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The influence of saccade length on the saccadic suppression of displacement detection

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The decrease in sensitivity to spatial displacement which accompanies a voluntary horizontal saccadic eye movement was measured as a function of the length of the saccade. Threshold for detecting the displacement increased linearly from about 0.3° to 1.2° as saccade length increased from 4° to 12°. The variability (standard deviation) of the discrimination increased linearly with saccade length as well, and hence also linearly with the displacement threshold. These results, along with our previous finding that the increase is not a consequence of the saccadically generated spatiotemporal smearing of the retinal image (Li & Matin, 1990), support the proposal that displacement detection is based on a constant internal signal/noise ratio whose denominator is a measure of the variability of the extraretinal signal regarding eye position, and that the reduction in sensitivity is a result of a transient increase of this variability in the temporal neighborhood of a saccade.

Sensitivity to spatial displacement is considerably reduced in the presence of saccadic eye movements. While the threshold for vernier offset during steady fixation can be as low as 2″ of arc (see Matin, 1972, 1986, for reviews), the threshold for detecting visual field displacement during a 10° voluntary saccade can be as large as 1.5° (Li & Matin, in press). Since all of the important conditions are not comparable between these two sets of measurements, the increase of 2,700× between them is by no means a fair one to employ in direct assessment of the consequences of intrusion by processes related to the saccade alone. Nevertheless, the smaller value provides an indication of the inherent capability of spatial discrimination in the visual system, and the larger value provides an indication of how poor spatial discrimination can be in the presence of a voluntary saccade. That the largest part of the middle ground between 2″ and 1.5° is, in fact, due to the intrusion of the saccadic process can be discerned by the twin facts that vernier thresholds during steady fixation do not rise above 1-2 minarc under any reasonable set of conditions and that displacement thresholds below about 45 minarc in the presence of 10° saccades have not been reported. In fact, even for saccades as short as 2° 11′, displacement thresholds can be larger than 10 minarc (L. Matin, E. Matin, & Pearce, 1969; L. Matin, E. Matin, & Pola, 1970; L. Matin & Pearce, 1965).

Several significant characteristics of the sensitivity loss have been described. Bridgeman and his colleagues have reported that the time course of the sensitivity reduction is similar to the time course of saccadic suppression of visibility (Bridgeman, Hendry, & Stark, 1975; Stark, Kong, Schwartz, Hendry, & Bridgeman, 1976). The threshold begins to rise shortly before the beginning of the saccade, it peaks at a point somewhat before the middle of the saccade, and it decreases thereafter, to reach values characteristic of steady fixation shortly after the saccade is over. Li and Matin (1990) have reported that increased duration of postsaccadic exposure of the displaced field from 33 msec to 400-500 msec brings about an improvement in sensitivity by a factor of two to three times for 10° saccades, and that additional increases of duration produce no further changes. They have also found that the retinal stimulus during the last three fourths of the saccade can be entirely eliminated (by electronic means) without any influence on the sensitivity loss. Since stimuli with brief postsaccadic exposures contain a visible, spatially extended, and smeared segment corresponding to the variation in retinal location of the saccadic stimulus (E. Matin, Clymer, & L. Matin, 1972; L. Matin & E. Matin, 1972), and since electronic elimination of the segment generating the visible smear does not influence the threshold for spatial displacement, it is clear that the saccadic suppression of displacement results from some loss of fidelity in processing the extraretinal information relating to eye position and eye position change, rather than to processes that sharpen the retinal image.

However, more basic information regarding the saccade-related loss of spatial sensitivity is needed. Bridgeman et al. (1975) have reported that increases in the sensitivity loss accompany increases in saccade length, but the form of the relation governing the increase has

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not yet been quantified. In the present article, we describe an experiment in which the displacement threshold was measured as saccade length was manipulated systematically, and we demonstrate that the increase of threshold as saccade length increases is linear.

METHOD

The experiment was carried out in a completely dark room on 2 psychophysical observers who monocularly viewed a stimulus display presented from the otherwise completely dark face of a computer-controlled cathode-ray oscilloscope (CRO) while the horizontal movements of the viewing eye were continuously monitored. The spatiotemporal characteristics of the visual display and trial-by-trial sequencing were determined by a program on a Linc-8 computer (DEC), which also recorded on-line the parameters of the stimulus display, the measurements of eye position, and the psychophysical report of the observer, and tabulated the experimental results of each experimental session.

