

SACCADIC EYE MOVEMENT LATENCIES TO MULTIMODAL STIMULI

INTERSUBJECT VARIABILITY AND TEMPORAL EFFICIENCY

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Abstract—The saccadic latencies to multimodal stimuli of 10 subjects were studied to determine the range of intersubject variations and to derive values which are representative of the normal population. Responses to simple step and pulse-step stimuli were measured where the target mode and pulse width were randomized. A matrix notation was introduced to describe all of the relevant latency variables without ambiguity. In comparing our results with other studies, we emphasized the importance of considering differing experimental conditions. We concluded that: (1) intersubject variation is a significant factor in data interpretation; (2) temporal efficiency is inherent in saccadic decision making; and (3) new visual information is continuously available to alter the latency or cause the cancellation of the initial saccade.

INTRODUCTION

The experiments of Wheelless, Boynton and Cohen (1966) produced results incompatible with the concept of a simple fixed-period impulse sampler which had dominated the modelling of the saccadic system since the work of Young and Stark (1963). Prior (White, Eason and Bartlett, 1962; Bartz, 1962; Leushina, 1965) and subsequent (Saslow, 1967a, 1967b; Becker and Fuchs, 1969; Täumer, Mie and Kommerell, 1972; Komoda, Festinger, Phillips, Duckman and Young, 1973) studies of saccadic latencies yielded conflicting data. While specific insights into saccadic control are evident in these reports, differences in experimental design have often led to misleading comparisons. In addition, insufficient subject populations have not provided an adequate basis for modeling the expected behavior of the saccadic subsystem. We undertook the present study to measure the intersubject variation of latencies hoping to explain the conflicting data in studies of single or only a few subjects. Furthermore, we wanted to provide more representative parameters of the decision-making processes responsible for saccadic eye movements. The application of these findings towards a system model is planned in a future report.

METHODOLOGY

We presented each of ten naive subjects with ten groups of 16 target motions. The target mode (step or pulse-step), initial direction (right or left), and pulse width (PW) were randomized. The PW of pulse-steps was varied in 40-msec increments from 40 to 200 msec and the initial target amplitudes were fixed at 5° for both the 10 pulses and six simple steps comprising each group. The pulse-step consisted of a target movement of 5° in one direction followed by a 10° shift in the opposite direction.

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Target presentation was by a variable stimulus arc (Dell'Osso, Troost, Patterson and Sacerio, 1974) which contained light-emitting diodes (LED) spaced around a 1.14 m arc. With the subject seated in the center of the arc each LED subtended a visual angle of 5° at the mid-interpupillary point. The 9-nsec rise and fall times of the LED eliminated transition time errors (Saslow, 1967a). All subjects were free of neurological disease and taking no medications. They were securely seated in a modified dental chair and heads were stabilized by the use of a bite bar.

Horizontal eye movements were recorded with an i.r. reflection technique which provided an input signal proportional to eye position to an eight-channel d.c. coupled recording apparatus with a 25-Hz bandwidth. The chart paper speed of 50 mm/sec allowed time measurements to within ± 5 msec. After calibration, each subject was asked to view the target and follow all changes in target position. Eye movement, target displacement and the temporal interval between the auditory warning signal and the onset of the target stimulus were monitored visually with an oscilloscope. The subject viewed the central target and was verbally cued before each target change which then came randomly 1.5–2 sec later. Each subject was allowed two rest periods during the test and was recalibrated prior to each phase of the testing. All latencies were manually measured from the eye movement records and statistical treatment of data was performed by computer. Tests for significance were accomplished using the one-sample *t*-test for matched pair data.

RESULTS

Definitions

Previous studies had considered only a few variables, the nomenclature was not consistent, and standardized identifying symbols have not been utilized. We adopted a consistent nomenclature based upon standard matrix notation to avoid the use of arbitrary symbols. Thus, L_{XY} refers to: "the latency of the *X* response as measured from the *Y* target motion."

