Latency of peripheral saccades

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Displaying the point of gaze to the observer in addition to a point target provides a secondary visual feedback (2VFB). Eccentric fixation is achieved using a biased 2VFB to yield an experimentally imposed "eccentric fovea." The target is suddenly moved to a new position and the task is to regain it, in the "eccentric fovea." It is found that the pattern of eye-movement response consistently starts with saccadric foveal exploration of the target, but its latency has twice the duration of a regular voluntary saccade. Practice, however, makes for the shortened latency tending asymptotically to the regular saccadic duration.

INTRODUCTION

When a subject is instructed to fixate on a point target and the target suddenly moves to a new position, time elapses between this displacement and the beginning of eye movement towards the new position. This effect is known as saccadic latency, and has been studied extensively ever since its existence was reported in the classic work of Dodge and Cline.[1] The average latency under normal conditions is approximately 200 ms, with a standard deviation of 30 ms,[2–4] but is affected by a variety of factors such as stimulus amplitude and intensity[5,6]; it is also known that prediction and practice[4,7] may shorten it, whereas fatigue,[8] neurological diseases,[9] and amblyopia[10] may lengthen it.

All the above refers to saccades that subserve foveation—the natural mode of exploration of a suddenly appearing peripheral object of interest.

Secondary visual feedback (2VFB) is a visual signal derived from continuous measurement of eye position and provides an indication of the point of gaze. 2VFB may be eccentrically displaced by biasing the measured eye position signal; subjects

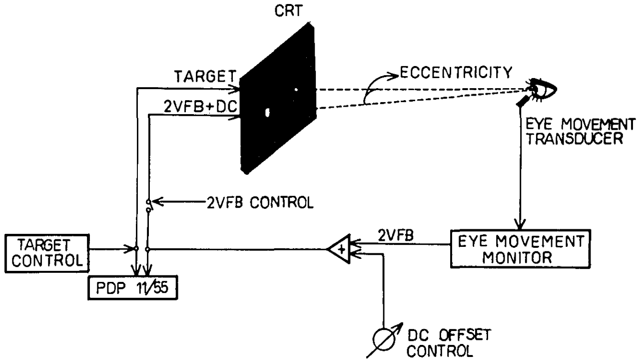


FIG. 1. Schematic diagram of setup for peripheral-saccade task, with the aid of secondary visual feedback (2VFB). The 2VFB signal is derived from continuous measurement of eye position and may be eccentrically displaced by addition of a dc signal.

are able visually to superimpose 2VFB onto the visual target and thus achieve and maintain eccentric fixation.[11] Having thus experimentally imposed "eccentric fovea" fixating on a point target, the target can be displaced to a new position as a stimulus analogous to the one used as a trigger for saccade. The question arises whether it is possible to execute a saccade-like quick jump converging the "eccentric fovea" on the target; and, if so, what is the latency characteristic of this peripheral saccade and how does it vary as a function of eccentricity and practice.

In this study it is shown that the task is performed consistently as a sequence of eye movements starting with foveal saccadic exploration of the target in its new position. Being a foveal saccade, the first quick jump would be expected to have a regular latency of about 200 ms, but was found to be twice as long. Practice, however, tends to shorten the latency, tending asymptotically to the foveal duration.

METHOD

In fixation on a stationary target or in tracking a moving target, there is involved a feedback process that serves for foveation of the target. The error in this feedback loop is equal to the angular distance of the target image from the fovea.[12] In addition to this "built in" primary visual feedback, there is the possibility of closing external loop by superimposing the eye position signal on the target display system. This provides a secondary visual feedback,[11] in which the position error equals the distance between the target and the 2VFB signal.

