Retinal location and visual processing rate

JOHN J. STERLING and TIMOTHY A. SALTHOUSE
University of Missouri—Columbia, Columbia, Missouri 65201

Although previous studies have shown that the time required to process visual stimuli increases for presentations away from the fovea, the evidence concerning the exact nature of this increase is inconclusive. Three experiments were conducted using both reaction time and tachistoscopic masking tasks to generate time-accuracy functions for stimuli at different retinal locations. All results indicated that only the time intercept parameter of the time-accuracy function is affected by retinal location of stimulation. This finding suggests that it takes longer for information to become available to some decision mechanism with stimuli displaced away from the fovea, but that the actual rate of extracting information is not influenced by retinal locus of stimulation.

At least since Poffenberger (1912), it has been known that reaction time increases as stimuli are located farther from the foveal center of the retina (e.g., Eriksen & Schultz, 1977; Lefton & Haber, 1974; Payne, 1966; Rains, 1963). The mechanism for this slower performance in peripheral locations is not yet clear, although it is known that the density of retinal receptors decreases with distance from the fovea. It might be presumed that more time is needed when fewer receptors are available, but the greater time might be required either for initial sensory integration or for actual information extraction. These two possibilities can be investigated by examining the functions relating time (in either reaction time or tachistoscopic masking tasks) to stimulus classification accuracy.

Salthouse (Note 1) has demonstrated that the time-accuracy functions can be characterized in terms of the intercept (the point in time at which accuracy begins to exceed chance), the slope (the rate of increase in accuracy per unit time), and the accuracy asymptote (the final level of accuracy achieved with unlimited time) parameters, and that these parameters are differentially sensitive to various experimental manipulations. For example, increased stimulus intensity reduces the time-axis intercept, while increased stimulus discriminability increases the slope of both reaction time and tachistoscopic masking time-accuracy functions. (See also Lappin & Disch, 1972; Link & Tindall, 1971; Pachella & Fisher, 1969; Swensson, 1972). Salthouse suggested that the intercept parameter reflects the duration of all processes except actual information extraction, while the slope represents the rate of extraction of information from the stimulus. The asymptote parameter, unlike the intercept and slope parameters, is independent of time and is therefore likely to reflect state, rather than process, limitations. For this reason, it is not of primary interest in this investigation and will not be discussed further.

The purpose of the present experiments was to determine which time-accuracy parameter, the slope or the intercept, is primarily affected by the retinal location of stimulation. Some relevant evidence is available, but it is presently contradictory. Estes (1978) described a tachistoscopic experiment in which a poststimulus mask was used to limit processing time, and he concluded that peripheral locations were associated with shallower slopes of the function relating processing time to identification accuracy. Eriksen, Becker, and Hoffman (1970), however, reported a similar study in which parallel (equal-slope) functions were obtained for stimuli at different retinal locations.

EXPERIMENT 1

The first experiment utilized speed-accuracy trade-off procedures (e.g., Salthouse, 1979, 1981; Wood & Jennings, 1976) to generate time-accuracy functions in a reaction time task. An eye movement monitor was used to ensure that subjects did not move their eyes to fixate on the peripheral stimuli.

Method

Subjects. Four right-handed females with normal or corrected-to-normal visual acuity served as subjects for 16 1-h sessions.

Apparatus. Stimuli were presented on a Mini-Bee CRT controlled by a PDP 11/34 computer. Eye movements were monitored by a Narco Biosystems Model 200 Eye Movement Recorder interfaced with the computer. Head position was held constant by a chin cup and a forehead restraint device.

Procedure. Target stimuli consisted of the .3-deg letters X and O presented 3.3, 5.6, or 7.6 deg to the left or right of center fixation. Subjects responded using either the second or third finger of the designated hand to press one of two specified keys on the keyboard. Stimulus-response pairings were balanced across subjects and sessions.