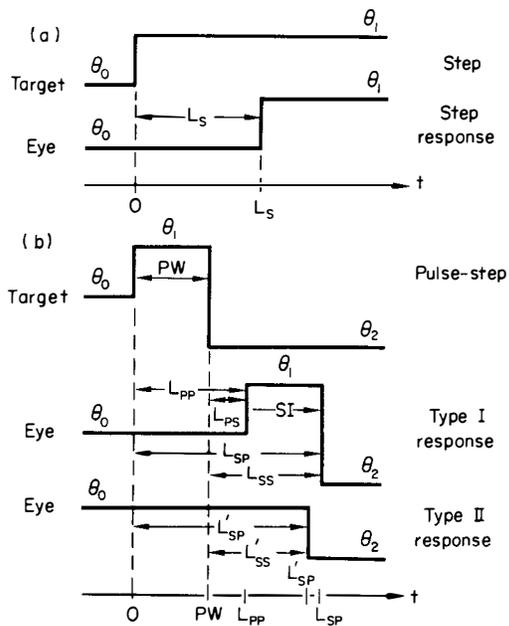


Fig. 1. Illustration of the various latencies to multimodal stimulation which related components of the eye response to those of the target displacements. (a) A target step movement from θ_0 to θ_1 and the saccadic response occurring after a latency L_S . (b) A pulse-step of target movement from θ_0 to θ_1 and then, after an interval PW , to θ_2 . The two possible saccadic responses (types I and II) with their associated latencies are depicted in the matrix notation described in the text. The primed variables denote a type II response. The time axes show initial and total latencies for all response possibilities.

Figure 1(a) shows the latency (L_S) of the step response. Figure 1(b) depicts the use of this notation in describing the latencies in the two possible responses to a pulse-step target motion; the three latencies (two for a Type I response and one for a Type II response), chosen to be cardinal variables, were measured from the initiation of target motion at $t = 0$

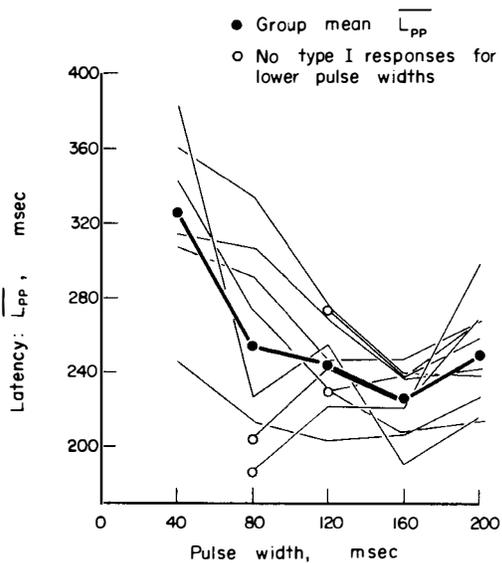


Fig. 2. Intersubject variation in mean values of latency L_{PP} and the group mean $\overline{L_{PP}}$ as a function of pulse width.

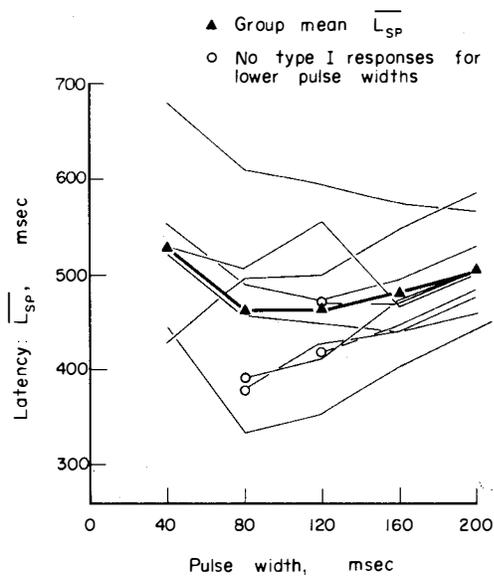


Fig. 3. Intersubject variation in mean values of latency L_{SP} and the group mean $\overline{L_{SP}}$ as a function of pulse width.

and appear on the time axis along with the time interval PW , which is the independent variable. L_{PP} was the latency of the initial response and L_{SP} the total latency for a Type I response. L'_{SP} represented both the initial and total latency for Type II responses. Saccadic interval (SI) was the time interval from the start of the first response to the start of the second, a definition consistent with prior usage (Täumer *et al.*, 1972; Becker and Fuchs, 1969). Thus, the two target modes (step or pulse-step) and the possibility of either of two types of responses to the pulse-step stimulus, resulted in seven different latencies and two time intervals of interest.