Thus, two distinguishable point signals are displayed on a cathode-ray tube (CRT): the target and a 2VFB. Target position is chosen by the experimenter, whereas the position of the second beam is controlled by the signal acquired from the eye movement monitor. A dc shift, which determines the degree of eccentricity (see Fig. 1), is added to the eye position signal. As long as the subject fixates on the target, there is a task-position error, defined by the spacing of the two-point signal. The subject is instructed to superimpose the two points by means of eye movements in order to eliminate this error. When this is achieved, both points fall on the same point of the retina whose eccentricity is determined by the dc biasing signal, and which is characterized accordingly as the

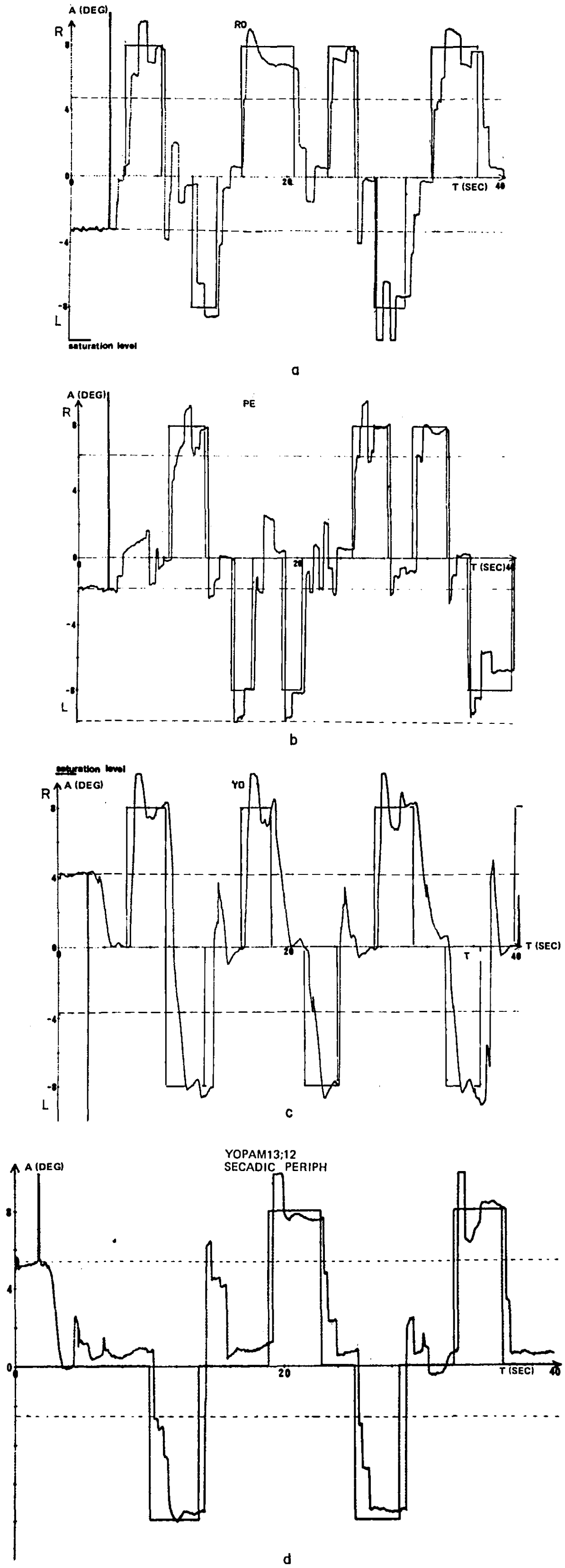


FIG. 2. Examples of typical eye movement patterns elicited in peripheral-saccade task (solid line indicates 2VFB including dc), superimposed on target position (solid fine line). Instant of closing the loop is indicated by the impulse, and foveation position (for both left and right) by broken lines. (a) Subject RO, 3.5° left eccentricity; (b) Subject PE, 2° left eccentricity; (c) Subject YO, 4° right eccentricity (note smooth response); (d) Subject YO, 5° right eccentricity (regular response).

TABLE I. Examples of latencies measured in two sessions.

Subject RO—Session 5 Target position	Saccadic latency	Subject YO—Session 10 Target position	Saccadic latency
R	1950[a]	*R*	230
C	440	*C*	310
L	370	*L*	190
C	370	*R*	260
R	400	*C*	260
C	440	*L*	240
L	330	*C*	400
C	420	*L*	230
R	260	*C*	1160[a]
C	330	*R*	330
L	400	*C*	330
C	400		
Mean	378	Mean	278
SD	51	SD	59

[a] Excluded from mean and SD calculations. R: right; C: center; L: left.

