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THE EFFECT OF SMOOTH TRACKING AND SACCADIC EYE MOVEMENTS ON THE PERCEPTION OF SIZE: THE SHRINKING CIRCLE ILLUSION

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Abstract—An illusory distortion is described in which the apparent diameter of the path of a target moving in a circle appears contracted at intermediate speeds. The apparent reduction of path diameter is highly correlated with smooth pursuit behaviour of the eye, and the distortion disappears with the emergence of saccadic movements at higher speeds. In the absence of tracking eye movement the magnitude of the distortion is greatly reduced. These data are discussed in terms of a possible interaction between smooth pursuit and saccadic eye movements in the perception of size, and possible differences in the utilization of information from the two eye movement systems.

INTRODUCTION

A fairly sizeable amount of evidence now seems to indicate that saccadic and smooth pursuit eye movements are independently generated and controlled. Some examples of evidence to this point are: (1) it is well known that there are large differences in the latencies of the two forms of eye movements, with typical latencies of 200–250 msec for saccadic eye movement (Bartz, 1962; Saslow, 1967; Wheeless, Boynton and Cohen, 1966; White and Eason, 1962) and 125 to 135 msec for smooth pursuit eye movements (Robinson, 1965; Young, Foster and Van Houtte, 1968); (2) the smooth pursuit and saccadic eye movement control systems are differentially affected by the administration of drugs such as barbituates (Rashbass, 1961); (3) most subjects can emit saccades on a voluntary basis, whether or not stimuli are visible in the field, while only a few subjects can emit smooth tracking eye movements voluntarily in the absence of a smoothly moving target unless trance states or supporting manual movements are employed (Brockhurst and Lion, 1951; Deckert, 1964; Steinbach, 1969; Westheimer, 1954); (4) pursuit movements are elicited by moving stimulus and appear to be primarily responsive to target locus (Fender, 1962; Rashbass, 1961).

To the extent that these eye movement systems are, in fact, independent, it is not unlikely that they may have different consequences in the formation of the conscious percept. We know, for instance, that attempted saccades are represented in consciousness. If we immobilize the eye and attempt an eye movement, the world will seem to jump in the direction of, and to the same extent as, the intended movement. This phenomenon has been interpreted as indicating that a copy of the emitted efferent command to the extraocular muscles interacts with the returning visual information so as to determine the resultant perception (Festinger, 1971; Held, 1961; Helmholtz, 1896; van Holst, 1954). Such a mechanism is extremely useful in maintaining the stability of the visual world under normal viewing conditions, since the efferent command generally cancels the movement of the stimulus across the retina, thus indicating that the eye has moved and the world has remained stable. In the case described above, however, the central nervous system apparently assumes that the eye has moved the distance called for in the efferent command. Since there was no image displacement across the retina, the percept reveals the world as jumping just enough to cancel the eye movement.

Less is known about the interaction of smooth pursuit eye movements and perception. Rock and Halper (1969) have demonstrated that subjects can accurately report the shape of the target path even when they are perfectly tracking a luminous target in the dark. This implies that some record of the path that the eye pursues must be available to the sensorium since, under accurate tracking conditions, the image of the stimulus remains continuously on the same spot on the retina. (Of course, the spot is actually only statistically on the same spot continuously, since minute oscillations of the eye, errors in tracking, and corrective flicks will be constantly shifting the actual locus of stimulation.) Festinger and Canon (1965) have provided data which suggest that the information available in this situation may be less precise than that available from saccadic eye movements in a comparable situation.

In line with this, there is an interesting feature of the smooth pursuit system which may have direct perceptual consequences. Using targets which oscillate along a linear path at sinusoidally varying velocities, it has been frequently demonstrated that the eye often tends to lag some distance behind the target. The magnitude of this lag (or phase shift) depends upon the target speed (Fender, 1971). This increase in phase lag with increasing speed of target movement has been shown a number of times, even where the target is oscillating in a predictable sinusoidal pattern (Dallos and Jones, 1963; Fender and Nye, 1961; Stark, Vossius and Young, 1962). One implication of this finding is that the target is frequently imaged at an off-foveal site for long periods of time. Of course, occasional saccadic corrections are made to minimize the distance between fovea and target, but these seem to appear only when the target has moved at least 0·25 to 0·40° off-fovea (Rashbass, 1961; Young, 1971). In fact, Puckett and Steinman (1969) seem to indicate that the smoothly-pursuing eye may lag a degree or more behind the target, without eliciting saccadic correction. The subjective experience when tracking such a target contains no hint of this inaccuracy. The observer feels quite confident that he is accurately tracking the target as long as the speed of oscillation is not too fast. If the speed of target movement increases until it reaches a frequency where numerous saccades begin to appear, the observer begins to report that he feels that he is sometimes losing the stimulus and thus is not tracking very well.