Intersubject variability

To assess intersubject variability, we plotted the individual subject mean values over PW for each of the cardinal variables. The plot for $\overline{L_{PP}}$ showed considerable intersubject spread in actual mean values but the general shapes of the individual curves over the entire range of PW were similar (Fig. 2). Several subjects made no response to short PW 's (see open circles indicating lowest PW eliciting a Type I response for individual subjects). The group mean $\overline{L_{PP}}$ revealed that at the lowest PW (40 msec) the latency was significantly greater ($P < 0.001$) than for PW values of 80, 120 and 200 msec. However, at $PW = 160$ msec the group mean was significantly lower ($P < 0.05$) than at the other PW 's. The implications of these findings will be discussed subsequently.

The intersubject variation in total latency for a Type I response ($\overline{L_{SP}}$) also demonstrated wide numerical differences but the general shapes of the curves were similar, particularly at higher PW 's (Fig. 3). The value of the group mean $\overline{L_{SP}}$ was high for the lowest PW and, after a slight drop, gradually rose with PW from its low point at 80 msec.

The total latency for Type II response ($\overline{L'_{SP}}$), the final major variable, showed even more intersubject variation (Fig. 4) than the Type I variables. Although there was a general increase with increasing PW , some curve shapes differed markedly. One subject had no

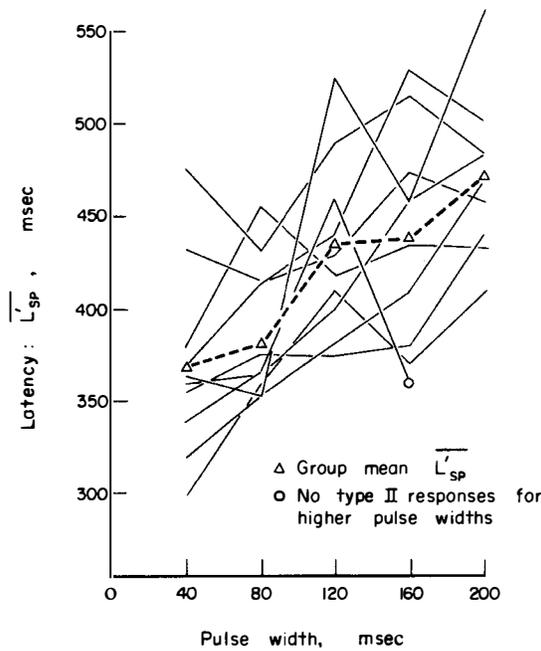


Fig. 4. Intersubject variation in mean values of latency L'_{SP} and the group mean \overline{L}_{SP} as a function of pulse width.

Type II response for $PW > 160$ msec (see open circle). The group mean \overline{L}_{SP} showed the expected increase with higher PW .

Response type

We plotted the per cent Type I response for each subject (Fig. 5) to determine the effects of PW on the saccadic decision making process. Despite large variations in absolute values (greater for intermediate than for both high and low PW 's) all curves increased with PW and the group mean showed an extremely linear relationship. The PW at which the per cent Type I response crossed the arbitrary 50 per cent level

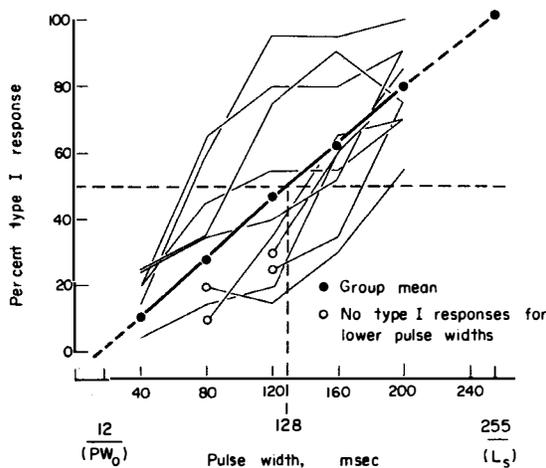


Fig. 5. Intersubject variation in mean values of per cent type I response and the group mean per cent type I response as a function of pulse width. The dashed extensions of the group mean curve reveal that the 0 and 100 per cent values correspond to 12 msec (\overline{PW}_0) and 255 msec (\overline{L}_S) respectively. The arbitrarily chosen 50 per cent value (dashed horizontal line) occurs at 128 msec.

