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# VISUAL THRESHOLD CHANGES RESULTING FROM SPONTANEOUS SACCADIC EYE MOVEMENTS[1]

GEORGE W. BEELER, JR.[2]

California Institute of Technology, Pasadena, California

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## INTRODUCTION

THE EFFECTS of saccadic eye movements on perceptual thresholds have been measured or noted several times in previous experiments. These experiments have dealt primarily with the changes in visual threshold which occur coincidentally with saccades. One of the first to note such effects was DITCHBURN (1955), whose subjects were asked to fixate a spot on an oscilloscope. The position of this spot was proportional to the subject's eye velocity, such that when spontaneous flicks[3] occurred, the spot jumped. Ditchburn's subjects were unable to see the target jumps, although an observer standing at the subject's side could readily perceive the motion. Subsequently VOLKMANN (1962) quantified the threshold change involved by presenting a 20 microsec flash to the fovea while the subject voluntarily produced large fixation changes. She noted a 0·5 log unit increase in the perceptual brightness threshold. Still later, LATOUR (1962) and BOUMAN (1964) reported experiments similar to Volkmann's except that the light flash was presented at random times with respect to the eye movement so that the threshold change as a function of time could be measured. The results of these experiments indicated that threshold changes occurred as much as 40 msec before the start of the eye movement, and lasted up to 80 msec after the saccade.

While previous work has covered many aspects of the problem, there remain several unanswered questions owing to the techniques and conditions used. First, both Volkmann, and Latour and Bouman used quite large saccadic eye movements elicited by either vocal or visual commands, and the extension of the results to smaller spontaneous saccades should be checked. Secondly, Latour did not control the retinal location of his stimulus presentation, with the result that potential time variations in threshold would be compounded with variations arising from different retinal areas. In order to answer these questions, one half of this report deals with the perceptual brightness threshold and its time course, as measured at the fovea using a stabilized target which is flashed in coincidence with the small, spontaneous flicks which arise during normal fixation.

In addition to the brightness threshold mentioned above, the results that Ditchburn noted suggest an alternate experiment. It has been shown by previous workers that the maximum brightness threshold change created by large saccades is less than one log unit,

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[2] Present address: U.S. Army Aeromedical Research Unit, Ft. Rucker, Alabama

[3] In order to differentiate between voluntary and involuntary eye movements, the saccadic eye movements are referred to hereafter as flicks when they are spontaneous, and as saccades when they are in response to target motion or experimenter command.

and this paper will confirm that finding for small flicks. Nevertheless, Ditchburn's subjects did not perceive the jump in the oscilloscope spot, even though that spot was presumably several log units above threshold. This suggests that an alternate neural mechanism prevents the subject from detecting a target motion which is coincident with a flick, even if the target itself is above threshold throughout the movement. The second half of this paper deals with an experiment to test this possibility.

## APPARATUS

The experimental apparatus used in this experiment required the subject to wear a full scleral seat contact lens, and to observe the targets through an optical system similar to that reported by CLOWES and DITCHBURN (1959). In this system, a small mirror attached to a stalk on the contact lens may be incorporated into the target projection optics so that the retinal image can be stabilized if desired. The various targets were placed at the focal point of a 20 cm focal length lens, and were transilluminated by parallel light. The targets were presented in Maxwellian view and appeared at infinity. In the descriptions to follow, target sizes will be expressed in terms of visual angle, and target luminance will be expressed in candles/m$^2$ (nit) as measured along the axis of the instrument. The measurement of eye position was made using a small lamp also attached to the contact lens stalk. This lamp was tracked with photo-multipliers to provide an electrical analog of eye position, as in the system described by BYFORD (1959).

In order to control stimulus presentations, it was necessary to detect the small saccadic eye movements as they occurred. This detection was performed with a simple differentiator-filter operating on the eye position signal. Data from ROBINSON (1964) show that saccadic eye movements of less than one deg arc tend to have a constant time course, and hence, fixed frequency components which can be detected with a filter. The unit used here was a first order differentiator followed by a low-pass filter with a third order cutoff above 40 Hz. The output of this detector was passed through pulse shaping networks, delayed, and then logically gated to control the stimulus.