"eccentric fovea." Once such eccentric fixation is achieved, the target is suddenly moved to a new position to the right or to the left of the eccentric fovea. The subject is then instructed to execute peripheral saccade—a sudden shift of the eye in order to keep the target in register with the eccentric fovea. As before, having the 2VFB superimposed on the target in its new position indicates to the subject achievement of the required task.

Measurement Set-up

Subjects viewed the CRT from a distance of 30 cm (the display spanning a visual field of $\pm 10^\circ$) with the head immobilized by means of a head rest and a bite bar. Only monocular movements of the right eye were recorded, with the left eye covered with an eye patch. Eye position was monitored with the aid of an IR photoelectric device,[11,13] adjusted by means of a micromanipulator having three degrees of freedom. Target position and 2VFB signals were sampled by a PDP-11/55 Computer at a rate of 100 samples per second per channel.

Procedure

In most sessions reported in this communication, eccentricity of about 4° was used and a typical run consisted of 40 s at a specific eccentricity.

A run begins with foveal fixation of the point target at which time there is no 2VFB signal. After about 5 s of foveal fixation, the 2VFB loop is closed abruptly. The subject is instructed to fixate on the target as long as there is no 2VFB, and to superimpose the latter on the target, by moving his eye, when both are present. Whenever eccentric fixation is achieved, the target is moved by the experimenter to a new position of 8° to the right or left of the eccentric fovea. More than ten peripheral saccades can be performed during this 40-s run. Fourteen such runs were repeated with each subject over a period of four weeks, with a few days' interval between each session.

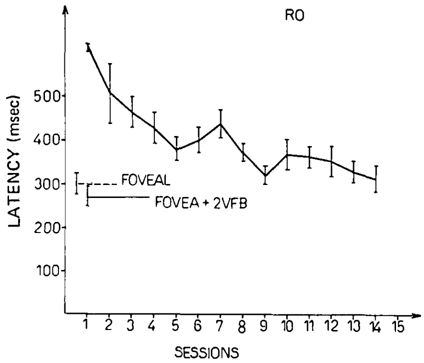
To facilitate later reference, the following classification is in order:

Eccentricity is defined in terms of visual field, not of retinal image.

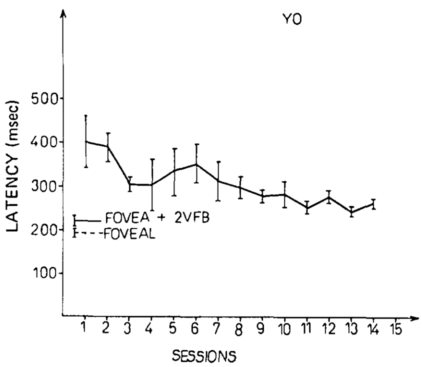
Left eccentricity refers to the case when the 2VFB is presented to the left of the foveated target, which means that the 2VFB image falls on the retina at a point to the right of the fovea [see Figs. 2(a) and 2(b)].

Right eccentricity is defined correspondingly [see Figs. 2(c) and 2(d)].

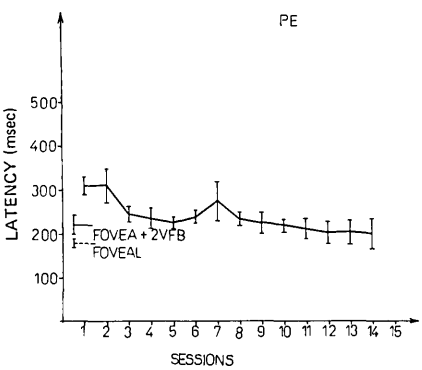
Since the target is moved either to the right or to the left, there are basically four possibilities. In terms of retinal image, however, there are only two distinct configurations: left eccentricity with target movement to the left (identical to the



(a)



(b)



(c)

FIG. 3. Mean latency duration in a session as a function of the number of sessions. Foveal latencies with and without 2VFB are indicated by solid and broken lines, respectively.

TABLE II. Saccadic latencies and task reaction time.[a] Mean ± SD (msec); (number of saccades).

