Vision Res. Vol. 16, pp. 431 to 433. Pergamon Press 1976. Printed in Great Britain.

LETTER TO THE EDITORS

FIGURE DISTORTION ACCOMPANYING PURSUIT EYE MOVEMENTS[1]

(*Received* 2 *June* 1975; *in revised form* 15 *August* 1975)

Interest in pursuit eye movements has recently been revived by observations that show the adequate stimulus for visual pursuit to be more complex than was previously thought. Pursuit can be maintained without a continuously present stimulus, and even target movement is unnecessary under some conditions.

The first modern demonstration of such effects was Stoper's (1967) "picket-fence illusion", where an entire row of vertical lines was stroboscopically illuminated while a small moving fixation target elicited tracking along the row. If the target moved just fast enough to cross one line for every flash of the stroboscope, the entire string of lines appeared to move smoothly along with it; each time the strobe flashed, a line was present at the same retinal location as the adjacent line during the previous flash. The tracked target was then removed and pursuit eye movements (EMs) continued without a moving stimulus to drive them. Stoper showed that pursuit was responsible for this effect by moving the top half of each line to the right so that it was half way between two of the original lines. With this staggered-line stimulus the illusion could again be elicited, and the lines appeared as they did in the picket-fence case. Thus pursuit not only elicited a movement illusion, but also made the figure appear different than it did during steady fixation.

LaMontagne (1974) described a similar effect with rows of stroboscopically illuminated dots, and Heywood (1974) showed by measuring EMs that smooth pursuit was necessary for the occurrence of the illusion. Festinger and Easton (1974) have demonstrated another illusion brought on by pursuit EMs. In this case the motion was real, but systematic tracking inaccuracies resulted in a changed perception. The perceived shape of a closed figure described by a moving spot was related to a combination of the path of smooth tracking and the path which the spot described on the retina. Differences between these two paths on one hand, and the perception of the figure's size and shape on the other, led to the inference that precise information is available to a subject about the direction of pursuit EMs but not about their velocity. A figure always seemed smaller when it was tracked than when it was observed during steady fixation or during fixations interrupted by saccades. (Coren, Bradley, Hoenig and Girgus (1975) have recently described the same illusion with a circular figure.) Johansson (1950) described other illusions of motion dependent upon the presence of other points in the visual field, in situations where the relative motions between the other points and the attended point influence the perceived motion of the attended point.

All of the above experiments have been performed in darkness, however, without the normal "ambient array" (Gibson, 1966) which usually gives the visual system reliable information about the position of the real world. Here we investigate the nature of the pursuit illusion when information is available in a normal ambient array which is theoretically adequate to eliminate the illusion.

We simplified the stimulus conditions by using a conventional sawtooth, with each cycle consisting of a ramp followed by an instantaneous return to the baseline. Visual pursuit made the slanted component look vertical. The display looked like an integrated figure moving horizontally across the screen. We measured EMs during perception of the illusion to assess their role in eliciting the distortion of the figure.

METHOD

Pilot experiments showed that with a constant X-axis sweep rate and constant sawtooth height, the slanted portion of the display was seen as vertical (the "illusion") if the sawtooth period did not exceed a critical value of approx 370 msec. Near this period, without changing the physical stimulus, the illusion was seen on some trials and not seen on others. We hypothesized that with this constant period the illusion would be reported only when the subject (*S*) pursued the display smoothly.

Apparatus

A repeating sawtooth pattern was displayed on a monitor (Tektronix 604, P15 fast-decay phosphor). With *S*'s cornea 44 cm from the minitor, the display was 7·0° high and subtended 17·4° horizontally. Sweep rate of the X-axis was constant at 8·7 deg/sec, so that the duration of each sweep was 2·0 sec. Monitor intensity was set so that the display was clearly visible, and room illumination was normal. (Neither intensity parameter was critical to the appearance of the illusion.)

S's head was restrained, and horizontal EMs were monitored with paired photocells which recorded the amount of i.r. light reflected from the iris–sclera border (Stark, Vossius and Young, 1962; Noton and Stark, 1971). The push–pull amplified output from the photocells was displayed on a storage oscilloscope using a time base synchronized with that of the sawtooth pattern. The records were photographed for later analysis.