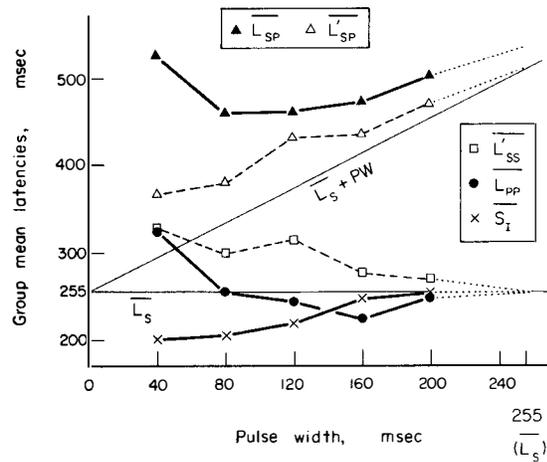


Fig. 6. Variation over pulse width of several important group mean latencies for both types I and II responses. The lines \overline{L}_S and $\overline{L}_S + PW$ serve as reference values for comparison. Dotted extensions illustrated expected values at a pulse width of 255 msec (\overline{L}_S).

was 128 msec. Extension of the linear group mean curve upward revealed a crossing of the 100 per cent level at $PW = 255$ msec which was the value of \overline{L}_S (the group mean latency to simple step changes in target position). Linear extension to lower PW 's resulted at a 0 per cent value at $\overline{PW}_0 = 12$ msec implying that, under these experimental conditions, pulses with widths of 12 msec or less would always be ignored, therein resulting in a Type II response.

Latency comparisons

The group mean latency data for three variables (\overline{L}_{SS} , \overline{L}_{PP} , \overline{S}_I) were plotted in relationship to \overline{L}_S and PW (Fig. 6). Also shown are \overline{L}_{SP} and \overline{L}'_{SP} as they related to the quantity $\overline{L}_S + PW$. The values of \overline{L}_{PP} differed from \overline{L}_S significantly at $PW = 40$ and 160 msec. Thus, there were two intervals of time during which the initial response latency could have been affected by a PW of the appropriate duration; this could have been to lengthen \overline{L}_{PP} (low PW) or shorten \overline{L}_{PP} (high PW). \overline{S}_I was independent of PW for both low and high values, being essentially equal to 200 msec at $PW = 40$ and 80 msec, then increasing to become equal to $\overline{L}_S = 255$ msec at $PW = 160$ and 200 msec. The third variable, \overline{L}_{SS} was relatively constant at a value significantly higher than \overline{L}_S for PW between 40 and 120 msec, but thereafter decreased to \overline{L}_S as PW increased. The two upper curves (\overline{L}_{SP} and \overline{L}'_{SP}), representing the total latencies for both Type I and Type II responses, differed markedly at low PW 's (40 and 80 msec) but then converged toward and ran parallel to the value $\overline{L}_S + PW$ as PW increased. All curves have been extended to indicate their expected values at $PW = \overline{L}_S = 255$ msec. The extension of \overline{L}_{SP} to a point 30 msec greater than \overline{L}'_{SP} at $PW = 255$ msec reflected the time required to execute the first saccadic response of 5° amplitude.

The relationship of several derived latency variables to PW is plotted in Fig. 7. Of particular interest was the curve $\overline{L}_{SS} - \overline{L}'_{SS}$ which became independent of PW at $PW = 120$ msec and maintained a value of approx 30 msec. This finding provided the justification for the extension of the \overline{L}_{SP} (Fig. 6), $\overline{L}_{SS} - \overline{L}'_{SS}$