The first four sessions were considered practice to stabilize performance and establish the time boundaries for the speed-accuracy manipulations. The remaining 12 sessions, consisting of 4 sessions with each location condition in a balanced order for each subject, each involved 7 blocks of trials. The first block consisted of

20 practice trials during which the subjects responded at their slowest time boundaries. The responses from this block were discarded and not utilized in any analyses. The remaining 6 blocks of 40 trials each were performed at one of the three speed-accuracy emphases. A goal region was defined in terms of a set of minimum and maximum reaction times within which the subject was instructed to attempt to produce all of her responses at whatever level of accuracy was appropriate to attain the desired speed. The minimum and maximum times of the three speed-accuracy regions were determined individually for each subject to produce approximate accuracies of 60%, 75%, and 90%.

A trial began with the subject fixating on a center asterisk for 1.5 sec. The termination of the fixation point was followed by the presentation of either an X or an O in one of the visual field locations on either side of the fixation point. Subjects responded by pressing one of two keys as rapidly as was consistent with the speed-accuracy region. The feedback after each trial consisted of the word CORRECT or WRONG printed on the screen, followed by a time line with vertical bars representing the minimum and maximum times acceptable in that goal region and an arrow indicating how fast the subject actually responded on that trial. Subjects were instructed to respond so that the arrow appeared between the vertical bars.

The speed-accuracy regions for each subject were counterbalanced within each session beginning with the slowest region (i.e., ABCCBA order).

Any deviation of the eyes from the center fixation point during the target presentation would result in unknown visual field location. Consequently, a deviation of more than 2 deg from the central fixation point detected by the eye movement monitor caused the computer to: (1) discard the trial; (2) instruct the subject to stop moving her eyes from the central fixation point; and (3) begin a new trial.

Results

Trials with reaction times greater than 900 msec were excluded from analyses. Less than 1% of the trials were deleted from each location condition. The remaining trials were subjected to linear regression analyses to determine the correlation, slope, and intercept parameters of the function relating reaction time to classification accuracy.[1] For each location condition, there were 24 reaction-time/accuracy pairs, corresponding to the number of blocks of trials during the experimental sessions. Pairs with accuracies less than 55% or greater than 95% were omitted from the computations to avoid inclusion of data from the chance accuracy and perfect accuracy segments of the time-accuracy function. The correlations between reaction time and percent correct for each subject ranged from +.49 to +.81, with a mean of +.67. These values are not particularly high, but they do indicate that subjects were able to trade speed for accuracy.

Because the slope and intercept of the speed-accuracy tradeoff functions are possibly correlated (i.e., Salthouse, 1979; Wood & Jennings, 1976), it may be unreasonable to expect that separate analyses of each measure will provide meaningful results. We therefore used the slope and intercept parameters to generate predicted reaction times at accuracies corresponding to 65% and 85% correct judgments. A 3 (location) × 2 (accuracy) analysis of variance con-
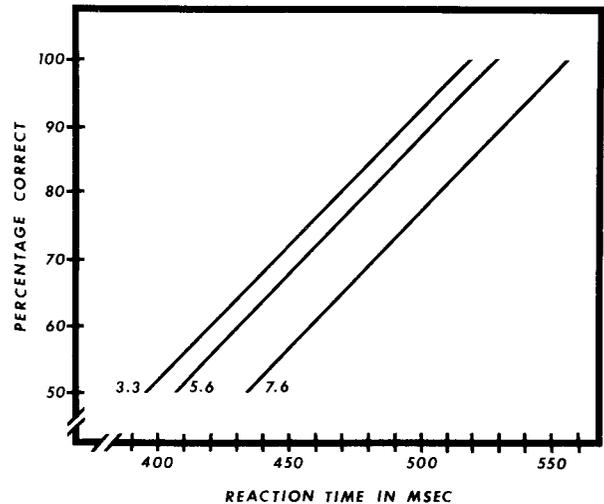

Figure 1. Mean regression lines for three stimulus locations derived by predicting reaction time at accuracies of 65% and 85% (Experiment 1).

ducted on these values revealed significant effects of accuracy [$F(1,3) = 24.25$, $p < .02$] and location [$F(2,6) = 7.81$, $p < .05$], but not the interaction of location × accuracy [$F(2,6) < 1.0$, n.s.].