If the distance the eye lags behind the target is lost to consciousness during tracking (as the phenomenology seems to indicate), and if the only information then available about the extent of target movement comes from a record of the actual extent tracked, several interesting perceptual distortions may be predicted. For instance, consider an observer tracking a target that is moving smoothly along a linear path. If the smooth pursuit system simply matches velocity and the eye lags continuously behind the target, the tracked path length should be shorter than the physical path length. If the perceptual centers act on information about the extent of the pursuit movement alone, without taking into account the retinal error information, there should be an underestimation of the extent of target movement. Mack and Herman (1972) have reported such underestimations, and the constant errors found by Festinger and Cannon (1965) are also in accord with such a prediction. To the extent that velocity judgements are based upon an estimate of the distance traveled by the target and the time taken for this excursion, one might also predict that there would be an underestimation of the velocity of a tracked stimulus relative to a non-tracked stimulus. Such a phenomenon has been frequently observed and is called the Aubert–Fleischl effect (Dichgans and Brandt, 1972; Fleischl, 1882).

Let us now consider a target moving smoothly in a circular path. Both the horizontal and vertical components in such a display may be described as oscillating movements varying with sinusoidal velocity. As noted above, we would expect the tracking eye to lag behind the target above a certain speed. Since the eye will now be lagging in both the vertical and horizontal dimensions, the eye should be describing a circular path of a diameter smaller than the diameter of the physical path of the target. If the information which reaches the conscious centers is based predominantly on the information associated with the actual path of movement of the pursuing eye, then the resultant percept should be of a circle with reduced diameter. Since the lag in the pursuing eye has been shown to increase as the target speed increases (Fender, 1971), we should find both a reduction in tracked diameter and a reduction in the perceived size of the circular target path with increasing target speed. In fact, the perceived diameter of the path would decrease steadily as target speed increases, until the image is far enough off fovea to trigger a saccadic correction. Saccadic eye movements apparently provide accurate information about target position (Festinger and Cannon, 1965), hence once the lag in the pursuing eye becomes large enough to begin to trigger corrective saccades, the target path should become more veridical. Thus in summary, we may predict that, as the speed of a spot of light moving in a circular path is increased, the smoothly pursuing eye will traverse circles of progressively smaller diameter. This should lead perceptually to a steady decrease in the apparent size of the circular path as long as the spot remains on or near the fovea and no corrective saccades are elicited. As the speed of the spot increases further, corrective saccades should begin to appear as the subject tries to keep the spot near the fovea. With increasing use of saccades, accurate information about target locus should be available and the perceived path of the target should begin to expand until it is again veridical.

EXPERIMENT 1

Experiment 1 was performed to test these predictions about the contribution of saccadic and smooth tracking eye movements to the perceived extent of target movement.

Method

Subjects. Twelve observers with normal vision served as subjects. Each subject served under all stimulus conditions.

Apparatus. The basic stimulus situation consisted of a luminous target moving in a circular path against a dark background. This target was a 0·5° circular spot of light with an intensity of 1 mL. The stimulus situation was created by mounting a light on the rim of a black disk that was 20° dia. The disk could be rotated by a synchronous electric motor, with the speed of rotation controlled by a calibrated mechanical transmission. In the dark, only the spot of light moving in a circular path could be seen. Between exposure periods, a manual shutter was placed between the subject and the target, thus occluding the stimulus.

The apparent diameter of the target path could be indicated by the observer through adjustment of the distance between two 0·5° spots of light similar to that used in generating the stimulus. These lights were mounted on the manual shutter and thus appeared immediately upon the disappearance of the rotating target.

