AMERICAN JOURNAL OF PSYCHOLOGY
June 1980, Vol 93, No. 2, pp. 207-234

0002-9556/80/0600-0207$02.70/0

Determinants of eye-fixation duration

Timothy A. Salthouse and Cecil L. Ellis
University of Missouri, Columbia

Four variables that might be presumed to contribute to the duration of an eye fixation were investigated in a series of seven experiments. These variables were stimulus processing time, relative emphasis on speed or accuracy, sequential dependencies across successive fixations, and amplitude of the preceding and following saccades. The pattern of results suggested a two-component model to account for the duration of single eye-fixations. One component is the minimum pause time of the eye, estimated to be about 200 msec without any stimulus processing. The second component involves stimulus processing, estimated to require a minimum of 50 to 100 msec, but subject to a number of influences that can substantially increase or decrease this duration. Although the authors did not generate this model to account for eye movements in complex tasks such as reading, they speculate about how complications could be added.

In reading and most other visual search activities the eyes typically move between two and five times per second in order to bring environmental information into the foveal region of clearest vision. The question of exactly what is happening during fixations, the periods of relative stability between eye movements, is still something of a puzzle. Several researchers have claimed that both oculomotor and cognitive processing factors contribute to the duration of an eye fixation (e.g., Russo, 1978; Tinker, 1958; Vaughan & Graefe, 1977), but there has been little agreement about the quantitative contribution of each set of factors. For example, Vaughan and Graefe (1977) estimate that oculomotor factors require approximately 200 msec and processing factors from 200 to 300 msec. Russo (1978), however, argues that the oculomotor factors (exclusive of the actual movement) may take only 60 to 90 msec, with the processing factors occupying from 0 to 110 msec. In the face of such discrepant estimates, it seems fair to claim that at the present time the determinants of an eye fixation are not very well understood.

One explanation for the lack of definite information about fixation-duration determinants is that much of the relevant eye movement data has been collected in the context of reading tasks where a number of uncontrolled variables complicate the study of fixation durations. Some of the variables that generally cannot be controlled in reading tasks and yet might influence fixation duration are: (a) comprehension difficulty—the syntactic and semantic context in which the fixated material is embedded, (b) peripheral information—the amount and type of material in the periphery, and (c) fixation location—the direction and distance of the eyes from one fixation position to another.

To control for these factors in order to identify the determinants of the duration of a single eye-fixation, the present experiments employed a simple, discrete, eye-movement task. Subjects were instructed to move their eyes to one or more letters, fixate as briefly as possible, move their eyes to a prespecified termination point, and then indicate whether a vowel had or had not been present among the set of letters. Comprehension factors were controlled and minimized by presenting very simple target material and requiring a low-level vowel/no vowel decision. Peripheral factors were controlled by presenting all targets within an area of 2°, separated from other material by at least 3°. And finally, location factors were controlled by requiring the same sequence of eye movements on all trials in a given block such that there was no positional uncertainty about the next fixation.

Four classes of determinants of eye-fixation duration were investigated in a series of related experiments. The first determinant was stimulus processing time, the time actually required for the subject to extract information from the stimulus. A second determinant concerns performance strategy: subjects might be capable of very brief fixation durations but do not normally fixate as briefly as possible because of the stress associated with continuous maximum performance. Sequential factors dealing with the effect one fixation has on the duration of a subsequent fixation constitute the third class of determinants. The final set of influences on the duration of an eye fixation investigated were the amplitudes of the movements preceding and following the fixation.

Another possible determinant of eye-fixation duration, saccadic suppression, was investigated in an earlier report (Salthouse, Ellis, Diener, & Somberg, Note 1). Stimulus identification accuracy was examined when the stimulus was briefly presented before, during, or after the eye fixation on the target location. The major result was that identification accuracy was equally high in the first and last 10 to 50 msec as in the middle of the fixation. On the basis of this finding it was concluded that saccadic suppression has very little effect in situations where the stimuli are of moderate duration and suprathreshold intensity. Since the current experiments employed the same stimulus conditions as the Salthouse et al. experiment, it was assumed that saccadic suppression probably was not a major factor contributing to the duration of eye fixations in the present context.

EXPERIMENT 1

It seems quite likely that a portion of the duration of an eye fixation is devoted to encoding and interpreting (i.e., processing) the fixated information, although the amount of time required for stimulus processing is still very much in dispute. Vaughan and Graefe (1977) estimate that approximately 200 to 300 msec is required for such processing, and Smith (1971) claims that information is picked up in a few hundreths of a second but that processing requires another 250 msec. Since the time of Dodge (1907), however, many other researchers have claimed that only about 100 msec is required for simple processing (e.g., Loftus, 1976; Potter, 1975; Tinker, 1958).

The most direct evidence for the duration of stimulus processing has come from experiments employing tachistoscopic presentations of visual stimuli. A variety of such studies (e.g., Eriksen, Becker, & Hoffman, 1970; Eriksen & Collins, 1964; Eriksen & Eriksen, 1971; Liss, 1968; Spencer, 1969; Spencer & Shuntich, 1970) have demonstrated that simple visual stimuli can be identified quite accurately if an interval of 100 msec or more elapses between the onset of the stimulus and the onset of the following mask. However, since it is virtually certain that methodological details such as the nature of the decision task and the type, size, and luminance of the stimuli influence the estimates of processing time, one must be careful in generalizing from these tachistoscopic studies to eye movement situations. For this reason, the present experiment was designed to obtain estimates of stimulus processing time in a situation that is directly comparable to that employed in the accompanying eye movement experiments.

The experiment, modeled after one by Sperling, Budiansky, Spivak, and Johnson (1971), involved sequential presentation of five letters in the same spatial position on each trial. One-half of the trials contained a vowel somewhere in the sequence, but its presentation was randomly varied among the five temporal positions. Only trials in which a vowel was presented in the second, third, or fourth sequence position are of concern here because of the interest in determining minimum processing time limited by both preceding and following stimuli.

The duration of sequence elements was varied across blocks of trials in order to examine the relationship between exposure duration and identification accuracy. Processing time will be defined as the duration at which the identification accuracy first exceeds a value comparable to approximately 95% correct decisions.

METHOD

Subjects

Four subjects with normal or corrected-to-normal vision participated in one practice and four experimental sessions of approximately 50 minutes each.

Apparatus and stimuli

A PDP-11/34 computer interfaced with a Mini-Bee CRT was used to present upper-case (.3°) letters. The CRT was equipped with a rapid-decay P4 phosphor and the luminance of the targets was approximately .4 cd/m^2 on a background of .1 cd/m^2

Procedure

Each session consisted of one practice block of 10 trials at 250 msec per letter, followed by six experimental blocks of 100 trials each at durations of between 40 and 140 msec per letter. On alternating sessions the durations were presented in the order 140, 100, 60, 40, 80, and 120 msec or in the order 120, 80, 40, 60, 100, and 140 msec.

A vowel was randomly presented on half of the trials and it was equally likely in any of the five sequence positions. A trial involved the subject fixating on the target location, inspecting the stimulus letters, and then indicating a decision by pressing one key on the terminal if a vowel had been presented, and pressing a different key if no vowel had been presented.