Individual experimental runs were comprised of 23 stimulus presentations. The construction of the presentations was performed by a logical control unit which divided the session into 46 time intervals averaging three sec each, with alternate intervals designated as stimulus and response periods. The first flick detected after the beginning of a stimulus period triggered a stimulus presentation after a delay time. The experimenter could vary this delay at will, or could inhibit the stimulus presentation to provide a measure of false-positive responses.[4] The subject was provided with a peripheral indicator light which flashed for 0·5 sec at the beginning of each response period, and he was instructed to report at that time whether or not he had observed a stimulus presentation during the interval since the last query.

This technique permitted the direct measurement of thresholds at fixed delays after the saccade, but in order to obtain stimulus presentations at times before the eye movement, it was necessary to make use of the recurrent nature of spontaneous flicks. It can be shown that each subject has a characteristic mean inter-flick time, with the result that if a stimulus is delayed by this mean time, it will, on the average, coincide with the subsequent flick. Using this technique, it was found that 45 per cent of the stimuli occurred within ±100 msec of the onset of the next flick. When these presentations were histogrammed in equal width cells, each cell yielded approximately the same number of samples.

## RESULTS

### *Brightness threshold after flick*

The first experiment performed involved the measurement of the brightness threshold for a stimulus flash occurring at fixed intervals after a flick. The visual field for this experiment consisted of three segments. The first of these was a uniformly illuminated background, six deg. arc in dia. with a luminance of 0·001 nt. Superimposed on this field was an annulus of 90 min arc i.d. and 110 min arc o.d., with a luminance of 0·0054 nt. This continuously illuminated annulus served to locate the flash stimulus at all times. The flash stimulus itself was an 80 min arc dia. disc concentric with the annulus. The disc had a nominal luminance of 0·0051 nt., and neutral density wedge filters provided

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[4] Approximately five per cent of the stimulus presentations in each experiment were inhibited to obtain false-positive measures. From these inhibitions, less than one per cent false-positive responses resulted in any given experiment. As this was such a small fraction, no correction was made in the data which follow.

continuous attenuation control below this level. All data were taken in terms of log units of attenuation below this level. The disc was flashed by moving a small aperture across a source point in the optical system. By using this source point interruption technique, it was possible to produce a 5 msec flash with 0·2 msec rise and fall times, and still have all areas of the target illuminated equally at any given instant.

In order to assure that the threshold was in fact being measured foveally, both the annulus and the flash stimulus were presented as stabilized retinal images, and before each experimental run the experimenter adjusted the targets on the subjects' instructions so that they were being centrally fixated. As the annulus was near threshold, it was subject to the perceptual fading which occurs in stabilized vision, as described by DITCHBURN *et al.* (1959). To prevent such fading, the annulus was oscillated horizontally at six Hz with a peak-to-peak amplitude of six min arc.

Four standard stimulus delays were chosen: 20, 60, 100 and 220 msec. The 23 stimulus presentations of each experimental run were arranged so that each of the standard delays was presented five times, and the stimulus was inhibited three times. The order of delay presentation was randomized. The level of flash illumination was changed for each experimental run within a given session, and the levels spanned an illumination range sufficiently large that the experimenter was assured of having bracketed the 50 per cent threshold for each of the delays. To obtain the best estimate of the 50 per cent threshold for each stimulus delay, a probit analysis was used.

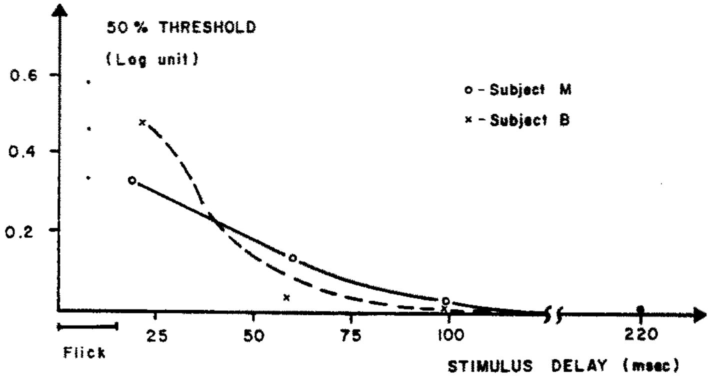

FIG. 1. Brightness threshold change in log units as a function of the time delay between stimulus flash and a flick. Data are related to a non-saccadic level of 0db. The points plotted at 7·5 msec delay are data recalculated from VOLKMANN (1962).