Electro-oculographic recording of horizontal eye movements was effected by the use of Beckman bio-potential electrodes and differential DC amplification from a Grass model 7 oscillograph. Vertical eye movement records are not taken because they tend to include an eye lid artifact which makes the actual measured extent of movement unreliable. To minimize drift, the subject's head was immobilized in a head and chin rest. Electrodes were affixed to the temporal canthus of each eye with a grounding electrode behind one ear. A recording preparation patterned after Coren and Hoenig (1972) and Fort, White and Lichtenstein (1958) was utilized to reduce noise. This preparation involves preparing the skin with acetone to dissolve dermal fat and oil, and scoring the surface of the skin to produce positive contact with the electrode. This procedure produces relatively low drift records with a resolution of 30′ or better. The recordings are linear for 20° rotations of the eye to either side of central gaze and no noticeable change in recording gain is found as long as the adaptive state of the eye remains constant.

Procedure. Six different rotational velocities were used: 0·18, 0·67, 1·13, 1·73, 2·47 and 5·20 cycles/sec. The five slower speeds give the appearance of a spot of light moving in a circular path, while the fastest speed provides the appearance of a fused circle.

Subjects were instructed to track the target as best they could, moving their eyes around the circle if the array was fused. Each stimulus was exposed for 20 sec after which it disappeared and the setting lights appeared. The observer was told to adjust the distance between the two lights until this distance appeared equal to the diameter of the target path he had just observed. The stimulus speeds were presented in randomly ordered blocks until four judgments had been made at each speed.

Results and discussions

We must consider the results in two segments: first the path that the eye actually traverses under these conditions and second, the perception of the size of the target path.

On the basis of the studies which indicated that the smooth tracking eye tends to lag behind the target increasingly as target speed increases (Dallas and Jones, 1963; Fender 1971; Stark *et al.*, 1962) we predicted that, for a target describing a circular path, the lag in both horizontal and vertical components should cause the eye to transcribe a circle whose diameter decreases as target speed increases. Beyond some speed, increasing numbers of saccades, correcting for the lag should begin to appear in the eye movement records. To check this prediction, the maximum excursion of the eye was assessed in all records where smooth tracking eye movements occurred.

Figure 1 shows several representative examples of recordings of actual patterns of eye movements. When the spot is moving at the velocity of 0·18 cycles/sec, we find virtually perfect smooth tracking movements. Saccades are infrequent and, when they occur, they are quite small. The horizontal excursion of the eye in tracking the target over 20° is quite close to 20°. As we increase the speed of the target to 0·67 cycles/sec, we begin to see more saccades in the eye movement records. In addition, the horizontal excursion of the eye at this speed is diminished by some 2°. Thus, although the target is describing a path of 20°, the eye is describing a circle with a diameter of 18°. Increasing the speed of target rotation to 1·13 cycles/sec produces truly dramatic results. For close to 80 per cent of the time we find the eye engaged in smooth tracking behavior. There are some saccades in the records, they are still surprisingly infrequent. The total horizontal excursion of the eye at this speed is greatly reduced. For a target path with a diameter of 20°, we find the eye describing a circular track with a diameter of only 14°. As the target speed increases still more, the ability of the eye to track the stimulus deteriorates. More and more saccades appear in the eye movement records at 1·73 cycles/sec, and tracking at this speed is, at best, sporadic (although when tracking does occur, the diameter of the path of the eye is greatly diminished). By the time a speed of 2·47 cycles/sec is reached the eye movement records no longer show any evidence of smooth pursuit. At both this speed and the fused circle speed (5·20 cycles/sec), only saccadic eye movements are found in the records.

Two major trends emerge from the analysis of the eye movement records: (1) as the target rotates at a faster and faster rate, the diameter of the circular pursuit path described by the eye decreases; and (2) as the target speed increases, the amount of time the eye spends in smooth pursuit, as opposed to saccadic movement, decreases. This latter finding, while not very surprising, replicates the work of Gerathewhol, Stringhold and Taylor (1957). The percentage of time spent not tracking increases steadily as target speed increases as can be seen in Fig. 2. This effect of speed on time engaged in smooth pursuit is statistically significant ($F = 642{\cdot}4$, $df = 5/55$, $P < 0{\cdot}01$).