RESULTS

Performance was assessed in terms of d' by considering correct judgments of a vowel being presented as hits, and considering incorrect "vowel present" judgments as false alarms. Separate d' values were computed for each sequence position by assuming a common false alarm rate for all sequence positions in a given block of trials. False alarms rates ranged from a mean of .02 with the 140 msec duration to a mean of .15 with the 40 msec duration. The d' measures for sequence positions 2, 3, and 4 were averaged for each subject and the means portrayed in Figure 1.

As an aid in interpreting Figure 1, note that a d' of 2.32 corresponds to approximately 90% accuracy, and a d' of 3.28 to approximately 99% accuracy in a two-alternative forced-choice task (Elliot, 1964). These results therefore demonstrate that subjects are quite accurate at clas-

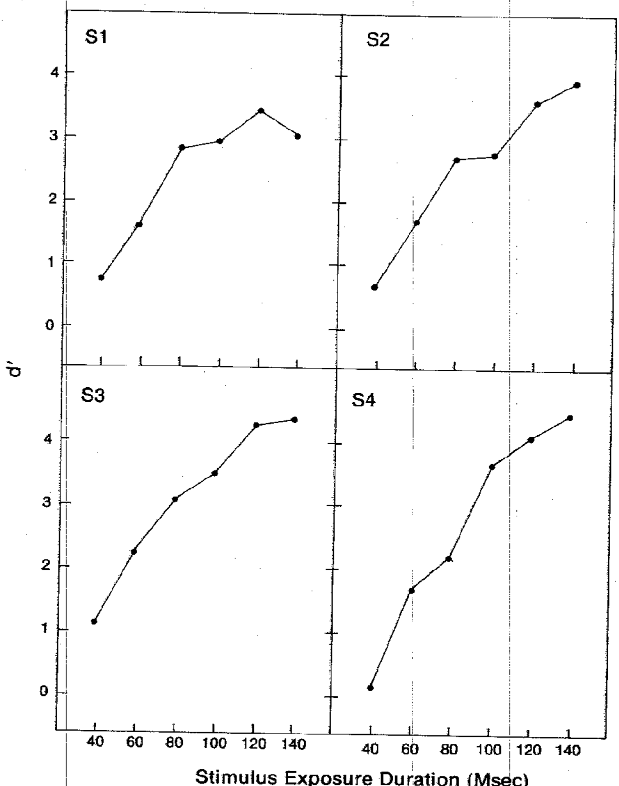

Figure 1. Accuracy (d′) as a function of exposure duration, Experiment 1

sifying a letter in a sequence as being a vowel or nonvowel if it is exposed for about 100 msec.

DISCUSSION

The present result confirms the inference based on earlier tachistoscopic studies that only about 100 msec is required to process a simple visual stimulus. Processing time in those studies and in the present experiment is defined as the duration, limited by the presence of a disrupting second stimulus, that is sufficient to allow adequate perception of a first stimulus. If one accepts 90 to 95% accuracy as evidence of adequate perception, the current data indicate that processing time is only about 80 to 100 msec for each of the four subjects tested.

EXPERIMENT 2

The 80 to 100 msec estimate of stimulus processing time is considerably less than the 200 to 500 msec durations of most eye fixations. One explanation for this discrepancy might be that the subject is not under any specific pressure to perceive rapidly when making eye movements. If the difference between the typical fixation duration and the tachistoscopic estimates of processing time is attributable to some sort of stress-minimizing strategy, then subjects should, with sufficient encouragement, be able to reduce their fixation durations to the minimum time required for stimulus processing, i.e., approximately 80 to 100 msec.

This implication is tested in the current experiment by having subjects attempt to produce fixation durations within specific temporal intervals regardless of the accuracy of their subsequent identification response. In this manner the relationship between fixation duration and identification accuracy can be examined, and the minimum duration at maximum accuracy determined. This duration should be the fastest possible and thus it can be compared with the value of 80 to 100 msec to test the hypothesis that a strategy factor is contributing to the duration of a typical fixation.

METHOD

Subjects

Two males with normal or corrected-to-normal vision participated in two practice, and four experimental, sessions of about 75 min each. One subject had served in the previous experiment.

Apparatus

The apparatus and stimuli were the same as those described in the previous experiment with the addition of an Eye-Trac Model 200 eye-movement monitoring system.

The algorithm for defining eye movements identified a movement as a .2° or more change in the eye position in the same direction on three consecutive samples separated by 10 msec each. In a similar fashion, a fixation was identified when the eye position differed by less than .2° for a period of 30 msec. Neither a movement nor a fixation was identified if eye position differed by more than .2° but less than .6° for a period of 30 msec. Eye position was calibrated at the beginning of each block of trials by requiring the subject to press a button when fixating successive stimuli separated by known distances.

Procedure

The four experimental sessions each consisted of eight blocks of 20 trials. A desired range of fixation durations was specified for each block and the subjects were instructed to attempt to adjust their eye movement patterns such that all fixation durations were within that range. The subjects were aided in their attempts to adjust their fixation durations by a visual display presented after each trial that portrayed the desired fixation durations and the actual fixation duration on that trial. No penalty was associated with a failure to produce a fixation within the goal times; these goals were merely intended to produce a variety of fixation times and identification accuracies. The values of the goal times were from 100 to 550 msec in 50 msec steps and 100 msec ranges, i.e., 100 to 200, 150 to 250, 200 to 300, etc.

A trial consisted of the following sequence of events. First, the word READY appeared on the left edge of the display, soon followed by an asterisk in the location previously occupied by the letter A of the word READY. Next, a single letter appeared 15° to the right of the asterisk. This was the signal for the subject to move his eyes to the letter, fixate as briefly as possible, and return his eye to the original asterisk. Upon refixating the asterisk, the subject's task was to press one button on the keyboard terminal if the target letter had been a vowel, and to press another button if the target letter had not been a vowel. One-half of the trials, selected at random, contained a vowel as the target letter.

RESULTS

Approximately 70% of the trials for each subject had appropriate eye movement patterns and were included in the analyses. An eye movement pattern was considered inappropriate if the fixation was not preceded and followed by a fixation 15° to the left, at the initial asterisk. Some rejected trials involved the subject anticipating the target and beginning the movements too early, while others involved the subject making a movement that was too short or too long and which required additional corrective movements.

Figure 2 displays the fixation duration and identification accuracy for each trial block for the two subjects. Both subjects are similar in achieving 100 percent accuracy at fixation durations of about 250 msec. This result suggests that the fastest possible fixation duration for the vowel/no vowel decision with a 15° preceding and following movement is approximately 250 msec.

DISCUSSION

Experiment 2 provides little support for the notion that subjects are capable of much briefer average fixation durations than the typical values of between 200 and 500 msec. Even under the special conditions of the present experiment it appears that the minimum duration of an average fixation is around 200 to 300 msec.