The results of this first experiment are shown for two subjects in Fig. 1. While the magnitude of the threshold change is different for the two subjects, the effect of the flick on the brightness threshold is apparent. Unfortunately, the experimental apparatus did not permit sampling of the threshold during the flick itself, owing to inherent delays in the flick detector and the logical circuitry. The data derived by VOLKMANN (1962), however, can be helpful in this respect. The results from her Fig. 5 have been used to calculate an equivalent threshold change during the flick for each of her three subjects. This threshold difference was then related to a non-flick threshold level of 0·0 log units, and plotted as three points on Fig. 1. As her data were always taken in the middle of the saccade, they have been plotted in the same location on this curve at 7·5 msec after the flick initiation. Despite the differences in the eye movements used, the experimental results are clearly compatible, and show a maximum threshold change of 0·5 log units during the flick. This threshold change then decays to normal within 60–90 msec after the flick.

*Time course of brightness threshold change*

The experiment described above shows that the threshold changes related to saccadic eye movements last up to 90 msec after the flick, and are true neural phenomena for foveal stimulation, not related to image movement or possible variability in retinal location. Moreover, these measurements were carried out on spontaneous eye movements which are an order of magnitude smaller than the saccades previously used. The next step, then, was to study the time course of the threshold change before the initiation of the spontaneous flick. This was accomplished using the long delay, random occurrence technique mentioned earlier. As has been noted, this technique results in only about 45 per cent of the stimulus presentations falling within 100 msec of a flick. Such a loss of experimental efficiency made it impractical to attempt to measure the 50 per cent threshold at each of several points in time around the flick. Instead, a method was used which traced the visibility of a single luminance level as the visibility changed due to a flick.

The visual conditions used were identical to those described in the preceding experiment. The delay of the flash stimulus was set approximately at the subject's mean inter-flick interval so that the stimulus occurred at random in the neighborhood of the subsequent flick. The 100 msec interval on either side of the subsequent flick was subdivided and the stimulus occurrences in each subdivision were lumped together to form a common statistic. The luminance of the flash stimulus was adjusted so that the subject perceived about 50 per cent of the total number of presentations. In this manner, the target was assured of being slightly above threshold under normal circumstances and below threshold in the immediate neighborhood of the flick.

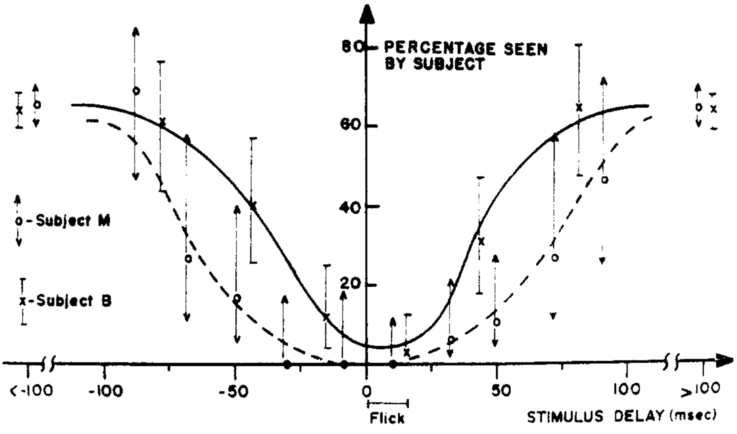

FIG. 2. Plots showing time course of brightness threshold change relative to flick initiation time. Vertical marks around data points indicate 99 per cent confidence intervals. There are approximately 45 samples per interior time interval for subject B, and approximately 30 per interval for subject M.