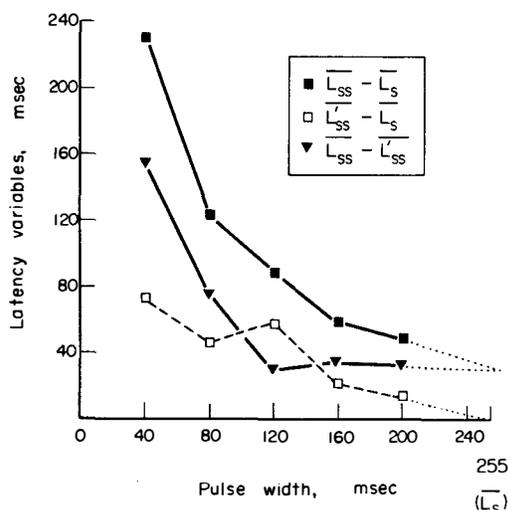


Fig. 7. Variation of several derived variables over pulse width. Note the independence of $\overline{L_{SS}} - \overline{L_{SS}}$ for higher pulse widths. Dotted extensions show expected values at a pulse width of 255 msec ($\overline{L_S}$).

and $\overline{L_{SS}} - \overline{L_S}$ curves (Fig. 7) to the values shown at $PW = 255$ msec. The curve $\overline{L_{SS}} - \overline{L_S}$ was the "cancellation time" of Wheelless *et al.*, (1966).

The plot of $\overline{L_{SS}}$ over PW is essentially the same curve as $\overline{L_{SS}} - \overline{L_S}$ (Fig. 7) and was not diagramed. The only remaining variable, $\overline{L_{PS}}$, showed a predictable monotonic decrease with increasing PW and was not particularly informative.

DISCUSSION

For consistency, the matrix nomenclature will be used exclusively when referring both to this study and to the previous works of others. Table A1 in the Appendix lists the equivalent symbols used by others.

Intersubject variability

The intersubject variability in saccadic latencies revealed in this study was analogous to our findings in an investigation of the saccadic velocity-amplitude relationship (Boghen, Troost, Daroff, Dell'Osso and Birkett, 1974). Despite the numerical differences in specific latency variables among subjects, their general relationships to PW were similar from subject to subject. There were, however, several instances where certain subjects demonstrated individualistic characteristics such as failure to respond to short PW 's with a Type I response, or failure to respond to 200-msec PW 's with a Type II response. This inherent variability, together with possibilities of strong individual peculiarities, should warn against generalizations based upon results from a small number of subjects.

Some of the differences between our own and previous studies might be explained by the small sample sizes used by others. $\overline{L_{PP}}$ was reported as not being a function of PW (Täumer *et al.*, 1972) and $\overline{L_{PP}}$ was found to be less than $\overline{L_S}$ for all PW (Wheelless *et al.*, 1966; Komoda *et al.*, 1973). In our study of ten subjects, we found that $\overline{L_{PP}}$ was a function of PW and $\overline{L_{PP}} \lesseqgtr \overline{L_S}$, depending on PW . Previous studies have concluded that \overline{SI} was a function of PW (Täumer *et al.*, 1972; Komoda *et al.*, 1973) and that $\overline{SI} < PW$

(Täumer *et al.*, 1972). While our results confirmed the former, they also showed that $\overline{SI} > PW$. The variable, $\overline{L_{SS}}$ has been reported as being equal to a constant (Wheelless *et al.*, 1966), but our data, in agreement with Komoda *et al.* (1973), indicated that it was a function of PW . We did concur with the previous findings that $\overline{L_{SS}}$ was greater than $\overline{L_S}$ for all PW (Wheelless *et al.*, 1966; Komoda *et al.*, 1973). (A summary of the above relationships may be found in Table A2 in the Appendix which shows the percentage of our subjects falling into each grouping.) A final comparison indicates that our finding of $\overline{L_{SS}}$ being a function of PW and greater than $\overline{L_{PP}}$ was contrary to Täumer *et al.*, (1972).