The mean regression lines for the three locations, computed by averaging the predicted values for each subject, are displayed in Figure 1. Notice that the time-accuracy functions are nearly parallel for the various location conditions.

Discussion

The major result of Experiment 1 is that the time-accuracy parameter sensitive to retinal location appears to be the intercept and not the slope. The Accuracy by Location interaction was not significant, indicating that the reaction time change between 65% and 85% accuracy was roughly equivalent for all location conditions. Since the time required to achieve a comparable increase in accuracy was not different, it can be inferred that the rate of accumulating information from different retinal locations also was not different.

EXPERIMENT 2

Experiment 2 was designed to demonstrate that retinal location affects the intercept but not the slope parameter in time-accuracy functions derived from tachistoscopic masking tasks, as well as those generated from speed-accuracy reaction time tasks. The previous results will also be reexamined with a modified speed-accuracy procedure that allows complete tradeoff functions to be derived within a single session. Eye movements were not monitored because there were relatively few contaminating movements detected in Experiment 1.

Method

Subjects. Forty-eight undergraduate psychology students with normal or corrected-to-normal vision served as subjects in a 1-h session. None of the subjects had participated in Experiment 1.

Apparatus. A PDP 11/03 computer, interfaced with a Hewlett-Packard Model 1311A Display Monitor and two 10-key telephone keyboards, was used to present stimuli and record responses.

Procedure. All subjects completed six blocks of trials—three in the reaction time task and three in the tachistoscopic task. The first two blocks were considered practice (one for each task), and the remaining four blocks (two for each task) were presented in counterbalanced order.

The target stimulus for both the reaction time and tachistoscopic tasks was an arrow subtending 1.5 deg of visual angle, pointing at a 45-deg angle to either the left or the right. For a given subject, the target stimulus appeared only at fixation or at 7.5 or 15.0 deg to the left or right of fixation. That is, the location variable was manipulated across subjects, with 16 subjects receiving targets at each location. The subjects were instructed to respond by pressing the key on the left of a keyboard if the arrow was pointing to the left, and to respond by pressing the key on the right of a keyboard if the arrow was pointing to the right.

Each trial in both tasks was initiated by the appearance of four center fixation dots placed at the corners of a square subtending 2.0 deg of visual angle. One second after the presentation of the fixation square, the arrow was presented in the appropriate location. The stimulus remained until the subject responded in the reaction time task but was presented for only 5 msec with a 5- to 130-msec blank interval before a poststimulus mask (a square with diagonal lines covering the shafts of the arrows) in the tachistoscopic task.

In the reaction time task, a time line with two vertical markers and an arrow pointer appeared on the screen after the subject responded. The subjects were instructed to respond within the designated time region regardless of the accuracy that might result. A trial block began with the desired time region between 375 and 475 msec, and the time region was reduced in 50-msec steps until it reached 125 to 225 msec. That is, in the first 10 trials, the subject was to respond between 375 and 475 msec, in the second 10 trials, he or she was to respond between 325 and 425 msec, in the third 10 trials, between 275 and 375 msec, and so on. The time region remained at 125 to 225 msec until the subject produced 10 responses within that interval, at which point the time region increased to progressively higher values after 10 responses at each interval or until a total of 250 responses had been produced. This is a procedure for generating reaction-time/speed-accuracy functions different from those used in Experiment 1, but it has the advantage of being much more efficient in the collection of data.

A trial block in the tachistoscopic task consisted of 20 trials at each interstimulus interval from 5 to 130 msec. Ten trials were presented at each interval, starting from the largest interval and then decreasing to the smallest interval before increasing again.

Results

Data from the two experimental blocks of the reaction time task were combined, and accuracies were determined for each 50-msec interval ranging from 175 to 475 msec. Regression parameters were then derived from these values after deleting points with excessively low or high accuracies to obtain the best-fitting regression line with a minimum of three pairs of values. The slope and intercept parameters were then used to predict reaction times at 65% and 85% accuracy for each subject. The correlations between reaction time and percent correct for these functions for each subject ranged from .43 to .99, with a median of .98. Note that the present procedure for generat-

ing reaction-time/speed-accuracy functions is not only more efficient, but also appears to better reflect the negative relationship between speed and accuracy than does the procedure used in Experiment 1.

