

FAILURE TO DETECT DISPLACEMENT OF THE VISUAL WORLD DURING SACCADIC EYE MOVEMENTS¹

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Abstract—Perception of the rapid displacement of a target is suppressed during saccadic eye movements. Suppression is complete if eye movement is more than about three times larger than target displacement, and some suppression occurs even for target displacements of 4°. These results can be interpreted with the addition of a threshold element to the algebraic sum of the corollary discharge and the visual signal.

The common observation that one's own rapid eye movements (saccades) are not visible in a mirror has never been explained, and raises the more general question of the perception of object displacement during saccades. The perceptual stability of the visual world despite saccades has classically been explained by postulating two parallel discharges from eye movement centers: one to the extraocular muscles, and a corollary discharge (CD) to the visual system to accurately subtract the effects of eye movement from the internal (as opposed to retinal) representation of the visual world (Helmholtz, 1867; Sperry, 1950; von Holst and Mittelstaedt, 1950). Difficulties arise for CD theories if object displacement is not detected, for any displacement of a target in the world during a saccade creates a retinal target displacement different in magnitude from that of the CD, so that the target displacement should be detected. The experiment reported here shows, however, that target displacement during saccades often goes undetected, quantifying the mirror observation.

METHOD

In order to simulate a normal visual world as closely as possible, we used an extended, differentiated target rather than a point stimulus. The stimulus was a row of 13 fixation points spaced 1° apart and surrounded by concentric circles and radiating lines so that each point was easily identifiable. Subjects were light-adapted by exposing them to the stimulus for several minutes before beginning each experimental session. The patterned stimulus covered a 13° square and was projected by a mirror onto a homogeneous surface bounded by two horizontal contours. When no projected stimulus is present, a horizontal eye movement across this surface results in no change in either the pattern or the location of the retinal image, and it can thus be called a "1-dimensional Ganzfeld". A hemi-cylindrical screen, 180° wide was visible between two horizontal baffles mounted near the eye, so that rotations of the mirror produced horizontal movements of the projected image but created no image motion relative to the upper and lower field boundaries.

Subjects' heads were restrained and their eye movements monitored with photocells mounted peripherally, so close to the eye that no clearly focussed contours were introduced (Noton and Stark, 1971; Stark, Vossius and Young, 1962).

A subject was instructed to make eye movements from one fixation point to another in an irregular pattern, and the stimulus was moved at $900^{\circ} \text{ sec}^{-1}$ either 1, 2 or 4° left or right at unpredictable times, with at least 1 sec between jumps. The subject's task was to move a switch whenever he saw the stimulus jump. Thus even a non-naive subject was "blind" with respect to whether or not a trial had occurred at a given instant. Because subjects were allowed to use any available cues to detect displacement, any imperfections in apparatus or design would favor higher probabilities of displacement detection, $P(D)$. Thus any noises made by the moving mirror, changes in stimulus brightness, etc., are possible cues which the subject might use in detecting a displacement (though the subjects reported no such disturbances). Luminances were: screen background, 0 log ft-L; target background, 1.8 log ft-L; and fixation points and lines (which appeared black), 0 log ft-L.

Experimental sessions lasted about 20 min. or until a subject felt fatigued, whichever came first. During each session a subject would make 1-2 saccades per second, and saccades which occurred within 100 msec of a target movement were used as data for Fig. 1. Saccades, target movements, and detections were simultaneously recorded on paper tape for later analysis. The eye movement recording system was calibrated before and after each session.

RESULTS

Detection of target displacement was strongly suppressed during saccadic eye movements. Figure 1 shows that target displacements are never detected if they occur about 10 msec after the initiation of a saccade which is at least three times as large as the target displacement (in the three graphs at the upper left of Fig. 1). Detection of image displacement is suppressed if the displacement occurs before a saccade, and maximum suppression is found when the displacement occurs during the eye movement. $P(D)$ is a function of the relative sizes of eye and target motions, for suppression curves on right-slanting diagonals in Fig. 1 are similar. The curves of Fig. 1 are superimposed in Fig. 2 with the ranges of all curves made equal to facilitate comparisons. The overlap suggests that the shape

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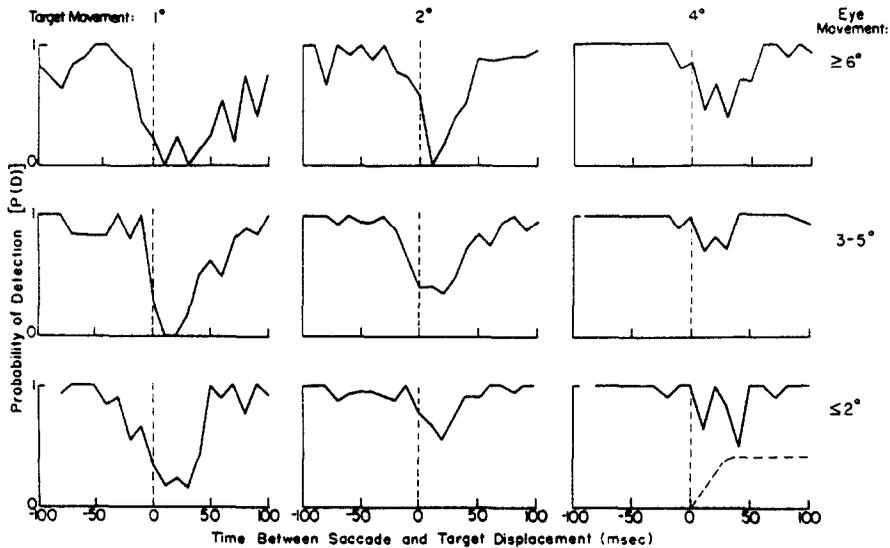