Measurement of Eye Movements

The seated observer's head was stabilized by a biteboard and forehead rest. The horizontal position of his right eye was continuously monitored with a Gulf and Western Model 200 eye movement monitor, which recorded the difference in signals from the regions near the left and right limbal junctions of the eye that resulted from the reflected invisible infrared radiation irradiating the front of the eye from a source that was stationary with respect to the head. The unit is insensitive to vertical ocular displacements (both rotations and translations), since these produce a simultaneous increase or decrease in the signals from both junctions, leaving the signal difference essentially unaffected. With this system, rotational differences in horizontal eye position over short time intervals (100 msec) can be readily resolved to about 0.04°; over longer time intervals (5-10 minutes), reliability is about 15 minarc. The short-time resolution limit is essentially set by the 4-msec time constant of the eye movement monitor, which determined the upper limit of temporal resolution of the entire recording system, and hence also the upper limit of spatial resolution for the measurement of eye position during rapid eye movements. The long-time limit on reliability is essentially a consequence of some degree of sensitivity of the unit to horizontal ocular translation. The calibration of eye position was linear over the entire 20° range.

Stimulus Display

The CRO was a 23-in. (diagonal) Hewlett-Packard unit (No. 6610) with a short-persistence phosphor, the P15.[1] The CRO was interfaced to the computer (housed in an adjacent room) through three 12-bit D/A converters, each of which controlled one parameter of the display (x- and y-axes, location; z-axis, intensity). Each luminous point of the display was actually a vertical bar 4′ in height and 1′ wide, with a luminance of 1.3 mL. The observer viewed the display with the right eye from a distance of 91 cm; the left eye was occluded by an eye patch.

Observers

The corrected Snellen visual acuity of each of the 2 observers (G.D. and W.L.) was 20/20. For W.L., correction was provided by a −3.00 diopter lens between the viewing eye and the face of the oscilloscope and was located at a distance of 6 cm from the viewing eye; G.D. wore correcting corneal contact lenses. Each observer was provided with extensive practice prior to the collection of data in each experiment, in order to minimize any influence of variations in practice during the experiment itself.

The Course of a Single Trial

Figure 1 outlines the essential spatial and temporal characteristics of the stimulus display that was used to measure displacement

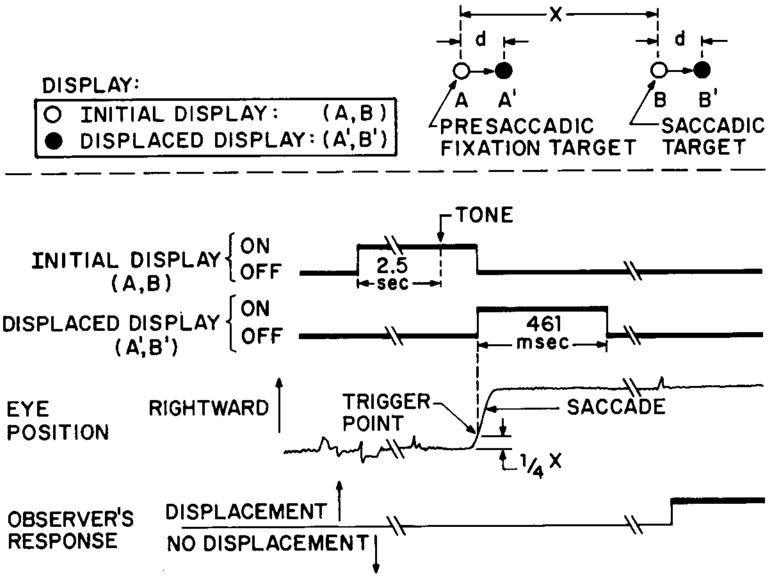

Figure 1. The spatial (above) and temporal (below) outline of a single trial: The initial display was made up of identical targets, A and B, separated by a distance x, where x was 4°, 5°, 6°, 8°, 10°, or 12°. The observer fixated Target A in the initial display; 2.5 sec following display onset, a tone was presented, which signaled to the observer that he was free to execute a saccade from A to B. When the eye crossed the trigger point, at one fourth of the projected saccade distance (x) from A, the initial display was extinguished. The displaced display (A′, B′) was presented for a duration of 461 msec. The observer reported whether or not he perceived a displacement.