EXPERIMENT 3

Since in normal vision, fixations are typically preceded and followed by other fixations, sequential effects among successive fixations may be

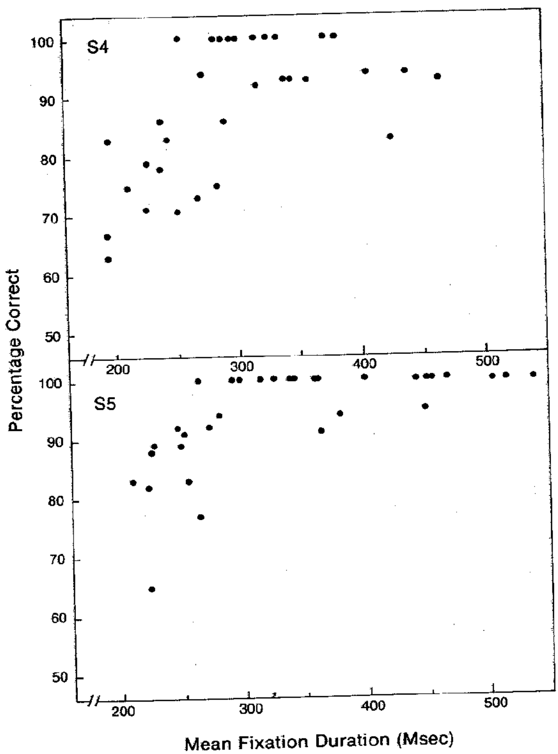

Figure 2. Speed and accuracy of fixation durations, Experiment 2

contributing to some of the duration of an eye fixation. At least two classes of sequential effects can be identified. One class might be termed temporal, in that the time spent on fixation n could influence the time spend on fixation $n + 1$, regardless of the information extracted on fixation n. The second class can be termed conceptual, in that the duration of fixation $n + 1$ might be influenced by the nature of the information extracted on fixation n regardless of the time required to obtain that information.

Both temporal and conceptual sequential effects were investigated in the present experiment by requiring subjects to fixate on two successive targets before making a response. Temporal factors were examined by determining the relationship, on both a trial-by-trial basis and on a grouped-trial basis, between the durations of the first and second fixations. Conceptual factors were investigated by manipulating the rule governing decisions. In one condition, the subjects were instructed to make a positive response only if a vowel was present in both the first and the second fixated targets (Both). In a second condition, the subjects were to make a positive response if a vowel was present in either the first or the second fixated target (Either). If the nature of the information from an early fixation can affect the duration of a subsequent fixation, the presence or absence of a vowel in the first fixation should lead to opposite effects in the two conditions. A decision is determined in the first fixation if there is a vowel in the Either condition, or if there is no vowel in the Both condition, and thus the subject need not fully process the stimulus in the second fixation. However, complete processing of the second stimulus is required if the first fixated target contains no vowel in the Either condition, or if it contains a vowel in the Both condition. The difference in the duration of the second fixation as a function of the presence or absence of a vowel in the first fixation can therefore be used as an estimate of the influence of conceptual sequential effects.

Two levels of target complexity (i.e., either two or four target characters) were included to obtain a measure of stimulus processing time that was independent of all other aspects contributing to the fixation duration. This measure was derived by computing the slope of the function relating fixation duration to the number of target characters and using that as an estimate of processing time per character. This estimate may not correspond to that derived from Experiment 1 as it has been interpreted as reflecting the duration of only one stage of the stimulus-processing sequence (e.g., Sternberg, 1969), but it can still serve as one index of processing time.

METHOD

Subjects

The subjects were the same as those from Experiment 1. Each served in one practice, and six experimental, sessions of approximately 50 minutes each.

Apparatus and stimuli

The apparatus and stimuli were the same as those described in Experiment 2 except that there were two fixation targets, each consisting of two or four horizontally arranged letters or asterisks. The targets were positioned 7.2° from each other and 7.2° from the left and right edges of the display.

Procedure

The task in this experiment involved the following sequence of events. First the subject fixated on an asterisk on the left edge of the display. When this asterisk disappeared the two targets appeared. The subject then moved his eyes to the right, fixated on the first target as briefly as possible, moved his eyes to the second target, fixated as briefly as possible, and then moved his eyes to the asterisk at the right edge of the display. At this point the subject indicated his decision by pressing one of two buttons on the keyboard.

The six experimental sessions consisted of the counterbalanced arrangement of two sessions for each of three conditions. Each session consisted of one practice block of 10 trials followed by four experimental blocks of 50 trials each.

The control condition, condition C, involved the presentation of two or four asterisks as the first target on the trial, and two or four letters as the second target. In this condition the subjects were required to fixate on the first target, but to ignore the material and make the decision solely on the basis of whether the second target did, or did not, contain a vowel.

The two experimental conditions, E (Either) and B (Both), involved the presentation of two or four letters in both the first and second targets with the subject instructed to fixate on both targets. A positive response (pressing a particular button on the keyboard) was to be made if a vowel was present in either the first or second target for condition E, and if a vowel was present in both the first and second targets for condition B. A negative response (pressing a different button on the keyboard) was to be made if neither target contained a vowel in condition E, or if a vowel was not present in both targets in condition B. The probability of a vowel was .5 in each of the first and second targets in conditions B and E, and in the second target in condition C.

Figure 3 contains an illustration of a stimulus array for conditions E and B and the action required of the subject at various times in the stimulus sequence.

RESULTS

Approximately 94% of the trials resulted in appropriate (i.e., fixation, right movement, fixation, right movement, fixation) eye movement patterns. The mean decision accuracies in the three conditions were: condition C = 99%, condition E = 98%, and condition B = 99%.

For the convenience of statistical analysis, only the data from conditions E and B were evaluated in an analysis of variance. The analysis on the fixation durations from the first fixation in the sequence involved Conditions (i.e., E and B), Target 1 Complexity (i.e., two or four characters), and Target 2 Complexity (i.e., two or four characters) as factors. Each cell in the design contained 32 entries, the means of the eight blocks for each of the four subjects.

The Target 1 Complexity factor was significant, $F\ (1, 3) = 20.63$, $p < .05$, but the Target 2 Complexity factor was not significant, $p > .25$. Only the interaction of Condition × Target 1 Complexity was statistically significant, $F\ (1, 3) = 10.89$, $p < .05$. A significant condition effect was evident in the data of subjects 1 and 2, $p < .0001$, but not in the data of subjects 3 and 4, $p > .15$, when separate analyses were performed on each subject's data.

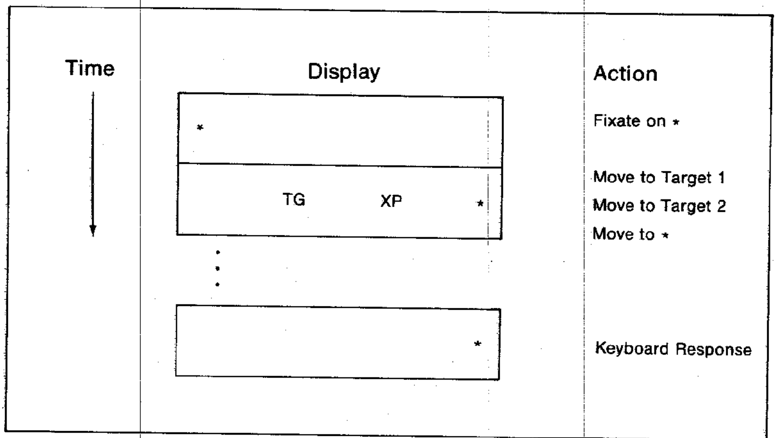

Figure 3. Illustration of the temporal sequence of display and action for conditions E and B, Experiment 3. Either two or four letters could be presented at each target position. Condition C differed in having asterisks rather than letters in the first target position

The absence of an effect of target 2 complexity on target 1 fixation duration indicates that the number of characters in the subsequent fixation does not affect the duration of the current fixation. This result is quite reasonable in that one would expect that sequential effects, when they exist, would operate in a forward, rather than backward, direction.