Subject Number of sessions	RO Saccadic latency	RO Reaction time	PE Saccadic latency	PE Reaction time	YO Saccadic latency	YO Reaction time
1	610 ± 14 (3)	···	310 ± 39 (7)	690	397 ± 119 (3)	1190
2	508 ± 134 (5)	···	311 ± 78 (6)	630	388 ± 68 (6)	···
3	466 ± 74 (5)	770	247 ± 40 (8)	630	303 ± 33 (3)	840
4	431 ± 76 (9)	550	233 ± 49 (11)	770	300 ± 122 (7)	···
5	378 ± 51 (11)	540	225 ± 35 (13)	560	333 ± 114 (6)	740
6	403 ± 65 (8)	440	241 ± 28 (13)	810	352 ± 88 (9)	580
7	442 ± 65 (5)	370	275 ± 90 (14)	670	308 ± 93 (11)	1160
8	373 ± 41 (8)	420	234 ± 29 (13)	600	293 ± 46 (11)	650
9	321 ± 42 (9)	···	226 ± 55 (13)	560	276 ± 34 (16)	810
10	372 ± 74 (15)	670	218 ± 27 (11)	···	278 ± 59 (10)	810
11	364 ± 54 (15)	700	212 ± 43 (12)	460	250 ± 29 (13)	1060
12	354 ± 69 (14)	600	203 ± 48 (11)	700	276 ± 33 (12)	810
13	329 ± 48 (17)	650	205 ± 54 (10)	560	242 ± 25 (14)	860
14	313 ± 58 (18)	600	202 ± 66 (15)	490	260 ± 30 (10)	950
Foveal	300 ± 44 (25)		177 ± 23 (19)		192 ± 22 (22)	
		573 ± 119 (11)		625 ± 98 (13)		846 ± 206 (12)
Foveal +2VFB	271 ± 43 (17)		220 ± 47 (27)		213 ± 24 (29)	

[a] The *reaction time* refers to the eccentric fixation task and is the latency of the first "antisaccade" (Ref. 14). The *saccadic latency* refers to the first foveal exploration in a peripheral saccade task.

case of right eccentricity with target movement to the right); and left eccentricity with target movement to the right (identical to the case of right eccentricity movement to the left), so the distinction is between target movement *in the direction* of the eccentricity and target movement *against the direction* of the eccentricity.

RESULTS

Peripheral saccades are executed quite easily even by an untrained subject. Unlike saccades that subserve foveation, in this case convergence to the "eccentric fovea" is achieved by means of an oscillatory pattern (see Fig. 2) quite similar to the transient pattern of eye movements entailed by the eccentric fixation task.[11] Here, however, we consistently find that the first step in the response is a saccade that serves for foveal exploration of the target in its new position; in most cases this is followed by a sequence of saccades converging on the target. Figure 2 illustrates examples of eye movement patterns typical of the peripheral saccade task obtained from three different subjects. It should be noted that while subjects RO and PE (a and b in Fig. 2, respectively) have sharp jumps, and the response therefore exhibits a combination of square wave and staircase patterns, subject YO (c in Fig. 2) has a relatively smooth response pattern that nevertheless has a similar sequencing of jumps. (The reason for his distinct control capability may be due to his deafness as a result of meningitis, which he had some 30 years ago.) It appears as though the pattern has been processed by a low-pass filter. This subject, who is very attentive in visual tasks, is capable of adopting a smoothing strategy, in which case—according to his explanation—he gains better control over the 2VFB signal. However, he can switch strategies when asked to respond in the regular sharp mode (d in Fig. 2).

Whenever the "eccentric fovea" corresponds to left (right) eccentricity and the target jumps further away to the left (right), the pattern of eye movements is characterized by damped square-wave oscillation. In terms of the task, the first foveal exploration saccade appears as an overshoot with

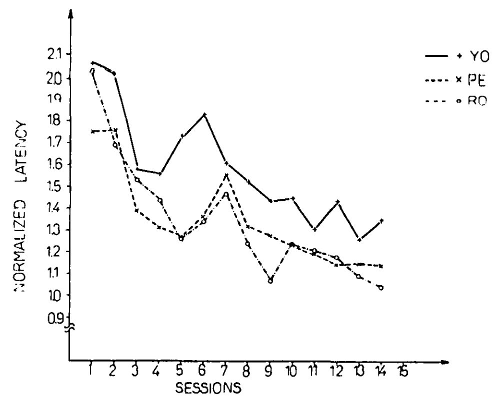


FIG. 4. Mean latency duration, normalized with respect to foveal saccade latency, as a function of the number of sessions.

amplitude equal to the degree of eccentricity, whereas in the case of left (right) eccentricity and a target jump to the right (left), crossing the fovea, the eye movements have a damped staircase pattern; here too the first step of the response is foveal exploration.