thresholds in the presence of voluntary saccadic eye movements during each trial of the experiment. Each trial began with the simultaneous onset of two single points, A and B.[2] The observer fixated Point A. A brief tone, presented 2.5 sec after the onset of the initial display, instructed the observer to execute a saccade to Point B as soon as he was ready to do so. When the eye reached the trigger point, one fourth of the projected saccade's distance to the right of the average eye position during the fixation period, both A and B were instantaneously extinguished, and at the same time a second display (A′, B′) was presented that was identical to the first display yet was displaced from it by a variable distance, *d*, to the right. The second display was extinguished after an exposure period of 461 msec. During the subsequent 2.5-sec period of complete darkness, the observer reported whether or not he had detected a displacement of the display during the time period associated with the saccade, by pressing one of two switches to signal "yes" or "no."

The two points, A and B, were horizontally separated by a distance, *x*, of 4°, 5°, 6°, 8°, 10°, or 12°. For each separation between A and B, the displacement magnitude, *d*, could assume one of six possible values on a given trial. These values were varied from trial to trial according to a randomized block design, with each block containing 16 trials. Within each block, each of the six values of *d* was presented twice; on the other 4 trials, the second display was not displaced ($d = 0$). The set of possible values of *d* was different for the different saccade sizes and was set to span the uncertainty range for each saccade size.

Each experimental session was made up of groups of 4 or 5 blocks of trials and lasted about 20 min (a "run"). Brief rests (10 min) were given between runs. Between three and five such runs made up a session, with each run involving a different *x*. Thus between 240 and 400 trials were taken in a single session. The data for each *x* was obtained in four to five sessions. The order of *x* within a session was counterbalanced across sessions. Enough sessions were run with each observer at each value of *x* so as to obtain between 26 and 32 trials with each value of displacement (six sessions for G.D., seven sessions for W.L.). The $x = 10°$ condition was not run along with the other *x* values but was part of another experiment in which postsaccadic duration was varied (Li & Matin, 1990); however, the blocked design there was the same as that described here, and the stimulus conditions, procedures, and number of trials for the 10° condition were in every way identical to those employed for the other values of *x*.

Calibration for Eye Position Measurements

Linearity of the eye position recording system was determined before the experiment from measurements of eye position during fixation at each of 11 points. The points were displayed along a horizontal line, with each one separated from the next by 2°. The correlation coefficient, *r*, between the computer read-out of the eye position measurement and the actual position of the target on the CRO for each subject was greater than +0.997. Calibration of the monitoring system for eye position was carried out before and after each block of trials, while the subject fixated each of the two endpoints of the display. The calibration value at each endpoint was the average of 1,000 digitized samples taken by the Linc-8 computer (9-bit A/D converter) at 1-msec intervals during a 1-sec period. The final values, which were stored by the computer, served as the reference values in the subsequent trial block.

RESULTS

Figure 2 displays the psychometric functions separately for each of the two observers along with best-fitting (least squares) cumulative normal ogives.[3] The false alarm rates (at abscissa = 0) range between 8% and 16% for each observer and do not differ systematically across the different saccade lengths. The best-fitting curves characterize the data well. They display an increase in slope that is systematic with saccade length; the curves for all saccade lengths appear anchored at similar ordinate values at zero displacement.