A 3 (location) × 2 (accuracy) analysis of variance conducted on the predicted reaction times revealed significant effects of accuracy [$F(1,45) = 624.97$, $p < .0001$] and location [$F(2,45) = 21.70$, $p < .0001$], but not of accuracy × location [$F(2,45) < 1.1$, n.s.]. (Similar results were obtained in an analysis conducted on the mean accuracies at each 50-msec reaction time interval. The location × time interaction was significant in this analysis, but the data illustrated in Figure 2 indicate that it is probably due to convergence of accuracies at the shortest reaction times.) The mean accuracies at each time interval for the three locations are illustrated in the right side of Figure 2. Both statistically and graphically, the present results confirm those of Experiment 1.

The data of Figure 2 suggest that there was no difference between the reaction times with stimuli at 7.5 and 15.0 deg from fixation. Subjects in both of these conditions often complained that it was difficult to respond to an arrow on one side of the screen when the correct response was to hit the key on the opposite side of the keyboard. It is therefore possible that a stimulus-response incompatibility effect was masking the effects of visual field location with the extreme positions.

The data from the two tachistoscopic trial blocks were combined, and the accuracy was determined for each interstimulus interval. Because accuracy had reached an asymptotic level by 105 msec in all conditions, only the intervals between 5 and 80 msec were examined in a 3 (location) × 4 (interstimulus
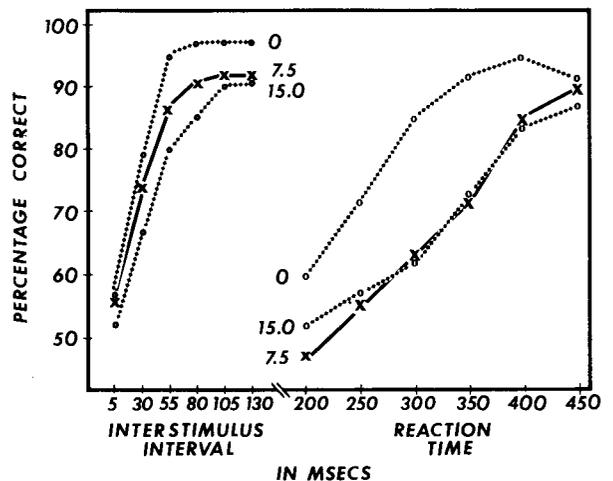

Figure 2. Left side: Mean accuracy as a function of interstimulus interval for three stimulus locations (tachistoscopic masking task, Experiment 2). Right side: Mean accuracy as a function of reaction time for three stimulus locations (reaction time task, Experiment 2).

interval) analysis of variance. Location $[F(2,45) = 7.87, p < .002]$ and interstimulus interval $[F(3,135) = 202.32, p < .0001]$, but not their interaction $[F(6,135) = 1.84, n.s.]$, factors were significant. The mean accuracies at each interval for the three locations are illustrated in the left side of Figure 2.

EXPERIMENT 3

Although the Interstimulus Interval by Location interaction for the tachistoscopic task in Experiment 2 was not significant, inspection of Figure 2 suggests that the slope parameter might be affected by visual field location. One possible interpretation of this result is that the interval increments (25 msec) were too large and thus the data were not precise enough to accurately depict the true parallel nature of the functions. Another possibility is that the apparent difference is real but that the between-subjects design used in Experiment 2 was not powerful enough to detect this difference. Experiment 3 was designed to investigate these alternative interpretations by using a smaller value (10 msec) of interstimulus interval increment and having each subject receive all stimulus locations to provide a more sensitive test of the Interstimulus Interval by Location interaction.

Method

Subjects. Sixteen undergraduate psychology students with normal or corrected-to-normal vision participated in a 1-h session. None of the subjects had served in the previous experiments.