The effect of target 1 complexity on target 1 fixation duration is illustrated in Figure 4 for each of the 4 subjects. Notice that in both conditions E and B, fixation duration is longer (by an average of 53 msec per character) when the target contains four characters than when it contains just two characters. This result is in marked contrast to the situation with condition C. Here, when only asterisks that the subjects are instructed to ignore are presented in the first target, the fixation duration is the same with either two or four characters. Apparently the subjects in condition C are merely fixating as briefly as possible without attempting to process any information as their fixation durations are independent of the complexity of the stimulus.

The analysis of variance on the fixation durations from the second fixation in the sequence involved Conditions (i.e., E and B), Prior Vowel (i.e., vowel or no-vowel in target 1), Target 1 Complexity (i.e., two or four characters), and Target 2 Complexity (i.e., two or four characters) as factors. As in the preceding analysis, each cell contained 32 means as entries.

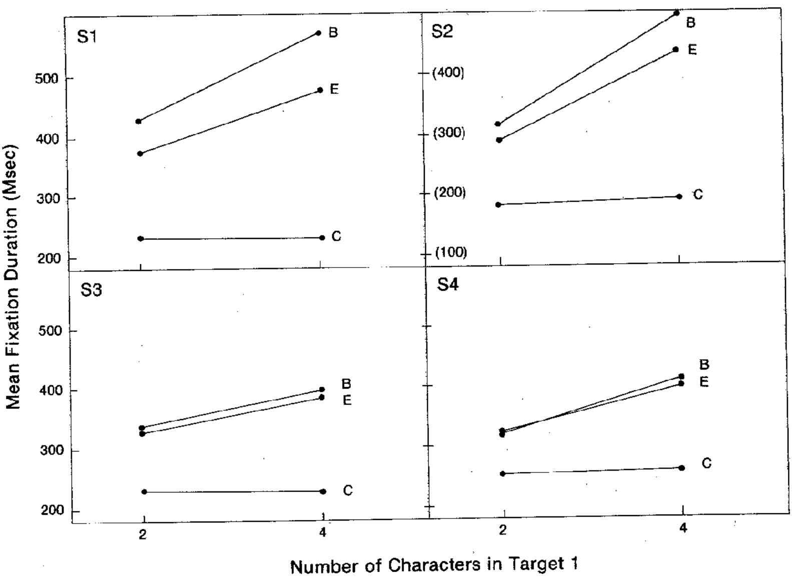

Figure 4. Mean fixation duration to the first target in conditions C, E, and B, Experiment 3

The following effects were significant in this analysis: condition, $F(1, 3) = 10.18$, $p < .05$; target 2 complexity, $F(1, 3) = 21.43$, $p < .05$; Condition × Prior vowel, $F(1, 3) = 95.38$, $p < .005$; and Condition × Prior Vowel × Target 2 Complexity, $F(1, 3) = 11.36$, $p < .05$.

The nonsignificant effect of target 1 complexity, $p > .25$, indicates that the number of characters in the first target does not influence the fixation duration on the second target. This result suggests that there is little relationship between the duration of successive fixations since the number of characters in the first target did have a substantial effect on the fixation duration on the first target. Trial-by-trial correlations confirm the absence of a temporal sequential effect as the mean correlations across fixation durations on the first and second target were .06 for condition C, .12 for condition E, and .03 for condition B. (Rayner and McConkie, 1976, have also reported very low (i.e., .13) correlations between the durations of successive fixations in a reading task, and thus these results are not specific to the present situation.)

The significant results from the statistical analysis can be clarified with the aid of Figure 5. Notice that, for each of the four subjects, condition B is slightly slower than condition E, and that targets with four characters are slower than targets with two characters. These trends account for the significant main effects of condition and target 2 complexity. Also note that the condition B trials in which a vowel was present in the first target are slower than the condition B trials in which a vowel was not present in the first target, but that this pattern is reversed for condition E. This consistent reversal is responsible for the Condition × Prior Vowel interaction. And finally, the three-way interaction among Condition, Prior Vowel, and Target 2 Complexity is reflected in the shallower slopes of the condition B no-vowel trials and condition E vowel trials, compared to the the condition B vowel trials and condition E no-vowel trials, respectively.

The significant Condition × Prior Vowel interaction and the pattern of results portrayed in Figure 5 indicate that there was a sizeable conceptual sequential effect. Figure 5 shows that when the second target has to be fully processed in order to make a decision (i.e., condition C, condition B following a vowel, and condition E following a nonvowel), fixation durations are considerably longer than when the information from the first target is sufficient for a decision (i.e., condition B following a nonvowel, and condition E following a vowel). The

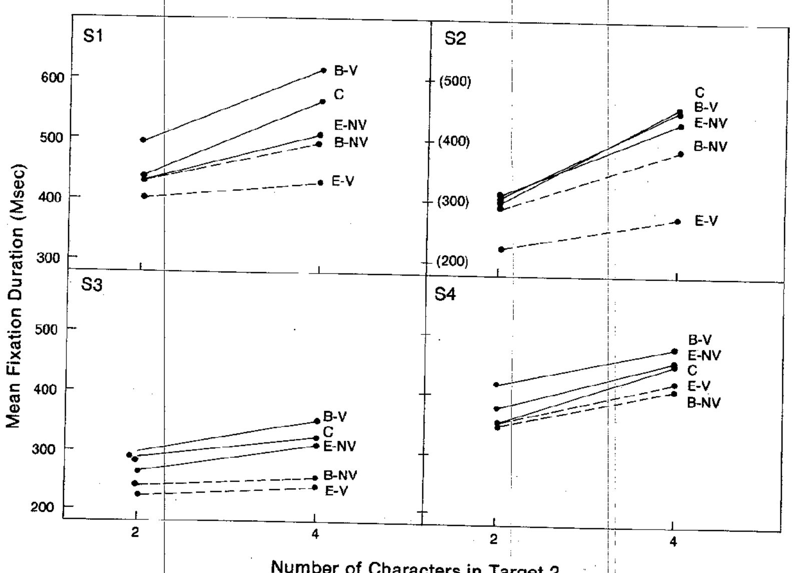

Figure 5. Mean fixation duration to the second target in conditions C, E, and B, Experiment 3. The V and NV following the condition designation indicate trials in which the first target contained a vowel (V) or no vowel (NV)

magnitude of this effect averaged 70 msec for condition B and 66 msec for condition E.

A pattern similar to that just described was also evident in the rate of increase in fixation duration with an increase in the number of characters. The slope of the functions relating fixation duration to number of characters was 53 msec per character for condition C, 49 msec per character for condition B with a prior vowel, and 40 msec per character for condition E with no prior vowel. In the reduced processing situation the slopes were 29 msec per character for condition B with no prior vowel, and 21 msec per character for condition E with a prior vowel. The conceptual sequential factor thus influences the rate of processing each character in addition to affecting the overall fixation duration.

DISCUSSION

The major conclusion from this experiment is that sequential effects among fixations can influence the duration of a fixation. There appear to be no strictly temporal effects from one fixation to another, but the influence of information-dependent carry-over effects is on the order of 60 to 70 msec.

EXPERIMENT 4

Experiments 1 and 2 established two facts. First, the minimum fixation duration while processing information is about 250 msec. And second, the time required for actual stimulus processing is less than half this duration, approximately 80 to 100 msec. Because eye fixations are preceded and followed by eye movements, it is possible that some of this discrepancy between average fixation duration and processing time is attributable to time required to recover from a past, or prepare for a future, movement of the eyes. If such a movement-related factor is influencing fixation durations, one might expect the magnitude of the effect to be proportional to the amplitude of the eye movement.

