 2, serial/spatial comparison for the two-digits-per-frame case. The plotting method is identical to the method used in Figure 5.

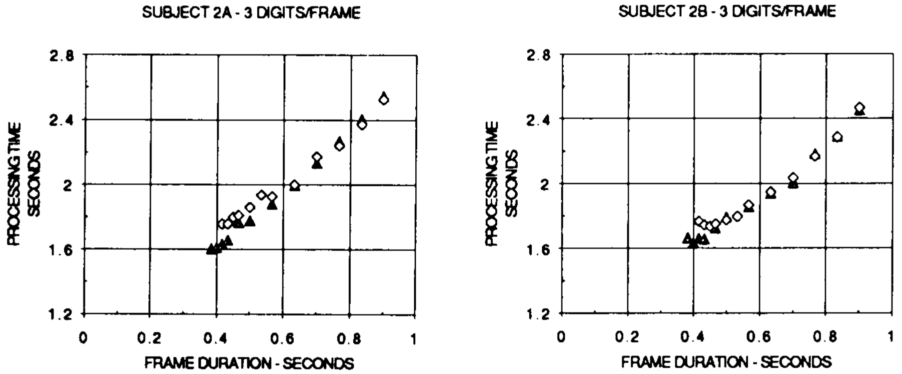

Figure 7. The results of Experiment 2, serial/spatial comparison for the three-digits-per-frame case. The plotting method is identical to the method used in Figure 5.

Saccadic Bottleneck

We formulated this hypothesis on the basis of various findings in the literature on eye movements and cognition. Specifically, we refer to experiments showing that approximately 200–250 msec are required for a saccade and the subsequent fixational pause, even if no particular processing is required during the pause (Arnold & Tinker, 1939; Salthouse & Ellis, 1980; Salthouse, Ellis, & Diener, 1981; Vaughan, 1983). A similar 200-msec value appeared in early studies of the saccadic RT (e.g., Westheimer, 1954), and this led to the influential sampled data model (Young and Stark, 1963). However, other procedures produced much shorter RTs (e.g., Becker, 1972; Nachmias, 1959; Saslow, 1967). In addition, there were large individual differences in the minimal fixation durations (e.g., the minima for Arnold & Tinker's subjects ranged from 116 to 276 msec).

Although a bottleneck as long as 200 msec/chunk does not appear to be imposed by any fundamental property of the oculomotor system per se, there must be some minimal eye movement/fixation time. This implies that the processing of data chunks that could be completely digested in a shorter time must necessarily be slowed down by the need to wait for the eyes to move before the next piece of information can be acquired.

Table 1
Minimum Values of Total Processing Time (in Milliseconds) and the Saccadic Overhead (Milliseconds/Saccade) in Experiment 2

Digits/Frame		Subject 2A	Subject 2B
1	Spatial	1,042	966
	Serial	780	779
	Difference	262	187
	Overhead	131	94
2	Spatial	1,286	1,293
	Serial	1,097	1,159
	Difference	189	133
	Overhead	94	66
3	Spatial	1,757	1,744
	Serial	1,606	1,655
	Difference	151	89
	Overhead	76	44

Assume for the moment that the eye movement system imposes no limitations other than this bottleneck (i.e., assume that the cognitive processing and the eye movement programming are otherwise strictly parallel tasks, with no mutual interference). The saccadic overhead would then be expected to diminish as a linear function of the cognitive processing time (task difficulty), with a slope of -1 and an intercept equal to the bottleneck value. The overhead would become zero when the processing time equaled the bottleneck (at about 200 msec). On the other hand, if we do not assume strictly parallel cognitive/eye movement processing, some overhead might still be expected at processing times longer than the bottleneck.

Departures From Hypotheses

The results of Experiment 2, which show a diminishing overhead with the difficulty of the task, are clearly incompatible with the fixed overhead hypothesis. Moreover, the quantitative properties of the overhead also rule out the bottleneck hypothesis: Although the overhead diminishes with task difficulty, it is still substantial for the three-digits-per-frame case, for which the minimal frame durations for both subjects are clearly far in excess of 200 msec (or any other conceivable bottleneck value).

It is also difficult to see how the present results could have been predicted by models that involve preprogrammed fixation durations (Bouma & de Voogd, 1974; Shebilske, 1975; Vaughan, 1978; Vaughan & Graefe, 1977). In such models and in the scan path model (Lévy-Schoen, 1981), fixation durations are globally determined by the average processing time for a particular text. However, there is no strict correspondence between the time needed for an individual stimulus and the fixation duration.

Given, particularly, that we used a blocked design and a highly stereotyped task without the complexities of ordinary reading, our experimental conditions should have optimized the subject's ability to preprogram the eye movements, perhaps even to the extent of obviating the necessity for any overhead. If we assume that the basic process is preprogramming with a lower limit on the fixation duration imposed by the bottleneck, the preprogramming models would presumably have predicted the bottleneck locus of points, with no overhead at all for the relatively difficult tasks with the long processing times. This was not the result that we actually obtained.

Conclusions

Although the present results are incompatible with the fixed overhead and the bottleneck hypotheses, they suggest no quantitatively specific alternative model for the saccadic overhead. They seem to indicate that the eye movements are actively interfering with the cognitive processing, perhaps drawing on a common resource pool. However, this conclusion is tentative pending further research with simultaneous eye movement measurements and with other types of information-processing tasks.

REFERENCES

Arditi, A., Knoblauch, K., & Grunwald, I. (1990). Reading with fixed and variable character pitch. *Journal of the Optical Society of America A*, **7**, 2011-2015.