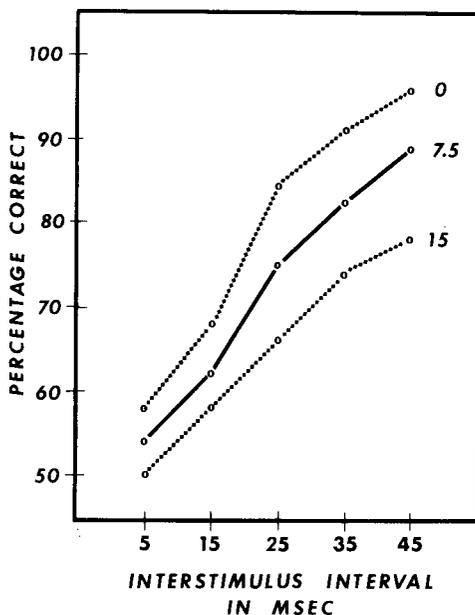**Apparatus.** The apparatus was the same as that used in Experiment 2.

Figure 3. Mean accuracy as a function of interstimulus interval for three stimulus locations (Experiment 3).

Procedure. The task was identical to the tachistoscopic task in Experiment 2, except that the interstimulus intervals were changed to 5, 15, 25, 35, and 45 msec. Subjects first completed a practice block of trials with the target arrow presented at 7.5 deg to the right or left of fixation with the interstimulus intervals from Experiment 2. Two blocks of trials were then administered at each of the three visual field locations, in an order balanced across conditions and subjects.

Results

Data for the two blocks completed at each visual field location were combined, and accuracy was determined at each interstimulus interval. These values were then subjected to a 3 (location) × 5 (interstimulus interval) analysis of variance. Main effects of location $[F(2,225) = 39.42, p < .0001]$ and interstimulus interval $[F(4,225) = 91.14, p < .0001]$ were significant, but not their interaction $[F(8,225) = 1.04, n.s.]$. The mean accuracies at each interstimulus interval are illustrated in Figure 3.

GENERAL DISCUSSION

The major finding of these experiments is that only the time intercept of the time-accuracy function is affected by the retinal location of stimulation. A difference in the time-accuracy slope would be reflected in an interaction of either location × accuracy or location × time. The interactions were not significant, but the main effects of location were significant, in all analyses. Moreover, the figures illustrated that shifting the locus of stimulation away from the fovea delays the time at which accuracy begins to improve above the chance level. These results were obtained when processing time was limited by the occurrence of the response in a speed-accuracy reaction time task (Experiments 1 and 2) and when processing time was limited by the occurrence of a poststimulus mask in a tachistoscopic masking task (Experiments 2 and 3).

The conclusion that retinal locus influences the time at which accuracy begins to improve above a chance level, but not the actual rate of improvement once it begins, is consistent with a finding by Eriksen, Becker, and Hoffman (1970). Estes (1978) argued that retinal location affects the rate of accuracy improvement, but his inference was based on unpublished data without reported statistical support, and thus it is difficult to evaluate.

The analysis of time-accuracy parameters is based on the assumption that the total time to achieve a given level of accuracy can be divided into two distinct components corresponding to (1) the amount of increase in stimulus information per unit time, and (2) the duration of all other processes except information extraction. The present results indicate that a reduction in the number of available receptors as the locus of stimulation is moved from fovea to periphery does not alter the rate at which accuracy (stimulus information) is accrued. Instead, a reduction in num-

ber of receptors increases the amount of time required before accuracy begins to improve above a chance level.

An interpretation consistent with these results is that the time intercept corresponds to, among other things, the duration necessary to establish an initial representation of the visual stimulus, and that the slope represents the rate of discriminating between alternative representations. A fewer number of receptors therefore delays the establishment of the initial representation but does not impair the speed of distinguishing between different possible representations. This interpretation is also supported by the results cited earlier with respect to manipulations of stimulus intensity and stimulus discriminability. Reduced intensity would be expected to hamper the formation of a representation, and reduced discriminability or distinctiveness would be expected to slow the discrimination process. This is precisely what has been found in several studies in which stimulus intensity has been reported to affect the time intercept, whereas stimulus discriminability has been reported to affect the slope (e.g., Lappin & Disch, 1972; Link & Tindall, 1971; Pachella & Fisher, 1969; Swensson, 1972; Salthouse, Note 1).