Some evidence for a movement-amplitude effect is available in data reported by Bartz (1962) and Rayner (1978). Both investigators measured naming reaction time after subjects had stabilized their eyes following a movement of variable amplitude. The function relating naming time to amplitude of the preceding eye movement ranged between 2 to 3 msec per degree in the Bartz study and between 10 to 20 msec per degree in the Rayner study. However, in contrast to these findings, Hyde (1959) reported that the time between successive saccades (i.e., fixation duration) did not vary across a range of saccade amplitudes from 15° to 90°.

Because all of these results were incidental findings in the studies, a direct test of the movement-amplitude hypothesis is necessary to determine its validity. The present experiment involved such a test by comparing the duration of eye fixations preceded by small, i.e., 6°, eye movements with those preceded by large, i.e., 18°, eye movements. The direction of the eye movements and the number of characters in the targets were also manipulated to determine whether these factors interacted with the movement amplitude factor.

METHOD

Subjects

Subjects 2, 3, and 4 were the same as in the preceding experiment; the remaining subject was a naive subject with normal vision. Each subject served in two practice and eight experimental sessions of approximately 50 minutes each.

Stimuli

The stimuli were one to four horizontally arranged letters displayed 6° or 18° away from an asterisk fixation point. Another asterisk was located 18° or 6° on the other edge of the display.

Procedure

The task in this experiment required subjects to fixate on the initial asterisk (at the left or the right edge of the display depending upon movement direction), move the eyes to the target as soon as it appeared, fixate as briefly as possible, and then move the eyes to the final asterisk at the opposite edge of the display and press a response key on the terminal. One key was to be pressed if a vowel had been present in the display, and another key was to be pressed if no vowel had been present.

Both the number of characters in the target, from one to four, and the presence or absence of a vowel in the target, were randomly determined within blocks.

Each session consisted of two practice blocks of 10 trials each followed by four experimental blocks of 50 trials each. The first and last blocks involved initial movements of 6°, while the second and third blocks involved initial movements of 18°. Movement direction was varied across sessions in a counterbalanced fashion.

RESULTS

Approximately 86% of the trials resulted in appropriate (i.e., fixation, movement in the correct direction, fixation, movement in the correct direction, fixation) eye movement patterns. Average decision accuracy was 98%.

The mean fixation durations from each of the four subjects are displayed in Figure 6. An analysis of variance (with amplitude, direction, and target complexity as factors and 16 means for each of four subjects as cell entries), revealed that the amplitude, $F\ (1, 3) = 431.58$, $p < .0001$, and target complexity, $F\ (3, 9) = 88.90$, $p < .005$, factors were the only significant sources of variance.

The slope of the function relating fixation duration to number of target characters averaged 55 msec per character.

The mean difference in fixation duration between fixations following 18° movements and fixations following 6° movements was 72 msec. The effect of prior movement amplitude is thus about 6.0 msec for each degree of eye movement.

EXPERIMENT 5

The major results from the preceding experiment were the significant effects of target complexity and prior movement amplitude, along with the absence of an interaction between these two factors. The present experiment was designed to explore the range of the movement amplitude effect by varying the amplitude of the prior movement from 3° to 21° in 3° steps. Two levels of target complexity, two or four characters, were also included in an attempt to replicate the main effect of target complexity and the absence of a Movement Amplitude × Target Complexity interaction.

METHOD

Subjects

The subjects were the same as those from the preceding experiment. Each subject served in one practice and fourteen experimental sessions of approximately 50 minutes each.

Stimuli

The stimuli consisted of two or four horizontally arranged letters presented 3°, 6°, 9°, 12°, 15°, 18°, or 21° to the right of an initial asterisk. A final asterisk was located 24° from the initial asterisk at the right edge of the display.

Procedure

The task was identical to that described in the preceding experiment with the exception that subjects always moved their eyes from left to right.

Each session consisted of two practice blocks of 10 trials each followed by four experimental blocks of 50 trials each. A given block involved only one move-

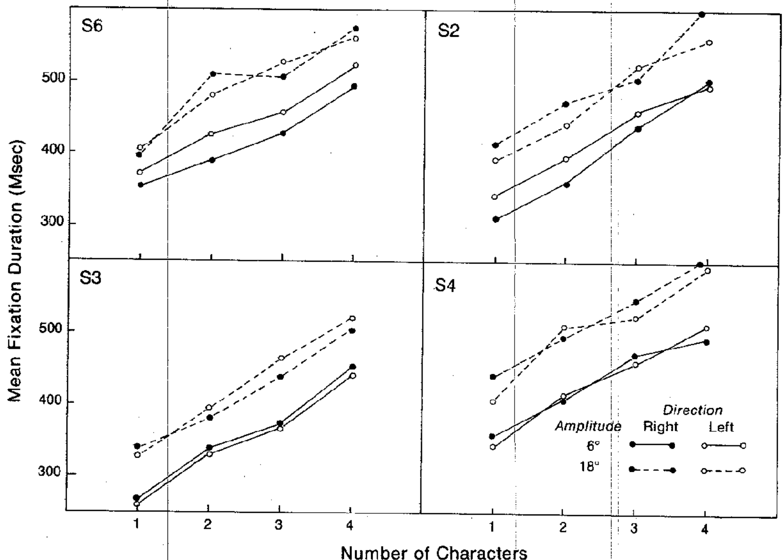

Figure 6. Mean fixation duration as a function of target complexity, movement direction, and movement amplitude, Experiment 4

ment amplitude. On different sessions the first and last blocks involved 3°, 6°, 9°, or 12° movements, while the second and third blocks involved 21°, 18°, 15°, or 12° movements, respectively. The order of amplitude pairs was counterbalanced across sessions such that the first and last sessions involved 3° and 21° movements, the second and second-to-last sessions 6° and 18° movements, etc.

RESULTS

Approximately 86% of the trials resulted in appropriate (i.e., fixation, right movement, fixation, right movement, fixation) eye movement patterns. Average decision accuracy was 99%.

An analysis of variance (with amplitude and target complexity as factors and eight means for each of four subjects as cell entries), indicated that the effects of target complexity, F (1, 3) = 16.39, $p < .05$, and amplitude, F (6, 18) = 5.81, $p < .01$, were both significant, but their interaction was not ($p > .50$). The results for each subject are illustrated in Figure 7.

relationship between movement amplitude and fixation duration. The remaining subjects averaged 7.6 msec per degree of movement ampli-

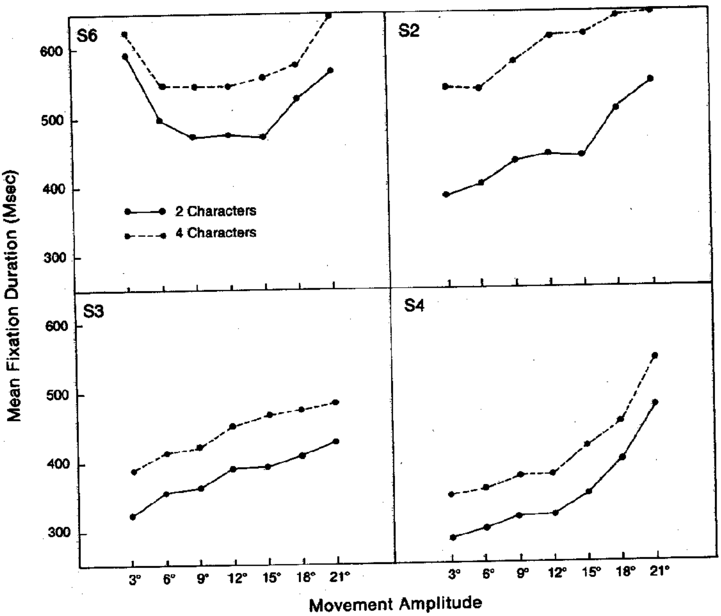

Figure 7. Mean fixation duration as a function of target complexity and movement amplitude, Experiment 5

tude in the fixation durations, a value comparable to the 6.0 msec per degree reported in the previous experiment.