Let us now turn to the apparent size data. We have assumed that, under smooth pursuit conditions, no information about the discrepancy between target position and foveal position is made available to the conscious centers unless the discrepancy becomes large

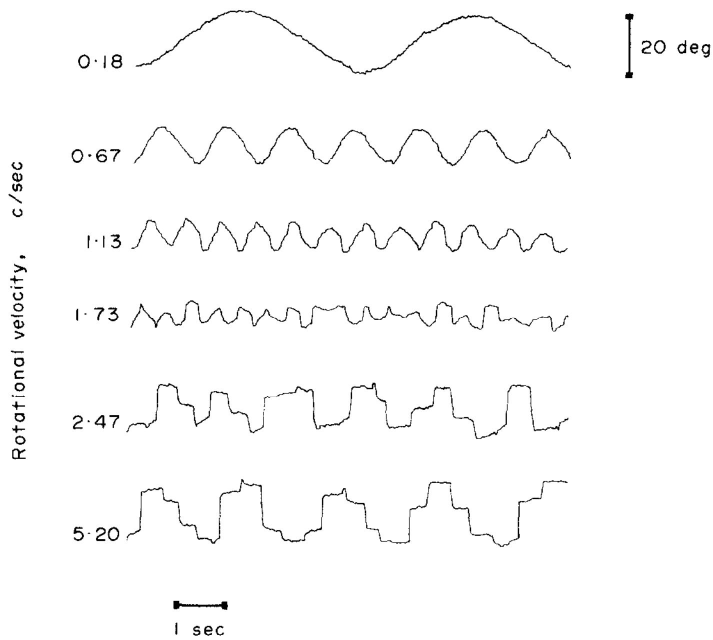

FIG. 1. Representative records of the horizontal component of eye movements for each of the six speeds of rotation. These recordings were all taken on the same subject. Note that as the target speed increases the diameter of the smooth pursuit decreases. As tracking breaks down and saccades begin to dominate the record, the diameter of ocular excursion again returns to 20°.

enough to trigger a saccadic correction. If the perceptual centers keep a record of the actual path that is tracked and this information is used to compute the perception of the extent of target movement, the apparent extent of the target path should decrease as the diameter of the eye movement path decreases. This relationship should, however, only hold at speeds below those where saccades begin to predominate, since saccades presumably provide error information about the diameter of the tracked target path. As smooth tracking eye movements begin to disappear and saccades begin to appear, the perception of the size of the target path should gradually increase until it becomes veridical. These predictions are verified by the perceptual estimates of apparent path diameter which are plotted as function of target speed in Fig. 2. It is clear that, as the speed of the target increases, the apparent diameter of the path decreases until we reach 1·73 cycles/sec and the time not tracking approaches 50 per cent. At this point, the perceived extent of the target path beings to increase toward veridicality. The effect of target speed on perceived diameter is significant ($F = 13{\cdot}2$, $df = 5/55$, $P < 0{\cdot}01$) as is the quadratic trend which was predicted above ($F = 60{\cdot}2$, $df = 1/55$, $P < 0{\cdot}01$). The significance of the quadratic trend, of course, indicates that the obtained function is reliably U shaped. The magnitudes of these effects are quite large, producing a better than 6° underestimation of the target path at the minimum of the curve (1·13 cycles/sec). The estimates of target diameter are undistorted at the slowest and fastest speeds. At the slowest speed (0·18 cycles/sec), this accuracy is probably due to the fact that the eye is able to track the target quite accurately, whereas at the two fastest speeds, the perceptual estimates are probably quite accurate because all of the information about path size is collected via saccadic eye movements. At intermediate speeds, where

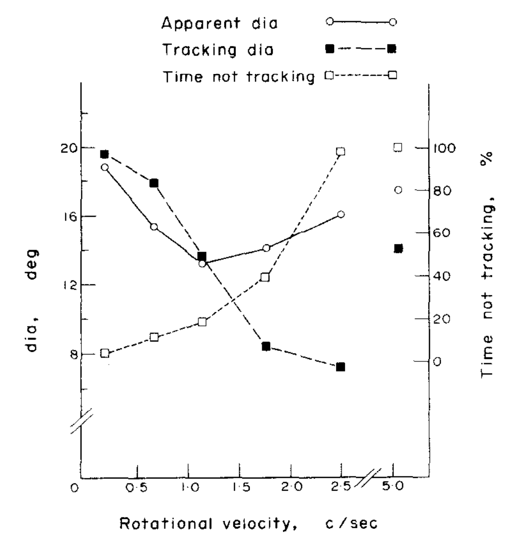

FIG. 2. The apparent diameter of the target path, the diameter of the path actually tracked by the eye, and the percentage of time that the eye did not engage in smooth pursuit are plotted as a function of speed of target rotation.

much of the perception of the path size is based upon information from the undertracking eye, we find an underestimation of path diameter.