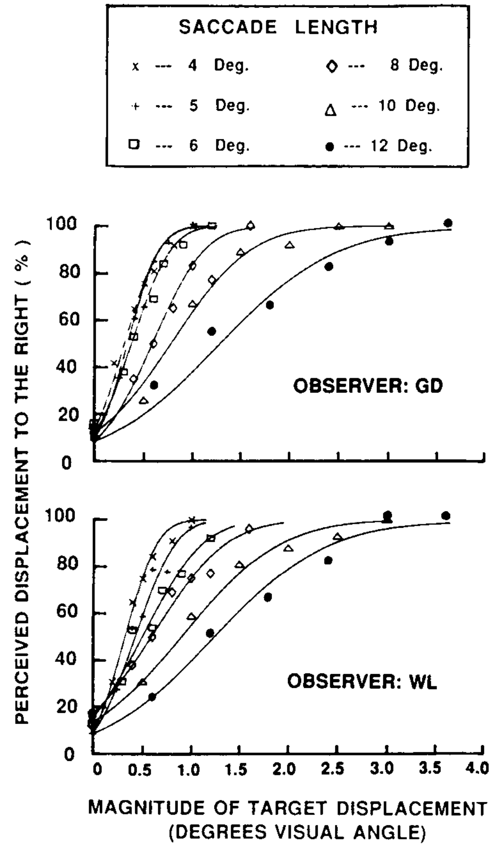

Figure 2. Psychometric functions displaying the percent of trials on which the observer reported that displacement had occurred are plotted against the magnitude of the spatial displacement of the visual field. Each of the smooth curves is the best-fitting (least squares criterion) cumulative normal ogive to the results for a particular saccade length.

Thresholds were calculated as 50% points of the best-fitting curves for the individual saccade lengths for each observer. These are plotted against saccade length in Figure 3 and are very similar for both observers. The relation of threshold to saccade length is reasonably approximated by a linear function for each observer, and best-fitting straight lines to these values yield slopes near 0.1 for both.

Since the data in Figure 2 are characterized by an increase in slope with increasing saccade length while the anchor at zero displacement is similar for all saccade lengths, the relation between the 50% thresholds and the standard deviations (*SD*s) of the set of functions would

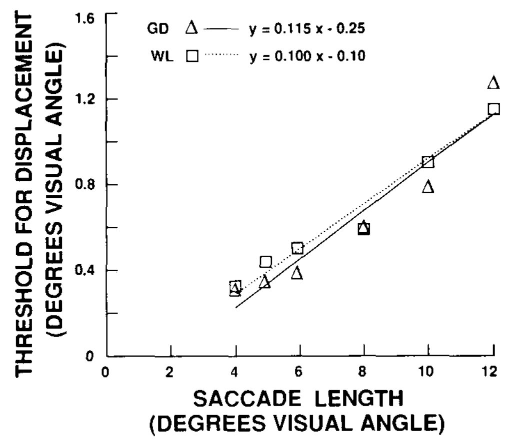

Figure 3. The 50% displacement threshold plotted against saccade length for each of the 2 observers. Each point is the value obtained from the corresponding best-fitting curve in Figure 2.

be expected to be linear, and indeed, as is displayed in Figure 4, a good linear fit is obtained for each observer, with slopes that are similar for both (+0.72, +0.74).

DISCUSSION

The displacement threshold increases linearly with saccade length, and is about one tenth of saccade length over the range of lengths from 4° to 12°. These are close to the displacement ratios (threshold/saccade distance) obtained under somewhat different conditions by L. Matin and Pearce (1965), L. Matin et al. (1969), and L. Matin et al. (1970) for saccades of 2° 11′ and 4° 32′, and by Whipple and Wallach (1978) with 7° saccades, but they are much smaller than the maximum displacement ratios of one third that were reported by Bridgeman et al. (1975), whose values refer to maxima of threshold-versus-time functions measured with variable saccade lengths. For all saccadic conditions reported, however, the displacement threshold during saccadic eye movements is still very much higher than that which is obtained during steady fixation, even under conditions in which a time interval between two brief stimulations is as long as 400 msec (L. Matin, Pola, E. Matin, & Picoult, 1981). This difference indicates again how severe the suppression of displacement is in the presence of a voluntary saccade and shows that the sensitivity loss must be associated with the saccadic process.

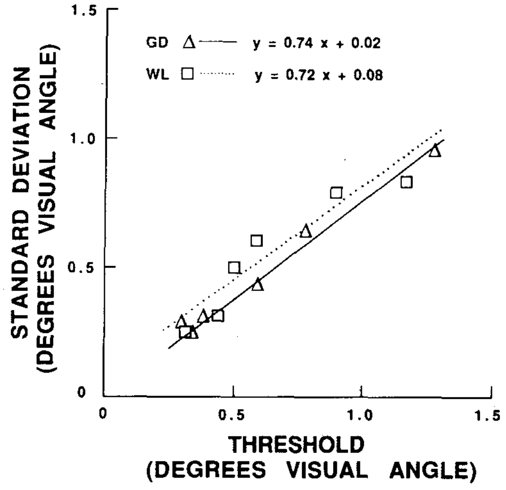

Figure 4. The standard deviation of the normal density underlying the best-fitting curve in Figure 2 is plotted against the 50% threshold; each point represents the values for a different saccade length. Both *SD* and threshold increase monotonically with saccade length for each observer.