The average difference between fixations with four characters and fixations with two characters was 84 msec, indicating a processing rate of 42 msec per character. The faster processing rate in the present experiment compared to the preceding experiments is probably attributable to the great amount of experience possessed by the current subjects; each had completed the 10 sessions of Experiment 4 before the 15 sessions of the current experiment.

All eye movements from the current experiment were tape recorded and subjected to detailed analyses to check on the possibility of movement artifacts influencing the pattern of fixation durations. Many of the eye movements exhibited overshoot phenomena, and nearly all involved divergence during the movement with postsaccadic convergence delay, but these effects were not systematically related to movement amplitude.

DISCUSSION

With the exception of subject 6, the results of this experiment replicate those of the previous experiment in both qualitative and quantitative respects. The major conclusions from these two experiments are that fixation duration is increased between 6 and 8 msec for each degree of the prior movement, and that this effect is independent of the manipulation of target complexity, which also had a sizable effect on fixation duration. This pattern suggests that there are at least two components contributing to the duration of an eye fixation, one related to stimulus processing and influenced by the complexity of the target stimulus, and the other concerned with recovering from the preceding eye movement and influenced by the amplitude of the eye movement.

EXPERIMENT 6

The preceding two experiments have established that the amplitude of the prior eye movement has a small but significant influence on fixation duration. In the present experiment the amplitude of the following movement was systematically manipulated to determine whether it had a similar effect on fixation duration.

METHOD

Subjects

Two subjects (*S*2 and *S*4 from the preceding two experiments) served in one practice and eight experimental sessions of approximately 50 minutes each.

Stimuli

Single letters located 5.4° or 11.5° from an initial asterisk served as target stimuli. A final asterisk was placed 5.4° or 11.5° to the right of the target to indicate the point of final fixation.

Procedure

The task for the subjects was to begin the trial by fixating on the left asterisk, move to the target when the asterisk disappeared and the target appeared, fixate as briefly as possible, move to the right asterisk, and press a button on the terminal indicating the presence or absence of a vowel. One-half of the trials, selected at random, contained a vowel.

Each session consisted of two practice blocks of 10 trials each, followed by four experimental blocks of 50 trials each. The amplitude of the following movement was held constant in all blocks in a session, but the amplitude of the preceding movement was counterbalanced across blocks within the session. The following movement amplitude was counterbalanced across sessions.

RESULTS

Approximately 92% of the trials resulted in appropriate (i.e., fixation, right movement, fixation, right movement, fixation) eye movement patterns. Average decision accuracy was 99%.

The results of an analysis of variance similar to those performed in the previous experiments revealed no statistically significant sources of variance. However, since with only two subjects there is only one degree of freedom in the denominator of the F-ratios, the test was extremely weak. Separate analyses (with prior amplitude and following amplitude as factors) on the data from each subject did yield significant effects of prior movement amplitude, i.e., $F(1, 28) = 56.17$ for Subject 2 and $F(1, 28) = 18.12$ for Subject 4, both $p < .005$, but no significant effect of following movement amplitude (i.e., $p > .05$ and $p > .30$, respectively). Mean fixation durations for Subject 2 were 285 and 368 msec for the 5.4° and 11.5° prior movements, respectively. The comparable durations for Subject 4 were 271 and 295 msec, respectively.

DISCUSSION

These results indicate that there is little or no effect of the amplitude of the following eye movement on the duration of an eye fixation. The conclusion from this experiment, therefore, is that recovery time from a prior movement is systematically related to movement amplitude, but preparation time for a future movement is not.

EXPERIMENT 7

An implication from the results of Experiments 4 and 5, specifically the noninteractive effects of target complexity and movement amplitude, is that the fixation component that is sensitive to target complexity (and presumably related to stimulus processing) is independent of the fixations component that is sensitive to the amplitude of the prior eye movement.

In addition to these two components concerned with stimulus processing and movement recovery, it might be postulated that eye fixations also contain a third component associated with the minimum time to stop and start the eyes. Arnold and Tinker (1939) not only assumed the existence of such a minimum pause component, but they also attempted to measure its duration. They had subjects move their eyes to either a dot or a letter, fixate as briefly as possible, and then move their eyes away. The instructions stated that subjects should merely fixate the dot, but fixate and attempt to identify the letter. Surprisingly, Arnold and Tinker found that fixations on the dots that did not require processing were longer (i.e., 172 msec vs. 157 msec), than the fixations on the letters that required processing for their identification. Unfortunately, the paradoxical result that the addition of a processing requirement reduced, rather than increased, fixation duration makes this finding difficult to interpret.

Westheimer (1954) also reported data that bear on the issue of the minimum pause time of the eye. He measured the fixation duration of the eyes when subjects were given a countermanding movement signal prior to the beginning of the fixation. In this situation the move and return signals were both presented before the subjects began to move their eyes and yet they typically fixated for about 200 to 250 msec before beginning the return movement. Similar results were reported by Feinstein and Williams (1972) and Megaw (1975).

Another estimate of the duration of these nonprocessing fixations can be obtained from the condition C data of Experiment 3 of the present report. The first fixations in that condition were meaningless, since the targets were noninformative asterisks rather than letters, and thus it can be assumed that subjects did not attempt to process the stimuli. Nevertheless, the average fixation durations were 226 msec for two asterisks and 227 msec for four asterisks.

The exact interpretation of the 226 and 227 msec values is somewhat clouded, however, because they were obtained from the first fixation in a sequence in an experiment that involved several rather complicated conditions. The purpose of the following experiment was to attempt to replicate the earlier findings in an experiment expressly designed to determine the duration of eye fixations that do not require stimulus processing.

Two factors were manipulated in this experiment. Target complexity, two or four letters, was varied as a converging operation to determine whether subjects are indeed ignoring the stimulus. If the target is being ignored, there should be no effect of the number of target characters on fixation duration, as observed in Experiment 3. Prior movement amplitude was also varied in order to assess the independence of the movement recovery and minimum pause time factors in the fixation. If the two components are independent, and if the present experiment is truly measuring minimum pause time, there should be no effect of movement amplitude in the current fixation durations.

METHOD

Subjects

The subjects were the same as those in Experiments 1 and 3. Each served in one practice, and two experimental, sessions of approximately 50 minutes each.

Stimuli

The stimulus arrangement was identical to that of Experiment 4 except that the target stimui were located 5.4°, 10.8°, and 16.2° from the initial fixation instead of 6° and 18°.