These data, while suggesting a possible casual relationship between the extent of pursuit movements and the perceived extent of the path of the target being tracked, prove merely that there is a high correlation between the perceptual and the ocular responses. It is possible that the perceived contraction of the target path is due to some kind of configurational factor and that the distorted percept then triggers the pursuit system to make correspondingly smaller eye movements. This, of course, reverses the explanation that we proposed above. Thus, to test more precisely the role of eye movements in the production of this distortion, the following experiment was conducted.

EXPERIMENT 2

If eye movements are needed to produce the apparent shrinking and expansion of the path of a moving target, then the elimination of eye movements should eliminate these perceptual effects.

Method

Subjects. Twenty-four observers with normal vision served as subjects. Each subject served under all stimulus conditions.

Apparatus. The same apparatus used in experiment 1 was used in Experiment 2, except that a stationary red fixation point was placed in the center of the rotating disk.

Procedure. The six speeds of target rotation used in Experiment 1 were also used in this experiment. Two viewing conditions were employed. On one-half of the trials *S*s were instructed to track the target as best they could for 15 sec of target rotation; on the other half of the trials, they were instructed to fixate the central fixation point during the 15 sec the display was visible. Immediately after each exposure, *S*s made a visual estimate of the diameter of the target path by adjusting the distance between two lights as in experiment 1. Two estimates of target path diameter were made for each speed and viewing condition. The order of presentation of target speeds was randomized within each viewing condition according to the balanced square principal. Half of the *S*s received the fixation condition first and half received the tracking condition first.

Results and discussion

If our theoretical speculations are correct, the illusory shrinking of the apparent size of the target path should occur only in the condition when the eye is freely moving. The results of this experiment are shown in Fig. 3. It is clear that the size estimates are considerably closer to 20° in the fixation condition than in the tracking condition. Tracking produces both smaller estimates in general and a massive underestimation of the diameter of the target path at intermediate speeds of rotation. The estimated path size is significantly reduced when the eye is tracking the target as compared with when the eye is fixating a central point. ($F = 51{\cdot}70$, $df = 1/23$, $P < 0{\cdot}01$).

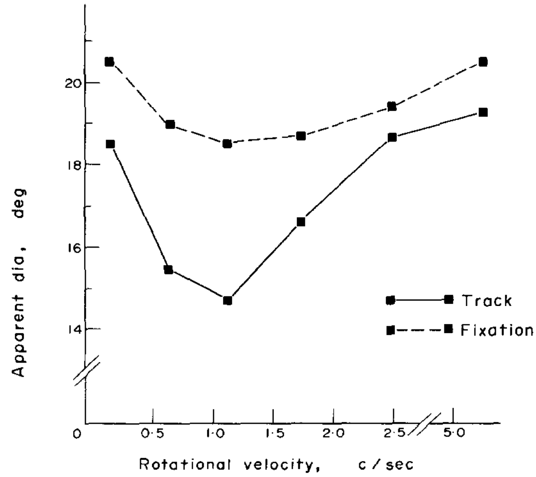

FIG. 3. The apparent diameter of the target path under fixation and tracking conditions is plotted as a function of the speed of target rotation.

Further analysis of the tracking data indicates that the significant quadratic component observed in experiment 1 has been replicated in this experiment ($F = 42{\cdot}8$, $df = 5/115$, $P < 0{\cdot}01$). It should be noted that there is also some evidence for a quadratic component in the estimates of path diameter made under fixation conditions ($F = 39{\cdot}2$, $df = 5/115$, $P < 0{\cdot}01$). The magnitude of this shrinkage under fixation conditions is not very large, however, and, at its maximum, results in only a 7 per cent distortion of the path diameter as opposed to 27 per cent underestimation of the diameter when the eye is tracking. This contraction may be configurational in nature as similar small effects have been shown for apparent movement displays (Brown and Voth, 1937; Koffka, 1935). Thus most of the distortion seems to be associated with conditions where the eye is moving. In the absence of such movement, the effect is greatly attenuated.