In our previous report (Li & Matin, 1990) we concluded that the reduction of sensitivity to displacement in the presence of a saccade is not a consequence of processes associated with the smearing of the retinal stimulus pattern caused by the saccade, since electronic elimination of the retinal stimulus during the saccade did not influence the reduction of displacement sensitivity. We suggested that the increase of the displacement threshold is mainly a consequence of a transient increase in variability of the extraretinal signal regarding eye position that is associated with the saccade, and we drew support for this view from our finding of a linear relation between the 50% threshold and the *SD* of the psychometric distribution under variation of postsaccadic stimulus duration. Since such a linear relation—Weber's law—is a classic sign of a signal/noise basis for discrimination, those experiments provided a strong case for the interpretation based on increased variability of the extraretinal signal associated with eye position. The linear relation between 50% threshold and the *SD* of the psychometric function under variation of saccade length (Figure 4) described herein provides additional support for this view.

However, two alternative explanations of the present results must be considered. The first can then be eliminated and the second relegated to a minor role:

1. The presence of a visual field during the saccade—either stationary or displaced—in combination with either no postsaccadic stimulus or a brief one allows the saccadic stimulus to appear as a spatially extended smear whose length increases with saccade length. If such a smear was visible in the present case, an argument could be made for some version of the following interpretation as an alternative to the one presented above: It is well known that the just discriminable change in line length increases linearly with line length. Since the increase in smear length with saccade length provides a situation similar to that required for discrimination of line length, a similar linear increase in the displacement threshold could have been carried out by the observers in the present experiment. However, with the long duration of postsaccadic stimulus employed in the present experiment, no spatially extended saccadic smear is visible (E. Matin et al., 1972); thus such an alternative cannot be offered to explain the present results. In fact, it was precisely because of the invisibility of the smear with a longer duration displaced stimulus (Li & Matin, 1990) that we were

led to employ a duration for the displaced display as long as 461 msec. In the light of our previous measurement of the ineffectiveness of the visual stimulus during the saccade as a mediator of the saccadic suppression of displacement even under conditions for which it was visible, an argument for its involvement when invisible does not appear to merit further consideration. Additional buttressing of these conclusions derives from the report of both observers, who indicated that they believed that they were discriminating the presence or absence of spatial displacement, and although they could not specify its basis, the visual aspects of the discrimination appeared to be no different than the discrimination of spatial displacement with a stationary eye.

2. The second possibility is of greater concern: For the condition involving a longer projected saccade, the peripheral targets in both the presaccadic and the postsaccadic views were both imaged on more peripheral retinal regions than were the peripheral targets in the condition involving a shorter projected saccade. In addition, since the decreased acuity of the peripheral retina provides a poorer guide for the eye to the saccadic target, the conditions involving longer projected saccade lengths would lead to increased errors in actual saccade length, a factor that has additional consequences for the postsaccadic retinal information involved in the spatial discrimination. In fact, additional experiments with the paradigm employed in the present experiment (Li, 1989; Li & Matin, 1988) have borne out these predictions regarding the involvement of these retinal influences on the displacement threshold, but they have also shown that together they are only a minor contributor to the increase of displacement threshold with saccade length, and that the major contribution derives from the imprecision in extraretinal eye position information as suggested above.