To the casual observer our results might seem completely at variance to those of Täumer *et al.*, (1972), except for our agreement that \overline{SI} is a function of PW . Using Täumer's work as an example, the following discussion will show why direct comparisons between different studies of ostensibly the same variable should not be made without prior scrutiny of respective methodologies. We studied intersubject variations, whereas Täumer *et al.*, conducted detailed analyses of single subject responses; although some data for three subjects were presented, most of the data and analysis was from one subject (DH). Additional considerations may also be relevant. To insure that the data reflect true disjunctive latencies to multimodal stimuli, at least two different target modes should be possible for any target presentation, and the experiment should be designed to eliminate predictive responses (Saslow, 1967b). Our methodology, consisting of a bimodal target possibility, with direction and PW randomized, presented at a variable time after an audible warning, satisfied the proper design criteria for doubly disjunctive latencies (Wheelless *et al.*, 1966). Täumer *et al.* used unimodal inputs (staircase and pulse-steps; both are two-step target movements), with randomized direction and PW 's which were presented at a constant rate of one target every 2.5 sec. Such periodicity and constancy of a two-step nature leads to predictive responses and is perhaps the reason for their low values of $\overline{L_{PP}}$ (160–180 msec) and their finding that $\overline{L_{PP}}$ was not a function of PW . Their study also included an obligate second target jump; only its timing and direction were unknowns. Thus, the alternative that a second target jump would not occur (i.e. the target movement would simply be a step change in position) was eliminated from the possibilities facing the subject. This would explain their finding that $\overline{L_{PP}}$ and $\overline{L_{SS}}$ were independent of PW . Their values for these variables were lower than ours because they represented only step responses to *expected* target steps of randomized direction; Becker and Fuchs (1969) have shown that increased uncertainty of target motion results in increased latencies. Thus, each study produced results compatible with their experimental design. What emerge from this comparison are not necessarily contradictory findings but different, equally valid, relationships among the same latency variables resulting from the saccadic system's performance of entirely different functions dictated by the particular target presentations. The implications for modeling the system(s) are that several operational modes must be possible, each selectable by some chosen biases dependent upon the expected tasks and input signal alternatives.

System observations

The variation of $\overline{L_{PP}}$ with PW (Figs. 2 and 6) revealed the effect of early conflicting input data on this initial response latency and also of new input information occurring during later stages of the decision making. These demonstrated that visual inputs were continuously available to the saccadic system and not intermittently sampled. Specifically, the early arrival of conflicting data interfered with the evaluation of target direction and approximate distance (Komoda *et al.*, 1973) and imposed the additional decision of whether to respond to the first target displacement at all. Alternatively, if the new target information arrived later in decision making, the time required to make a Type I response was reduced. Since the target was no longer at θ_1 degrees, the eye movement to that area was of no benefit in foveating the target (in fact, the eye movement actually increased the retinal error to the θ_2 degree target). The advantage of decreasing L_{PP} was simply to reduce the total time (L_{SP}) required to foveate finally the target at θ_2 degrees. This suggests that temporal efficiency is inherent in the saccadic decision-making process to minimize the time to foveate a target at its final position. The region of decision making, during which L_{PP} can be reduced, was limited to some time interval in the region of 160 msec. Outside this range, the occurrence of a second target jump did not serve to reduce the latency of the response to the initial jump (L_{PP} actually increased for small PW).

The time saved by cancelling the first response and making a Type II response for low PW 's is evident in the upper portion of Fig. 6. For PW 's less than 120 msec the total latency for a Type II response (L_{SP}) was significantly lower than for a Type I response (L_{SP}). Beyond a PW of 120 msec, the time difference between L_{SP} and L'_{SP} remained constant at a value equal to the time necessary to actually execute the first saccade (about 30 msec for a 5° saccade). This dramatizes the significance of the previously mentioned changes in $\overline{L_{PP}}$ caused by the occurrence of a second target jump at various PW 's. The decrease in $\overline{L_{PP}}$ for mid-range PW 's was sufficient to offset the increase in \overline{SI} and preserve the slowly increasing nature of $\overline{L_{SP}}$ at a rate equal to $\overline{L_S} + PW$. From these curves it can be predicted that the transition from Type II to Type I responses should occur in the region about $PW = 120$ msec since little time savings resulted from response cancellation for greater PW 's. Also supportive of such a prediction is the variation of cancellation time with PW ($\overline{L_{SS}} - \overline{L_S}$ in Fig. 7) which reveals a sharp drop for $PW > 120$ msec after remaining fairly constant at levels between 50 and 75 msec for lower PW 's. The linear increase of per cent Type I responses over PW (Fig. 5) was consistent with the notion of temporal efficiency. At PW 's greater than 128 msec, the system response was Type I greater than 50 per cent of the time. Extension of this curve to a PW of 255 msec, which was equal to the mean latency for a simple step response ($\overline{L_S}$), yielded the expected result of 100 per cent Type I response. Extension in the other direction resulted in the prediction that for $PW \leq 12$ msec, no Type I responses will occur—a statement, in the context of this linear model of mean behavior of the saccadic system, that should not be confused, or regarded as incompatible, with the known ability of subjects to respond

in a Type I manner to PW 's as low as 1 msec (Barnes and Gresty, 1973). What the system is *capable* of doing under one set of experimental conditions and what it will *probably* do under another set of conditions are different, but not contradictory, responses. This important concept must be considered when modeling such a system.