Procedure

Subjects were instructed to ignore the the letters in the target and merely fixate as briefly as possible without attempting to identify the stimulus. A trial consisted of the subject fixating on the left asterisk, moving to the target when it appeared, fixating as briefly as possible, moving to the right asterisk, and pressing the same button on the terminal after each trial. Each session consisted of two 30-trial blocks for each movement amplitude, presented in counterbalanced order.

RESULTS

Approximately 85% of the trials had appropriate (fixation, right movement, fixation, right movement, fixation) eye movement patterns.

An analysis of variance (with amplitude and target complexity as factors and four means for each of four subjects as cell entries), indicated that there was a significant effect of movement amplitude, $F(2, 6) = 5.30$, $p < .05$, but no effect of target complexity and no Movement Amplitude × Target Complexity interaction ($p > .20$). Figure 8 illustrates the mean fixation durations for each of the four subjects.

The mean fixation durations were 193 msec for two-character targets and 196 msec for four-character targets. Slopes relating fixation duration to amplitude of the preceding movement averaged 2.7 msec per degree.

DISCUSSION

These results suggest that it is reasonable to consider minimum pause time, the time required to stop and start the eyes, as a substantial component contributing to the duration of an eye fixation. Subjects require between 190 and 200 msec, on the average, to stop and re-start the motion of their eyes. This value is consistent with the earlier estimates from Arnold and Tinker (1939) and Westheimer (1954), and is also close to the fastest fixation durations from Experiment 2 (cf.

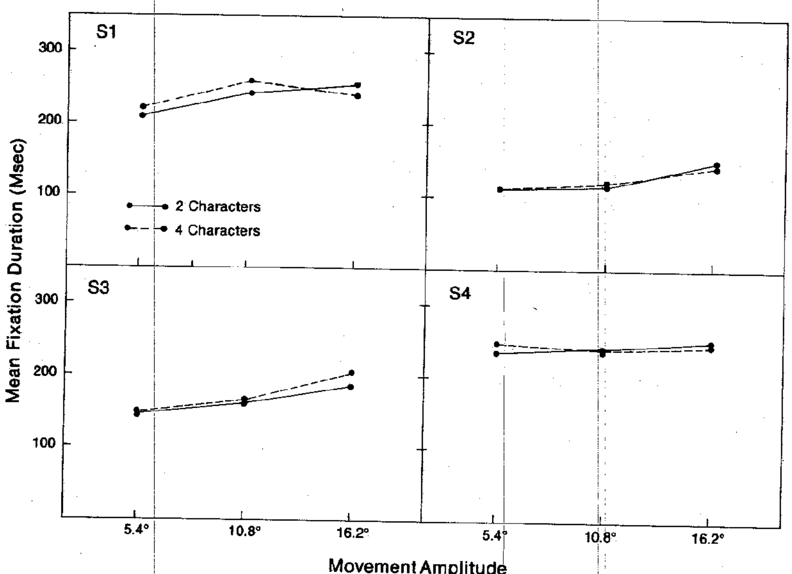

Figure 8. Mean fixation duration under no-processing instructions as a function of target complexity and movement amplitude, Experiment 7

Figure 2) obtained when subjects were instructed to emphasize speed rather than accuracy.

It is important to point out that these figures are merely averages. All subjects occasionally produce very brief fixations, and some subjects (e.g., *S*2) consistently average under 150 msec in their nonprocessing fixations. Generally, however, it seems to be the case that even when no processing of the target stimulus is required, subjects typically do not fixate for less than about 200 msec.

Comparison of Figures 7 and 8 indicates that the effect of prior movement amplitude was substantially smaller in the current experiment than in previous experiments. Indeed, the magnitude of the amplitude effect averaged only 2.7 msec per degree in this experiment compared to the 6.0, 7.6, and 9.0 msec per degree values reported in Experiments 4, 5, and 6, respectively.

GENERAL DISCUSSION

The results of the current experiments support a model in which two independent components serve as the mediators through which variables exert their influence on fixation duration. Although superficially similar to the two-component suggestions of earlier investigators (e.g., Russo, 1978; Tinker, 1958; Vaughan & Graefe, 1977), the present model is more specific as to the nature of the fixation duration determinants and the quantitative contribution of each. One component, labeled minimum pause time, was found to be affected by only one variable, prior movement amplitude. Minimum pause time is the greatest determinant of overall fixation duration; approximately 200 msec seems to be required to stop and re-start the eyes, and thus this component may be responsible for the lower limit on most fixation durations.

It is important to note that minimum pause t me is logically distinct from oculomotor reaction time. According to convention, reaction time refers to the delay between the presentation of a specific stimulus that reduces temporal or response uncertainty and an appropriate response. As used in the present report, minimum pause time does not require an informational stimulus and thus it is more like a physiological refactory period than a reaction time. Indeed, Young and Stark (1963) actually use the phrase refractory period to describe the minimum interval between successive saccades. Although perhaps a minor distinction, the present term is preferred to emphasize the fact that no stimulus processing is involved in this component. There is also some empirical support for this distinction, as Westheimer (1954) reported that oculomotor reaction time averaged 150 msec, while the minimum fixation duration between successive saccades ranged between 200 and 250 msec.

The second eye fixation component, concerned with stimulus processing, is assumed to have a minimum duration of between 50 and 100 msec (based on the sequential display results from Experiment 1), but it is influenced by at least two variables that can substantially increase or decrease this duration. Additional stimulus items beyond one require approximately 50 msec per item (i.e., Experiments 3, 4, and 5), and prior information can reduce processing time of both the initial item and additional items by 20 msec or more (i.e., Experiment 3).

One problem with this model is that the effect of the amplitude of the prior movement is assumed to be localized in one component, and yet when that component was isolated the effect was less than one-half the magnitude evident when both components were present (i.e., the movement amplitude effect was only 2.7 msec per degree in Experiment 7 compared to the 6.0 to 9.0 msec per degree effects in Experiments 4 through 6). It is difficult to account for this result without postulating a third component contributing to the duration of a fixation, but there is no other evidence to justify such a third component and thus the explanation of this result remains a puzzle.

The model explicitly assumes that the two components are independent determinants of the duration of an eye fixation. The evidence for the independence of the components derives from two classes of results. The first is the finding that the amplitude of the prior movement influenced minimum pause time (i.e., Experiment 7), but did not affect processing time per item as measured by the slope of the function relating fixation duration to number of target characters (i.e., Experiments 4 and 5). The second class of evidence is the finding that the fixation duration is influenced by the number of characters in the target when the target stimulus must be processed and a processing component is involved (i.e., Experiments 3, 4, and 5), but is independent of the number of characters when no processing is required and only the minimum pause component is present (i.e., Experiments 3 and 7). Thus, for each component it has been shown that a factor that has an effect on one component has no effect on the other component. The absence of significant interactions between the prior-movement-amplitude and number-of-characters factors in Experiments 4 and 5 is also consistent with this assumption of two independent components, each with its own set of influencing factors.

The above speculations have been deliberately stated using the term "component" rather than the term "stage" in order to avoid the sequential connotation associated with the latter. The model as presented is completely neutral with respect to the issue of whether the minimum pause time and stimulus processing components operate in a serial or parallel fashion. It may be that the duration of a fixation is not influenced by the time for stimulus processing unless the latter exceeds the minimum pause time (i.e., the components might operate in a temporally overlapped, or parallel, fashion), or that stimulus processing time always influences fixation duration (i.e., the components might operate in a temporally additive, sequential, fashion).