Work on the saccadic suppression of displacement arose in the context of the investigation of the mechanism responsible for the fact that the world normally appears to be stationary when we change our direction of gaze by means of saccadic eye movements. The central concern regarding that mechanism has been to understand why identical displacements of the retinal image lead to the appearance of stimulus movement or displacement when the eye is stationary but to the appearance of a stationary visual field—the appearance that nothing moves, nothing is displaced—when the direction of gaze is changed. Several related experimental paradigms have been developed to explore the question. These paradigms have typically been designed to measure the way in which the shift has taken place between the retinal image and visually perceived direction as a function of time, eye position, saccade length, spatiotemporal changes in the visual field, and so forth. The important measure employed in these paradigms is the change in spatial localization at different values of the parameters above. Typically this has been measured by the change in spatial location of a point of subjective equality for a stimulus flashed in close temporal proximity to the saccade judged relative to the perceived spatial location when the eye was quiescent; the saccadic suppression of displacement is the measurement of the increase in spatial uncertainty in the temporal vicinity of the saccadic eye movement. Thus, the main concern regarding the mechanism for perceptual stability is the shift in the relation between the map of visual direction and the map of retinal location (a measure of accuracy—i.e., a change in constant error on a psychometric function), and the saccadic suppression of displacement is the increase in uncertainty associated with that shift (a measure of precision—a change in threshold—as measured by the *SD* of a psychometric function). It will ultimately be necessary to explain both the change in constant error and the change in standard deviation in terms of the same mechanism.

Placed in the context of the broader problem, then, our isolation of a substantial influence of the extraretinal signal on the increase in spatial uncertainty (threshold) in the previous report (Li & Matin, 1990) and in the present one has been brought about by means of a specific experimental paradigm designed particularly to extract this influence. However, attention should be called to the employment of other paradigms in which conditions are weighted so that retinal factors may also play a role. Thus, for example, an analysis by O'Regan (1984), which was essentially aimed at exploring the variation in constant error (the remapping) by means of a paradigm originally introduced by Bischof and Kramer (1968), led to the conclusion that two retinal factors are the major contributors to the substantial systematic errors in localization that are generated with that paradigm. In fact, the variability associated with the change in constant error in the experiments done by Bischof and Kramer (1968) and by O'Regan (1984) was of a magnitude that reflects the presence of the saccadic suppression of displacement—1°-2° with 12° or 16° saccades. Although it is clear that this paradigm does elicit an important contribution of retinal factors to the shift of constant error, no analysis has yet been carried out to determine whether the increased variability is also due to retinal factors, to extraretinal influence, or to both.

Through the employment of a number of variations of several basic approaches, then, it has become clear that the relative contributions of retinal and extraretinal factors to perceptual stability in the face of saccadic eye movements—as seen in the changes in both constant error and variability—is not fixed (cf. Bischof & Kramer, 1968; Bridgeman & Stark, 1979; Grüsser, 1986; Hallett & Lightstone, 1976; Honda, 1989; Mateeff, 1978; L. Matin, 1986; L. Matin et al., 1969; L. Matin et al., 1970; L. Matin & Pearce, 1965; Monahan, 1972; Pola, 1976; O'Regan, 1984; Shebilske, 1977), although a simple statement cannot yet be made regarding the basis for the changes in their relative contributions.

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NOTES

1. Visible persistence decays exponentially to 10% in less than 2.8 μsec (JEDEC); with our instrumentation, persistence was unobservable (less than 0.005% beyond 30 μsec following termination of the input to the *z*-axis). (See Li & Matin, 1990, for more detail.)

2. The computer program controlling the CRO made use of a 1-msec timing unit. At a specific moment within each 1 msec period, a pulse to the D/A converter controlling intensity turned on the CRO spot at the location and intensity determined by programmed settings of the D/A converters; following each intensification, a countdown clock turned the CRO off 20 μsec later. At the same point in the next 1-msec period, the CRO could be intensified for another 20-μsec period at the same spatial location or at a new location, or not intensified at all; a 980-μsec period of complete darkness followed each 20-μsec exposure. "Simultaneous" exposure of the two targets, A and B, during the fixation period was accomplished by exposing A within one 1-msec period, exposing B within the next 1-msec period, and repeating this alternating sequence for the duration of the fixation period; thus, A and B were each exposed every 2 msec (500 times/sec) during alternating 20-μsec periods separated by 980-μsec dark periods. Except for the time consumed delivering the microinstructions to the D/A converters, the computer was free during the remainder of the time to carry out its other business, which included recording the eye movements and the psychophysical responses of the observer.

3. The best-fitting normal ogive accounted for an average of 97% of the variance in the 12 sets of data of the experiment reported here, with no less than 90% of the variance being accounted for in the fit to any single set. In short, the fits were extremely good. This was not substantially different from the goodness with which semilog curves (employed by Whipple & Wallach, 1978) fitted the present results; however, semilog curves do not deal rationally with false alarm data (values at zero displacement), and these cannot be included in the fitting procedure.

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