Each of the patterns in Fig. 2 starts with 3–4 s of egocentric foveal fixation. The impulse indicates the instant of closing the loop—presenting the 2VFB on the screen. An untrained subject (in an eccentric fixation task) would respond with a saccade towards the 2VFB signal after a latency of the order of 200 ms typical of his foveal saccadic latency. To execute the required task takes, however, a much longer reaction time—the time elapsing between closing the loop and the first saccade. It should be noted that this first saccade, elicited by closing the loop, is different from a regular foveal saccade, as it drives the retinal image of the target further away from the fovea. It is what Hallett calls "antisaccade."[14] Reaction time durations from 14 sessions and their mean values are presented in Table II.

The latency of the first foveal exploration saccade exceeds considerably the duration of a regular voluntary saccade; this is so in spite of the functional similarity of the two in the sense that both bring the target in register with the fovea. Two examples of raw data extracted from typical sessions are given in Table I. In calculating the mean and standard deviation (SD) of saccadic latencies we excluded extremely long durations ($T >$ mean + 3 SD). These, such as the two indicated in the examples given in Table I, are presumably due to momentary lack of attention. Mean and SD of latencies extracted from 14 consecutive sessions are summarized in Table II and Fig. 3. Each of the peripheral saccade latency data points is averaged over 3–18 saccades, according to the number of jumps covered during the session. For each of the three subjects, we also measured the two reference points of foveal-saccadic latencies with and without 2VFB. In the first session of a peripheral saccadic task, the duration of the latency is about twice as long as the duration typical of a voluntary foveal saccade. Practice, however, tends to shorten the latency, as demonstrated in Fig. 3, tending asymptotically the regular saccadic duration.[15,16] Since there is intersubject variability in the duration of foveal saccade, we normalize the data in order to compare the effect of practice on the performance of three subjects. This is shown in Fig. 4.

DISCUSSION

In our earlier report,[11] it was shown that it is feasible to fixate with extrafoveal vision, using 2VFB. It thus becomes possible to select an extrafoveal subfield and consider it as an "eccentric fovea" in the sense of having this new fovea track and/or fixate a point target. Transition to an eccentric fovea is not a straightforward process. To begin with, there is a natural tendency to register the target within the foveal field even when eccentric fixation is achieved, and it is reasonable to assume that the system exerts inhibition to suppress that tendency. This is presumably an important factor determining the processing time required to execute the first saccade in the proper direction after closing the 2VFB loop; the same can be inferred from the fact that an untrained subject responds with the first jump in the wrong direction, in order to achieve foveation of the 2VFB signal, in which case the latency (and apparently also the processing time) is only about 200 ms. Another factor that may contribute to lengthening the reaction time of this first jump on closing the loop is the complexity of the task in terms of "programming." Unlike foveation, where the saccadic system has to program the jump with reference to the same point (namely the fovea), here the starting point is again the fovea but the end point is the "eccentric fovea," which calls for reversal of movement. The complexity is due in part to the presence of two independent point targets; indeed, it has been shown that increasing the dimensionality of the stimulus lengthens the reaction time.[17]

The currently discussed peripheral saccades have as their starting point the "eccentric fovea," where fixation can be maintained by a shift of attention,[11,18] combined with an inhibitory effort. In order to understand their characteristics, one must therefore consider the conditions imposed by both the starting and end points. In terms of the task, unlike the first saccade for eccentric fixation, we have here the same starting and end point. However, since, as we found, the first saccade is foveal exploration, we have the opposite of what we had in eccentric fixation: namely, the starting point is eccentric but the end point is foveal. As shown in the results, the latency in this case is about twice as long as the latency of a regular foveal saccade. While this may appear surprising at first glance, it is reasonable to assume that extra processing time is needed to eliminate the inhibitory state. The lengthening of the latency is also due to the fact that we have here, as before, a dual target situation.