Arnold, D., & Tinker, M. (1939). The fixational pause of the eyes. *Journal of Experimental Psychology*, **25**, 271-280.

Becker, W. (1972). The control of eye movements in the saccadic system. *Bibliotheca Ophthalmologica*, **82**, 233-243.

Bouma, H., & de Voogd, A. (1974). On the control of saccades in reading. *Vision Research*, **14**, 273-284.

Carpenter, P., & Just, M. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 275-308). New York: Academic Press.

Chen, H.-C. (1986). Effects of reading span and textual coherence on rapid-sequential reading. *Memory & Cognition*, **14**, 202-208.

Cocklin, T., Ward, N., Chen, H.-C., & Juola, J. (1984). Factors influencing readability of rapidly presented text segments. *Memory & Cognition*, **12**, 431-442.

Dlhopolsky, J. (1982). Software synchronization of video displays and Z-80 processing in the Model III TRS 80. *Behavior Research Methods & Instrumentation*, **14**, 539-544.

Dodge, R. (1900). Visual perception during eye movement. *Psychological Review*, **7**, 454-465.

Forster, K. (1970). Visual perception of rapidly presented word sequences of varying complexity. *Perception & Psychophysics*, **8**, 215-221.

Juola, J. (1988). The use of computer displays to improve reading comprehension. *Applied Cognitive Psychology*, **2**, 87-95.

Just, M., & Carpenter, P. (1987). *The psychology of reading and language comprehension* (pp. 25-60). Boston: Allyn & Bacon.

Lévy-Schoen, A. (1981). Flexible and rigid control of oculomotor scanning behavior. In D. Fisher, R. Monty, & J. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 299-316). Hillsdale, NJ: Erlbaum.

Lévy-Schoen, A., & O'Regan, K. (1979). The control of eye movements in reading. In P. Kolers, M. Wrolstad, & H. Bouma (Eds.), *Processing of visible language: 1* (pp. 7-36). New York: Plenum.

Matin, E., & Boff, K. (1988). Information transfer rate with serial and simultaneous visual display formats. *Human Factors*, **30**, 171-180.

Matin, E., & Boff, K. (1990). An adaptive (tracking) procedure for measuring visual search. *Perceptual & Motor Skills*, **70**, 243-255.

Matin, E., Boff, K., & Donovan, R. (1987). Raising control/display efficiency with rapid communication display technology. *Proceedings of the 31st Annual Meeting of the Human Factors Society* (pp. 258-262).

McConkie, G. (1979). On the role and control of eye movements in reading. In P. Kolers, M. Wrolstad, & H. Bouma (Eds.), *Processing of visible language: 1* (pp. 37-48). New York: Plenum.

McConkie, G. (1983). Eye movements and perception during reading. In K. Rayner (Ed.), *Eye movements in reading* (pp. 65-96). New York: Academic Press.

Nachmias, J. (1959). Two-dimensional motion of the retinal image during monocular fixation. *Journal of the Optical Society of America*, **49**, 901-908.

O'Regan, K., & Lévy-Schoen, A. (1987). Eye movement strategy and tactics in word recognition and reading. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 363-383). Hillsdale, NJ: Erlbaum.

Osgood, S., Boff, K., & Donovan, R. (1988). Rapid communication display technology efficiency in a multi-task environment. *Proceedings of the 32nd Annual Meeting of the Human Factors Society* (pp. 1395-1399).

Potter, M. (1984). Rapid serial visual presentation (RSVP): A method for studying language processing. In D. Kieras & M. Just (Eds.), *New methods in reading comprehension research* (pp. 91-118). Hillsdale, NJ: Erlbaum.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin*, **85**, 618-660.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading* (pp. 113-187). Englewood Cliffs, NJ: Prentice-Hall.

Rubin, G., & Turano, K. (1992). Reading without saccadic eye movements. *Vision Research*, **5**, 895-902.

Salthouse, T., & Ellis, C. (1980). Determinants of eye fixation duration. *American Journal of Psychology*, **93**, 207-234.

Salthouse, T., Ellis, C., & Diener, D. (1981). Stimulus processing during eye fixations. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 611-623.

Sanders, A. F., & Houtmans, M. (1985). There is no central stimulus encoding during saccadic eye shifts: A case against general parallel processing notions. *Acta Psychologica*, **60**, 323-338.

Saslow, M. (1967). Effects of components of displacement-step stimuli upon latency for saccadic eye movement. *Journal of the Optical Society of America*, **57**, 1024-1029.

Shebilske, W. (1975). Reading eye movements from an information processing point of view. In D. W. Massaro (Ed.), *Understanding language* (pp. 291-311). New York: Academic Press.

Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. (1971). Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science*, **174**, 307-311.

Vaughan, J. (1978). Control of visual fixation duration in search. In J. Senders, D. Fischer, & R. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 135-144). Hillsdale, NJ: Erlbaum.

Vaughan, J. (1983). Saccadic reaction time in visual search. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 397-412). New York: Academic Press.

Vaughan, J., & Graefe, T. (1977). Delay of stimulus presentation after the saccade in visual search. *Perception & Psychophysics*, **22**, 201-205.

Westheimer, G. (1954). Eye movement responses to a horizontally moving visual stimulus. *AMA Archives of Ophthalmology*, **52**, 932-943.

Young, L., & Stark, L. (1963). Variable feedback experiments testing a model for eye tracking movements. *IEEE Transactions on Human Factors in Electronics*, **4**, 38-51.

(Manuscript received May 18, 1992;
revision accepted for publication September 3, 1992.)