The results of this time course measurement are shown in Fig. 2. The horizontal axis in the figure is the time of the stimulus occurrence relative to the time of the initiation of the flick; thus, a negative time implies that the test flash preceded the flick. The actual duration of the eye movement is shown by a marker running from zero to fifteen msec. The vertical axis is simply the percentage of the stimulus presentations that the subject perceived. The percentage of responses which were elicited outside the 200 msec range of interest are lumped together and plotted at both ends of the graph. In order to permit the assessment of the significance of these results, 99 per cent confidence bands from the binomial distribution have been plotted around each point. The results clearly demonstrate that the threshold change measured in the first experiment starts before the initiation of the flick as well as extending after the completion of the eye movement.

*Variation in motion perception*

While the experiments reported above show that there is a measurable threshold change as the result of small, spontaneous flicks, they do not explain the results that DITCHBURN (1955) reported. In his experiment, where the subject was observing his eye velocity signal on an oscilloscope, there should have been no perceptual failure due to the brightness threshold changes measured here, as the spot was presumably several log units above normal threshold and an 0·5 log unit change would not be noticed. The fact that his subjects failed to observe spot motions caused by flicks suggests that, in addition to the small brightness threshold change, there may be a second effect which prevents the subject from detecting target motions which occur in the neighborhood of a spontaneous eye movement.

In order to test this possibility, an experiment very similar to the threshold time course measurement was set up with a different stimulus. In this instance, the subject was asked to fixate a two min arc dia. pinhole, with a luminance of 0·102 nt. against a dark background. The stimulus was continuously illuminated and was presented in normal vision, rather than as a stabilized retinal image. The stimulus event to be detected by the subject was a 15 min arc step in the horizontal position of the target. Such a stimulus step can be shown to be slightly larger than the mean amplitude of spontaneous saccades, and while the step is readily perceived, RASHBASS (1961) shows that it is not large enough to elicit a following

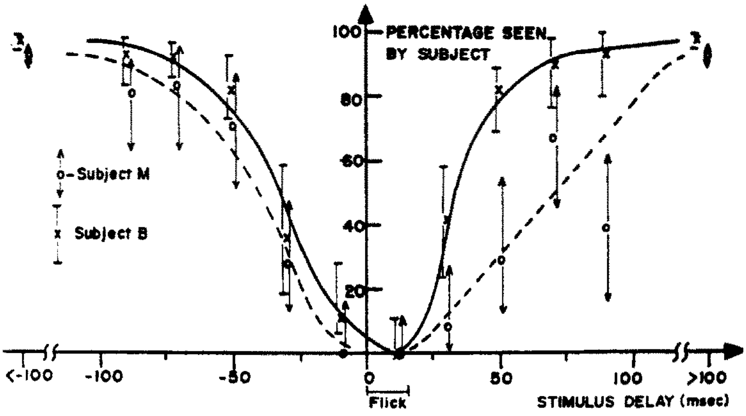

FIG. 3. Plots showing the time course of the suppression of position detecting ability relative to the time of flick initiation. Vertical marks around data points indicate 99 per cent confidence intervals. There are approximately 35 samples per interior time interval for each subject.

movement from the eye. As in the preceding experiment, the stimulus steps were delayed sufficiently long after the detection of a flick to fall at random in the neighborhood of the succeeding flick. In each experimental run, three stimulus inhibitions were randomly interspersed with 20 presentations.

The results of this experiment are presented in graphical form in Fig. 3. The form of this presentation is identical to that of Fig. 2, and the visual effect here is quite clear. The subjects saw more than 93 per cent of the stimulus presentations which were separated from a flick by more than 100 msec, but were unable to detect any of the stimulus movements which coincided with a flick. Moreover, this degradation of motion detection starts about 40 msec before the flick, and lasts about 50 msec after the eye movement.

## DISCUSSION

The first two experiments reported here serve to confirm previous measurements of brightness threshold changes in the neighborhood of saccadic eye movements, and do so with additional constraints that further define the mechanism being observed. First, the retinal image whose threshold luminance was being measured was stabilized so that image movements on the receptors were eliminated. Secondly, the eye movements used were spontaneous flicks whose amplitude seldom exceeds 30 min arc. Finally, the flicks were not consciously generated in response to any visual or verbal command to move the eyes. Previous studies had used such commands, and had elicited saccades from 5–30 deg arc amplitude. Despite these constraints, there is a definite 0·5 log unit threshold change as a result of the flicks, and this change starts before the flick and lasts after the completion of the eye movement.