A consistent, important finding is the strong influence of practice on peripheral saccade latency. Normalizing the duration with respect to the latency of foveal saccades, we find that in spite of intersubject variability, due in part to visual fidelity and to individual attentive capability, the duration in the first session is about twice as long as the foveal-saccade latency, which is also the asymptote to which a subject tends within less than 14 sessions. It should be noted that there is no improvement in reaction time, the latency of the first saccade, with practice. This is consistent with Hallett's findings concerning "antisaccade" latencies. Quantitatively, we find almost twice as long reaction time in our task, in comparison with the "antisaccade" latencies. This indicates that the extra time required in order to execute the first saccade is not due solely to direction reversal which characterizes both tasks. This may provide further support for the hypothesis of the existence of inhibitory signal in the dual task.

In our earlier study of eccentric fixation, using 2VFB, we have shown the relationship between acuity as a function of eccentricity and performance in eccentric fixation task. It is therefore interesting to note that results of practice effect similar to ours were obtained by Johnson and Leibowitz in a study of peripheral visual resolution.[19] However, these practice effects were not observed for the near periphery, the central field spanned in our study.

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[1] R. Dodge and T. Cline, "The angle velocity of eye movements," Psychol. Rev. 8, 125–157 (1901).

[2] G. Westheimer, "Mechanism of saccadic eye movements," Arch. Ophthalmol. **52,** 710–724 (1954).

[3] G. Westheimer, "Eye movement responses to horizontally moving visual stimulus," Arch. Ophthalmol. **52,** 932–941 (1954).

[4] L. Stark, G. Vossius, and L. R. Young, "Predictive control of eye tracking movements," IRE Trans. Human Factors Electron. **HFE-3,** 52–57 (1962).

[5] L. L. Wheeless, G. H. Cohen, and R. M. Boynton, "Luminance as a parameter of the eye movement control systems," J. Opt. Soc. Am. **57,** 394–400 (1967).

[6] A. E. Bartz, "Eye-movement latency, duration, and response time as a function of angular displacement," J. Exp. Psychol. **64,** 318–324 (1962).

[7] R. B. Hackman, "An experimental study of variability in ocular latency," J. Exp. Psychol. **27,** 548–558 (1940).

[8] W. R. Miles, "The reaction time of the eye," Psychol. Monog. **47,** (whole No. 212), 268–293 (1963).

[9] R. W. Buloh, V. Honrubia, and A. Sills, "Eye tracking and optokinetic nystogmus: results of quantitative testing in patients with well-defined nervous system lesions," Annals Oto. Rhinol Laryngol. **86,** 108–114 (1977).

[10] K. J. Ciuffreda, R. V. Kenyon, and L. Stark, "Increased saccadic latencies in amblyopia eyes provide further evidence for processing delays over the central retina," (private communication, 1978).

[11] Y. Y. Zeevi, E. Peli, and L. Stark, "A study of eccentric fixation with secondary visual feedback," J. Opt. Soc. Am. **69,** 669–675 (1979).

[12] L. R. Young and L. Stark, "A discrete model for eye tracking movement," IEEE Trans. Mil. Electron. **MIL-7,** 113–115 (1963).

[13] A. T. Bahill, M. R. Clark, and L. Stark, "Dynamic overshoot in saccadic eye movements is caused by neurological control signal reversals," Exp. Neurol. **48,** 107–122 (1975).

[14] P. E. Hallett, "Primary and secondary saccades to goals defined by instructions," Vision Res. **18,** 1279–1296 (1978).

[15] Statistical trend analysis (see Ref. 16) using F test of the combined delay data (for the three subjects) indicates the existence of a trend—confidence level of 99%. The best fit linear trend is of -11.2 ± 2.1 ms/session.

[16] A. L. Edwards, Trend analysis, in *Experimental Design in Psychological Research* (Rinehart, New York, 1960).

[17] P. Morasso, G. Sandin, V. Tagliasco, and R. Renato Zaccaria, "Control strategies in the eye-head coordination system," IEEE Trans. Syst. Man Cybern. **SMC-7,** 639–651 (1977).

[18] H. Von Helmholtz, *Handbuch der Physiologischen Optik.* Translation from German edition, edited by J. P. C. Southall (Dover, New York, 1962).

[19] C. A. Johnson and H. W. Leibovitz, "Practice Effects for Visual Resolution in the Periphery" (private communication, 1978).