It is important to stress that there is no intrinsic temporal relationship implied between the two components of the present model of the time-accuracy functions. That is, the processes contributing to the time intercept may precede, follow, or occur simultaneously with the processes responsible for the slope. This is particularly apparent in the comparison of the reaction time and tachistoscopic time-accuracy functions. The time intercepts of the former are much larger than those of the latter, presumably because response preparation and execution are required in the measured interval for the reaction time task. In the reaction time functions, therefore, it may be speculated that the time intercept is due to the establishment of the stimulus representation, which at least partially precedes the discrimination process, and to the preparation and execution of the response, which follows the discrimination process. However, the similar finding of retinal location affecting the intercept and not the slope in both reaction time and tachistoscopic functions suggests that the current finding is not merely a reflection of response factors.

We suggest that this two-component model of time-accuracy parameters may prove extremely useful in analyzing the processess involved in simple perceptual decisions. The slope and intercept parameters have already been demonstrated to be differentially sensitive to a variety of experimental manipulations under several procedures for generating time-accuracy functions. Whether the present interpretation of these parameters is correct must await more extensive analytical investigation of the type reported here.

REFERENCE NOTE

1. Salthouse, T. A. *Parameters of the time-accuracy relationship.* Paper presented at the 20th Annual Meeting of the Psychonomic Society, Phoenix, Arizona, November 1979.

REFERENCES

ERIKSEN, C. W., BECKER, B. B., & HOFFMAN, J. E. Safari to masking land. *Perception & Psychophysics,* 1970, **8,** 245-250.
ERIKSEN, C. W., & SCHULTZ, D. W. Retinal locus and acuity in visual information processing. *Bulletin of the Psychonomic Society,* 1977, 9, 81-84.
ESTES, W. K. Perceptual processing in letter recognition and reading. In E. C. Carterette & M. P. Friedman (Eds.), *Handbook of perception* (Vol. 9) *Perceptual processing.* New York: Academic Press, 1978.
LAPPIN, J. S., & DISCH, K. The latency operating characteristic: II. Effects of visual stimulus intensity on choice reaction time. *Journal of Experimental Psychology,* 1972, 93, 267-272.
LEFTON, L. A., & HABER, R. N. Information extraction from different retinal locations. *Journal of Experimental Psychology,* 1974, 102, 975-980.
LINK, S. W., & TINDALL, A. D. Speed and accuracy in comparative judgments of line length. *Perception & Psychophysics,* 1971, 9, 284-288.
PACHELLA, R. G., & FISHER, D. F. Effect of stimulus degradation and similarity on the tradeoff between speed and accuracy in absolute judgments. *Journal of Experimental Psychology,* 1969, 81, 7-9.
PAYNE, W. H. Reaction time as a function of retinal location. *Vision Research,* 1966, 6, 729-732.
POFFENBERGER, A. T. Reaction time to retinal stimulation with special reference to the time lost in conduction through nerve centers. *Archives of Psychology,* 1912, 23, 1-73.
RAINS, J. D. Signal luminance and position effects in human reaction time. *Vision Research,* 1963, 3, 239-251.
SALTHOUSE, T. A. Adult age and the speed-accuracy tradeoff. *Ergonomics,* 1979, 22, 811-821.
SALTHOUSE, T. A. Converging evidence for information processing stages: A comparative-influence stage-analysis method. *Acta Psychologica,* 1981, 47, 39-61.
SWENSSON, R. G. The elusive tradeoff: Speed vs. accuracy in visual discrimination tasks. *Perception & Psychophysics,* 1972, 12, 16-32.
WOOD, C. C., & JENNINGS, J. R. Speed-accuracy tradeoff functions in choice reaction time: Experimental designs and computational procedures. *Perception & Psychophysics,* 1976, 19, 92-101.

NOTE

1. The percent correct measure of accuracy was utilized because Salthouse (1979, 1981) had reported that this measure yielded reaction-time/accuracy correlations at least as large as those obtained from more theoretically dependent measures such as information transmitted, d', (d')2, and log odds correct to incorrect responses.