There is some evidence relevant to this issue, but it is not very consistent and is therefore difficult to interpret. In the experiment described earlier by Arnold and Tinker (1939), it was reported that fixation duration actually decreased when a processing requirement was added to the subject's task. This result is obviously inconsistent with a sequential component model, but it also poses problems for a simultaneous model since the durations should have been the same in processing and no-processing conditions. More recently, Vaughan and Graefe (1977) argued that the components can operate simultaneously because they found that increased delay in stimulus presentation led to a reduction in the time needed to begin the next eye movement. However, they also reported data indicating that overall fixation duration increased with increased stimulus delay, suggesting that the processing component operates in an additive fashion with the minimum pause component. The available data make it quite apparent that additional empirical information is needed before the question of the relationship between components can be resolved.

A second issue about which the current model is necessarily vague concerns the relationship between saccadic suppression phenomena and the effect of prior movement amplitude demonstrated in Experiments 4, 5, 6, and 7. It is tempting to suggest that the present movement effect is merely a manifestation of saccadic suppression, in that the increased fixation duration associated with large prior eye movements may be a consequence of the reduction in perceptibility reported in saccadic suppression. Indeed, Mitriani, Yakimoff, and Mateef (1970) have shown that the magnitude of saccadic suppression effects is directly related to the amplitude of the saccadic movement. A problem with this interpretation is that if saccadic suppression does actually reduce the perceptibility of a stimulus, it should affect the stimulus processing component in the present model. However, the results discussed above led to the conclusion that the amplitude of the prior movement influences the minimum pause time component and not the stimulus processing component. Another problem with explaining the movement amplitude effect in terms of saccadic suppression is that a similar experiment by Salthouse et al. (Note 1) found no evidence for saccadic suppression with stimuli of the size and brightness as those employed in the present experiments. Until these apparent contradictions are resolved, the details of the exact relationship between the prior movement effect and saccadic suppression must remain unclear.

The applicability of these speculations about eye fixations to more complicated tasks such as reading depends upon whether one considers single eye fixations to be the appropriate level of analysis (e.g., Carpenter & Just, 1976). To the extent that the duration of a fixation is accepted as a meaningful dependent variable in such tasks, the present two-component model can be extended to account for a variety of complicating factos. For example, the need to process for information about position as well as content (i.e., Abrams & Zuber, 1972), for peripheral as well as foveal information (i.e., Rayner, 1975; Rayner, McConkie, & Ehrlich, 1978), and for memory as well as detection (i.e., Potter, 1975), can all be formulated as factors affecting the stimulus processing component. Whether all these factors affect the same stimulus processing component and whether other factors can be identified that affect the minimum pause component are questions for future research.

Notes

This research was supported by a Research Council Grant from the Graduate School, University of Missouri. Reprint requests should be directed to Timothy A. Salthouse, Department of Psychology, University of Missouri, Columbia, Mo. 65211. Received for publication June 11, 1979.

Reference note

1. Salthouse, T. A., Ellis, C., Diener, D., & Somberg, B. Stimulus processing during eye fixations. Manuscript in preparation.

References

Abrams, S. G., & Zuber, B. L. Some temporal characteristics of information processing during reading. *Reading Research Quarterly,* 1972, *8,* 40–51.

Arnold, D. C., & Tinker, M. A. The fixational pause of the eyes. *Journal of Experimental Psychology,* 1939, *25,* 271–280.

Bartz, A. E. Eye-movement latency, duration, and response time as a function of angular displacement. *Journal of Experimental Psychology,* 1962, *64,* 318–324

Carpenter, P. A., & Just, M. A. Linguistic influences on picture scanning. In R. A. Monty & J. W. Senders (Eds.), *Eye movements and psychological processes.* Hillsdale, N.J.: Erlbaum, 1967.

Dodge, R. An experimental study of visual fixation. *Psychological Monographs,* 1907, *8,* (No. 35), 1–92.

Elliot, P. B. Tables of d′. In J. A. Swets (Ed.), *Signal detection and recognition by human observers.* New York: Wiley, 1964.

Eriksen, C. W., Becker, B. A., & Hoffman, J. E. Safari to masking land: A hunt for the elusive U. *Perception & Psychophysics,* 1970, *8,* 245–250.

Eriksen, C. W., & Collins, J. F. Backward masking in vision. *Psychonomic Science,* 1964, *1,* 101–102.

Eriksen, C. W., & Eriksen, B. A. Visual perceptual processing rates and backward and forward masking. *Journal of Experimental Psychology,* 1971, *89,* 306–313.

Feinstein, R., & Williams, W. J. Interactions of the horizontal and vertical human oculomotor systems: the saccadic systems. *Vision Research,* 1972, *12,* 33–44.

Hyde, J. E. Some characteristics of voluntary human ocular movements in the horizontal plane. *American Journal of Opthalmology,* 1959, *48,* 85–94.

Liss, P. Does backward masking by visual noise stop stimulus processing? *Perception & Psycholophysics,* 1968, *4,* 328–330.

Loftus, G. R. A framework for a theory of picture recognition. In R. A. Monty & J. W. Senders (Eds.), *Eye movement and psychological processes.* Hillsdale, N.J.: Erlbaum, 1976.

Megaw, E. D. Saccadic eye-movements and the refractory period. In P. M. A.

Rabbitt & S. Dornic (Eds.), *Attention and Performance V*. New York: Academic Press, 1975.

Mitriani, L. Yakimoff, N., & Mateef, S. Dependence of visual suppression on the angular size of voluntary saccadic eye movements. *Vision Research*, 1970, *10*, 411–415.

Potter, M. C. Meaning in visual search. *Science*, 1975, *187*, 965–966.

Rayner, K. The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 1975, *7*, 65–81.

Rayner, K. Eye movement latencies for parafoveally presented words. *Bulletin of the Psychonomic Society*, 1978, *11*, 13–16.

Rayner, K., & McConkie, G. W. What guides a reader's eye movements? *Vision Research*, 1976, *16*, 829–837.

Rayner, K., McConkie, G. W., & Ehrlich, S. Eye movements and integrating information across fixations. *Journal of Experimental Psychology: Human Perception and Performance*, 1978, *4*, 529–544.

Russo, J. E. Adaptation of cognitive processes to the eye movement system. In J. W. Senders, D.A. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions*. Hillsdale, N. J.: Erlbaum, 1978.

Smith, F. *Understanding reading: A psycholinguistic analysis of reading and learning to read*. New York: Holt, Rinehart, & Winston, 1971

Spencer, T. J. Some effects of different masking stimuli on iconic storage. *Journal of Experimental Psychology*, 1969, *81*, 132–140.

Spencer, T. J., & Shuntich, R. Evidence for an interruption theory of backward masking. *Journal of Experimental Psychology*, 1970, *85*, 198–203.

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

Sternberg, S. The discovery of processing stages: Extension of Donders' method. *Acta Psychologica*, 1969, *30*, 276–315.

Tinker, M. A. Recent studies of eye movement in reading. *Psychological Bulletin*, 1958, *55*, 215–231

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

Westheimer, G. H. Eye movement responses to horizontally moving visual stimulus. *A.M.A. Archives of Ophthalmology*, 1954, *52*, 32–941.

Young, L. R., & Stark, L. Variable feedback experiments testing a sampled data model for eye tracking movements. *I.E.E.E. Transactions, Human Factors in Electronics*, 1963, *4*, 38–51.