We extended the curves of Figs. 5, 6 and 7 to their expected values at $PW = \overline{L_S} = 255$ msec and, in most cases, the values chosen were easily derived from the data or by defining relationships among the variables. The extension of $\overline{L_{SP}}$ to a value 30 msec greater than that of $\overline{L'_{SP}}$ (Fig. 6) requires comment. This result could be predicted from simple observation of the two curves up to $PW = 200$ msec and realization that, even in the limiting case where $PW = 255$, L_{SP} must always be greater than L'_{SP} by the amount of time necessary to execute the additional (i.e. the first) saccade required for a Type I response. This is further confirmed in Fig. 7 where the curve, $\overline{L_{SS}} - \overline{L_{SS}}$ remains at a value of 30 msec for all $PW > 120$ msec, therein demonstrating independence of PW .

In summary, the presence of cortical decision-making in the saccadic subsystem requires careful experimental procedure if one is to eliminate, or minimize, the inherent predictive ability of such a pathway. Specifically, by maintaining unpredictability of target mode, data more relevant to casual, non-predictive modeling are obtained. In addition, subject variability requires a large enough sample population be tested to eliminate biases due to individualistic responses. Our data suggest multiple, parallel pathways are operant in saccadic decision-making and that the ultimate decisions are influenced by the temporal relationships of the input presentations toward the end of minimizing the total latency from initial target motion to final eye movement. To achieve this temporal efficiency, responses may be cancelled or have their latencies decreased; the former occurs when early conflicting input presentations cause increased latencies to any response to the initial target motion. The increase in $\overline{L_{PP}}$ for low PW is consistent with the findings of Levy-Schoen and Blanc-Garin (1974) that motor programming of a saccade is linked to perceptual localization and cannot be set in operation while this localization is impaired (such as the case for low PW where two target localities appear in a very small time interval). The concept of "grouped programming" of these authors is also supported by our finding that \overline{SI} decreases to 200 msec for low PW from its value of 255 msec = $\overline{L_S}$ at higher PW .

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APPENDIX

Two tables are provided herein to facilitate comparisons of the results of various authors (Table A1) and to provide a profile of the 10 subjects used for this study with regard to several key variables (Table A2). For each of these variables (\overline{L}_{PP} , \overline{SI} and \overline{L}_{SS}) the corresponding matrix shows the number of subjects for whom the variable was either a function of PW , not a function of PW or equal to a constant. In addition, the number of subjects in each of these categories is shown with relation to the comparison of the variable and the mean step-response latency, \overline{L}_s .

Table A1

	Wheless (1966)	Täumer <i>et al.</i> (1972)	Komoda <i>et al.</i> (1973)
L_s	T_s		
L_{PP}	T_{ps}	RT_1	L_p
L_{PS}	$T_{ps} - W$		
L_{SP}		RT_2	
L_{SS}			
L_{SP}	T_{sp}		
L_{SS}	$T_{sp} - W$		L_f
SI		SI	L_s^*
PW	W	V	

$L_s = SI$ —saccadic duration.

Table A2

\overline{L}_{PP}	$< \overline{L}_s$	$\cong \overline{L}_s$	$> \overline{L}_s$	
f(PW)	3	4	2	90*
#f(PW)	0	1	0	10
	30	50	20	%

\overline{SI}	$< \overline{L}_s$	$\cong \overline{L}_s$	$> \overline{L}_s$	
f(PW)	5	3	0	80*
K	1	0	1	20
	60	30	10	%

\overline{L}_{SS}	$< \overline{L}_s$	$\cong \overline{L}_s$	$> \overline{L}_s$	
f(PW)	0	2	4	60*
#f(PW)	0	1	3	40
	0	30	70	%