The third experiment, however, presents a different phenomenon—the suppression of target position information by the saccade—and sheds some additional light on the efference copy mechanism first proposed by VON HOLST and MITTELSTAEDT (1950). One of the postulated functions of this mechanism is to allow the discrimination between retinal image motion which occurs as a result of stimulus motion, and that which results from eye movements. The postulate is that the command efferent signals to the extraocular muscles are also sent to a cortical processing level to be compared with retinal image motion in order that net stimulus motion may be derived. The mechanism is clearly not that efficient, however, as this experiment shows that stimulus motion is not always detected in the presence of eye movements. A continuously functioning efference copy mechanism would result in the cortical detection of the net image movement which is due to stimulus motion. With this evidence at hand, it would be safer to postulate a passive form of efference copy such that whenever retinal image motion is detected, an interrogation of the efferent levels is made to determine whether a similar eye movement has been commanded in the immediately preceding time interval. If such an eye movement has been made, then the total retinal image motion is assumed to be the result of the eye movement. A mechanism of this sort would allow a subject to retain visual orientation in all normal conditions, but would account for the results seen here.

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**Abstract**—Visual thresholds were measured during the 200 msec interval spanning small, spontaneous saccadic eye movements. Brightness thresholds measured foveally with a stabilized retinal image showed a maximum increase of 0·5 log units, starting 60 msec before the flick and lasting 75 msec afterwards. Another experiment measured the subject's ability to detect 15 min arc target motions. Ninety-three per cent of these step movements were visible normally, but none were perceived when they coincided with the eye movements. This effect spans the saccade by 100 msec, and is not the result of the brightness threshold change.

**Résumé**—On mesure les seuils visuels pendant les intervalles de 200 msec entre les petits mouvements spontanés des yeux (saccades). Les seuils de luminance mesurés fovéalement avec une image stabilisée montrent un acroissement maximum de 0,5 unité logarithmique, commençant 60 msec avant le mouvement et finissant 75 msec apres. Dans un autre expérience on mesure la possibilité que le sujet détecte des mouvements du test, de 15 minutes d'arc. Quatre vingt treize pour cent de ces mouvements sont visibles normalement, mais aucun n'est perçu quand ils coincident avec des mouvements des yeux. Cet effet étend sur 100 msec la durée de chaque saccade, et n'est pas une conséquence du changement du seuil de luminance.

**Zusammenfassung**—Visuelle Schwellen wurden in dem 200 msec Intervall zwischen den saccadischen Augenbewegungen gemessen. Foveale Helligkeitsschwellen, die mit stabilisierten Netzhautbildern gemessen wurden, zeigten eine Maximumzunahme von 0,5 log Einheiten die 60 msec vor der Bewegung anfing und 75 msec danach andauerte. In einem anderen Experiment wurde die Fähigkeit des Beobachters gemessen, Objektbewegungen von 15′ festzustellen. 93% dieser ruckartigen Bewegungen waren normalerweise sichtbar, aber keine wurde gesehen, wenn sie mit einer Augenbewegung zusammenfiel. Dieser Effekt überbrückt die Saccade mit 100 msec und ist kein Ergebnis der Helligkeitsschwellenänderung.

**Резюме** — Зрительные пороги были измерены во время интервала в 200 мск между небольшими саккадическими движениями глаз. Пороги светлоты измерялись для фовеальной области при условии стабилизации ретинального изображения, при этом наблюдалось максимальное их повышение на 0,5 логар. единиц, начиная от 60 мск до начала движения и до 75 мск после него. В другом эксперименте измерялась способность испытуемого к обнаружению движений в 15 угловых минут. Девяносто два процента этих скачкообразных движений были видимы нормально, но не замечались, если они совпадали с движениями глаз. Этот эффект охватывал саккадическое движение в 100 мск, и не являлся результатом изменения порога светлоты.