Fig. 1. Saccadic suppression of displacement. A 4-dimensional matrix displays size of saccade (vertical axis between graphs), probability of detection $P(D)$ (vertical axis within graphs), size of target displacement (horizontal axis between graphs), and latency of target displacement from the beginning of eye movement (horizontal axis within graphs). There were four subjects in the 2° condition and two in the 1° and 4° conditions. Total number of saccades was 482 in the 1° condition, 999 in the 2° condition, and 493 in the 4° condition. The three graphs in the upper left corner of the matrix (top row left and center, middle row left) show no detections in 42 trials at +10 msec. The number of observations at high negative latencies (left of each graph) was reduced, perhaps by the "cancellation phenomenon". Graphs along right-slanting diagonals are similar, showing that ratio of target displacement to size of saccade was more important than absolute size of either parameter in determining $P(D)$. Eye movements, rounded to the nearest degree, were grouped to yield an approximately equal number of observations in each row. A 6° saccade is shown schematically in the lower right graph (dashed line) to indicate its onset and duration.

of the saccadic suppression curve remains the same for all of the conditions of Fig. 1, with a single parameter increasing the amount of suppression as a function of the ratio of eye movement magnitude to target movement magnitude. There is a possible "floor" effect for the strongest suppression curve (largest eye movement, smallest target movement).

Despite the lack of relative-motion cues, the displacement was clearly visible: when no saccade occurred within 100 msec of a target movement, $P(D)$

was greater than 0.98 for every condition. The "false alarm" rate was negligible. Failure of detection was statistically independent of the direction of eye movement relative to target movement ($\chi^2 = 0.87$); the absolute size of the error between the saccade and retinal displacement is apparently more important than its sign. $P(D)$ as a function of size of eye movement is shown in Fig. 3.

In the 4° target displacement condition, subjects sometimes reported being aware that the stimulus had

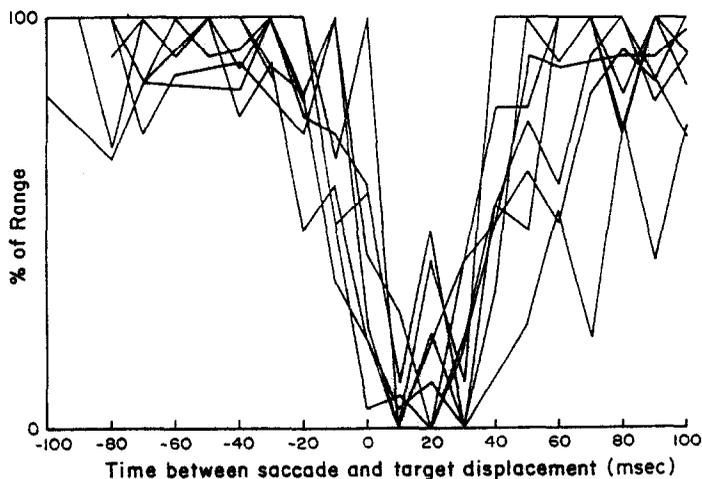


Fig. 2. The curves of Fig. 1 superimposed and replotted so that each point is represented as a percentage of the total range of the curve to which it belongs. The weakest saccadic suppression curve (smallest eye movement, largest target displacement) was so small and irregular that it was not plotted. The overlap of the curves shows that they differ by only a single parameter.

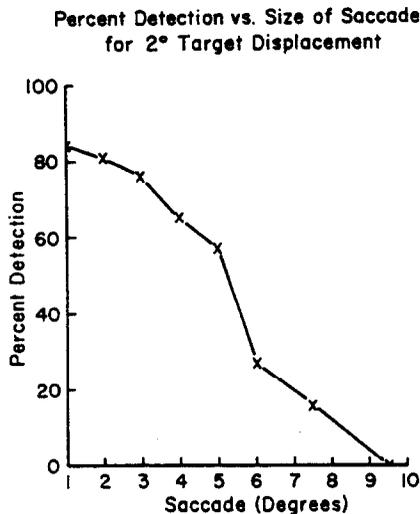


Fig. 3. Decrease in $P(D)$ as eye movements increase in size. Data are plotted for 2° target displacements occurring between 10 msec before and 40 msec after the start of a saccade (-10 to +40 msec in Fig. 1).

been displaced without ever having seen it jump, as if some very rough information about absolute position were available. This perception resulted in several long-latency detections of displacement (up to 1 sec), which were counted as detections for the data analysis.