Taken together, these two experiments provide some interesting suggestions about how smooth tracking eye movements and saccades interact in the formation of the conscious percept. To begin with, there is the implication that the path that the eye smoothly tracks is utilized in the perceptual computation of path diameter. As the eye tracks over smaller and smaller diameters, the apparent path length seems correspondingly contracted. It should be noted that, at the speeds where this contraction occurs, the observer has the subjective impression that the target is accurately fixated, even though it may be several degrees from the foveal center. Since the principal function of the smooth pursuit system seems to be velocity matching, it may be relatively insensitive to these placement errors. Thus, information about target locus on the retina is not passed on to the higher centers. It is as if, within limits, the smooth tracking system assumes that the target is on fovea and therefore that the path of the target is the same as the tracked path of the eye. When the error becomes large enough, however, and exceeds some threshold value, the discrepancy between target and foveal position becomes salient and a saccadic eye movement is used to place the image back on or near the center of the fovea. Since the execution of a saccadic eye movement implies extraction of the spatial locus of the target relative to fovea, this information must now be available to the higher centers. It seems reasonable to assume that this error information is combined with the record of the distance that the eye has tracked to yield the eventual perception of path size. As more and more saccadic involvement appears, more and more error information is available and the perception of the target path becomes more and more veridical despite continued under-tracking during smooth pursuit. Such differences support the suggestions of researchers such as Fender, 1962; Rashbass, 1961; and Westheimer, 1954, who have suggested that smooth tracking and saccadic eye movements represent different systems.

In summary, when smoothly pursuing a moving target, size estimates seem to be primarily based on the extent of the actual eye movements, even when those eye movements are considerably smaller than the actual target path because the eye undertracks the target. The pursuit system seems to have considerable tolerance for placement of the target off fovea and percepts based on information from smooth tracking eye movements do not seem to take this retinal error information into account. Saccadic eye movements, on the other hand are apparently programmed on the basis of such error information and provide more reliable information to the sensorium. As the percentage of saccadic eye movements increases, the size estimates become more veridical. It should be noted, in addition that fixation conditions also led to relatively accurate size estimations. This might lead to the speculation that size perception is based on eye movement information when it is available and on retinal information when no eye movements are possible.

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Résumé—On décrit une illusion de distorsion qui contracte aux vitesses moyennes le diamètre apparent du trajet d'une cible se déplaçant en cercle. La réduction apparente du diamètre du trajet est en forte corrélation avec le comportement de poursuite continue de l'oeil, et la distorsion disparait aux vitesses plus grandes avec l'apparition de saccades. En l'absence de mouvement de poursuite de l'oeil, la grandeur de la distorsion diminue fortement. On discute ces résultats en termes d'une interaction possible entre poursuite régulière et mouvements saccadés des yeux dans la perception de la taille, et de différences possibles dans l'utilisation de l'information du système binoculaire de mouvement des yeux.

Zusammenfassung—Es wurde eine scheinbare Verzerrung beschrieben. Der sichtbare Durchmesser der Bahn eines Sehdings, das sich durch einen Kreis bewegt, scheint bei mittleren Geschwindigkeiten verkürzt.

Die scheinbare Verkürzung des Bahndurchmessers ist eng korreliert mit langsamen Folgebewegungen des Auges und die Verzerrung tritt auf, wenn sich bei höheren Geschwindigkeiten Sakkaden einstellen. Ohne Suchbewegungen ist die Verzerrung gering. Diese Ergebnisse werden im Hinblick darauf diskutiert, dass es eine mögliche Wechselwirkung zwischen langsamen Suchbewegungen und Sakkaden bei der Grössenwahrnehmung gibt und mögliche Unterschiede bei der Informationsverarbeitung durch das Bewegungssystem beider Augen.

Резюме—Описано иллюзорное смещение, которое выражается в том, что кажущийся диаметр траектории тестового объекта, движущегося по кругу, при средней скорости вращения, уменьшается. Кажущееся уменьшение диаметра траектории находится в высокой корреляции с плавными прослеживающими движениями глаза. Но это смещение исчезает, если появляются саккадические движения более высокой скорости. При отсутствии прослеживающего движения глаза, величнаи смещения в значительной степени уменьшается. Эти данные обсуждаются, исходя из возможного взаимодействия между плавными прослеживающими и саккадическими движенями глаз при восприятии величины и возможных различий в использовании информации от двух систем движений глаз.