The direction of displacement was almost always correctly detected, with subjects reporting either displacement in the correct direction or no motion at all.

DISCUSSION

Some theories attempt to define the optic array itself as stable (Koffka, 1935; Mackay, 1962; Gibson, 1966). Gibson (1966) concludes: "The reason the world does not seem to move when the eyes move, therefore, is not as complicated as it has seemed to be. Why should it move? The movement of the eye and its retina is registered instead; the retina is proprioceptive" (p. 256). Though attractively simple, such theories lack explanatory power. For example, they are silent on why passive movement of the eye produces the impression of movement of the visual world.

Helmholtz (1867) gave five reasons for originally postulating a quasi-sensory aspect of motor discharges to eye muscles: (1) apparent motion of the visual world occurs when an eye movement is attempted under paralysis; (2) apparent motion of the visual world occurs when the eye is moved passively; (3) after-images are spatially stable when the eye is moved passively; (4) displacement of the image is compensated in normal saccades; and (5) adaptation to displacing prisms transfers intermanually (adaptation to constant movement or constant displacement of the visual world persists when the movement or displacement ceases). Sperry (1950) provided a neural basis, the "corollary discharge" (CD), for Helmholtz's "intensity of the effort of will". Von Holst and Mittelstaedt (1950) also treated this problem with an early control diagram supporting the Helmholtzian concept.

Our results require modification of CD theories, according to which perceptual stability requires a zero sum of CD and visual signal. Thus for a mismatch

between retinal displacement and size of eye movement to go undetected, it is necessary to degrade visual information during saccades.

The saccadic suppression of many visual functions is consistent with this necessity. Though the time course of suppression varies from one visual function to another, the suppressed stimulus can usually begin before the onset of a saccade, and suppression reaches a peak for stimuli given during or just before the saccade. Suppression of flash detection has been found under many conditions (Latour, 1962; Volkman, 1962; Zuber and Stark, 1966; Volkman, Schick and Riggs, 1968), including light backgrounds where retinal image movement occurs and dark backgrounds where no image movement occurs; thus suppression of flash detection cannot be entirely due to image movement on the retina (MacKay, 1970), with its resulting "metacontrast" masking (Matin, Clymer and Matin, 1972; Grüsser, 1972). Saccadic suppression has also been found for the pupillary light response (Zuber, Stark and Lorber, 1966), visual evoked response (Gross, Vaughan and Valenstein, 1967; Chase and Kalil, 1972), single-unit response (Michael and Ichinose, 1969), and pattern recognition (Stark, 1971). The present experiment adds image displacement to the list, quantifying earlier observations (Sperling and Speelman, 1966; Wallach and Lewis, 1965).

Our data can be reconciled with CD theories if it is assumed that the error between the extent of a saccade and the corresponding retinal image displacement must reach a threshold before a displacement of the world is detected. With this assumption the computed comparison need be only fast and accurate enough to maintain visual-motor coordination, but the existence of such a computation would still account for the phenomena classically cited in support of CD theories. Saccadic suppression could inhibit perception when the CD and visual information do not match. Matin (1972) maintains that an extra-retinal signal (CD) alone cannot account for subjective stability of the visual world; the signal develops too slowly and is imprecise.

These data confirm and extend the results of Ditchburn (1955) and of Beeler (1967), who found suppression of displacement detection during microsaccades according to a function similar in shape to the functions of Fig. 1. An important difference between the present experiment and Beeler's, however, is that we tested for and found suppression of detection even for target displacements of several degrees rather than of 15' of arc. Because Beeler's displacements were not large enough to elicit following movements, his result might still be compatible with a CD theory, having a small allowable error between CD and image motion. Our result, however, requires alternative mechanisms as well as the CD to account for the precision of spatial orientation after eye movement. In two earlier studies (Sperling and Speelman, 1966; Wallach and Lewis, 1965) movements of simple targets during saccades were not detected, though neither study provided parametric data. Two other studies (Gross *et al.*, 1967; Chase and Kalil, 1972) showed decreases in the visual evoked response to a 10-msec pulse displacement (displacement and return) of a grating stimulus during saccades, though again no parametric psychophysics was done and detection of simple step displacement was not measured.

A quantitative explanation of why eye movements cannot be seen in a mirror can now be given. Because a displacement error is not detected when it is less than about one-third as large as the saccade, simple trigonometry shows that to make detection possible the mirror must be about 1 cm from the eye. Attempted saccades with a paralyzed eye result in apparent motion because the "displacement error" is just as large as the intended saccade. Eye movement can be detected if one changes the perceptual conditions so that the images before and after the movement are different, or if a magnifying mirror is used to increase the ratio of image motion to eye motion.

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