Procedure

The period of the sawtooth for which the illusion was visible approx 50% of the time was determined for two

[1] This research was supported by grants to B. Bridgeman and to M. Mayer from the Santa Cruz Division of the Academic Senate of the University of California.

naive Ss. Each S then observed at least 100 trials in which the repeating sawtooth was presented once across the display monitor. EMs were recorded, and S reported at the end of each trial whether the illusion was seen. Trials on which S could not make a judgment were repeated. Before and after each block of trials, the EM monitoring system was calibrated by having S track a spot moving horizontally at the standard sweep speed. Several saccade-free tracks were made to check for gain and linearity.

In order to eliminate the effect of changes in eye position associated with starting and stopping of tracking at either end of the display, only the middle 0·75 sec of the EM photographs were scored for saccades. A saccade was defined as any abrupt change in eye velocity.

RESULTS

Typical EM records are shown in Fig. 1.

Each S's data were tallied in a 2×2, Illusion × Saccade Yes–No decision matrix. A χ^2 test for independent samples showed no significant difference between Ss (χ^2 (3) = 2·37, $P > 0·50$); therefore, the Ss' data were combined (see Table 1.) A phi coefficient (four-fold point correlation) for the combined data of the 2×2 table was highly significant ($\phi = 0·256$, $P < 0·001$). Most of the correlation resulted from the fact that when Ss reported seeing the illusion, they were very likely to have a record showing smooth tracking. If Ss did not report seeing the illusion, however, there was still no saccade on half of the trials.

DISCUSSION

The pursuit illusion described here depends upon the visual system directing the eye not to the true location of the target stimulus, but to its average location integrated over time. Thus smooth pursuit can be elicited by a target which does not move smoothly, and the changes in its appearance can be accounted for by the differences between target movement and eye movement.

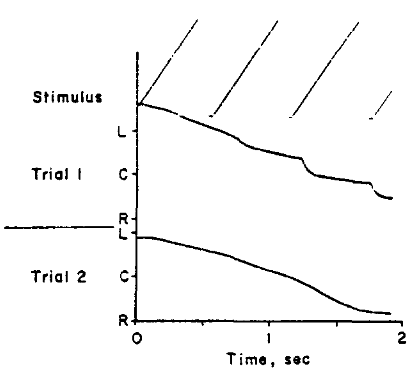

Fig. 1. Horizontal eye movements (EMs) during pursuit, with the path traced by the stimulus shown at the top. The final 100 msec of each trial is not shown. Trial 1 shows pursuit interrupted by saccades; in this trial, the S reported no illusion. Trial 2 shows saccade-free pursuit: the S reported a good illusion, with the line appearing vertical in spite of inaccuracies in pursuit. The inaccuracies are represented by the curves of the EM record. During calibration, EMs at a constant speed resulted in a record with a constant slope. See text for stimulus and eye position parameters. L = left edge of screen; C = center; R = right.

Table 1. Presence or absence of the tracking illusion vs presence or absence of saccadic eye movements

		Saccade		
		Yes	No	Total
Illusion	Yes	25	76	101
	No	51	52	103
	Total	76	128	204

The maximum degree of difference between the stimulus movement and the eye movement describes the ability of the pursuit system to integrate visual position information in generating pursuit motor commands. The critical variable appears to be the length of time that the stimulus deviates from the fixation point before returning, or in our case the oscillation frequency of the target. With a stimulus moving at a constant horizontal speed but undergoing a sawtooth oscillation in the vertical direction, we found that a period averaging 370 msec could be tolerated before the system broke into saccades. Allowing for differences in stimulus and technique, this period is consistent with the 3/sec oscillation frequencies found by Robinson (1965) for the pursuit system under increased feedback.

Although the relationship between success of smooth pursuit and appearance of the illusion was highly significant near the "break point" of the illusion, the eye movement data accounted for only a small proportion of the variance in the appearance of the illusion. There are two reasons why this might be so. First, by limiting observations to the narrow range of stimulus periods where the illusion was seen about 50% of the time, we introduced a range restriction which unavoidably reduces correlations. Second, the illusion often broke down at the end of the scan, so that Ss often had difficulty in deciding whether or not the illusion had occurred on a given trial. Thus a temporary breakdown of the illusion near the end of a trial might induce a spurious "no" response in spite of a lack of saccades in the scoring interval. The illusion is nearly always seen at higher oscillation rates, however, and this condition will be discussed below.

The major conclusion of this study is that during pursuit eye movement the visual system does not preserve information relating the tracked stimulus to a background frame of reference. The most obvious interpretation of this phenomenon is that the S sees what is "written" on his retina, for the moving dot's projection on the retina traces a vertical meridian. Though this would account for the basic phenomenon, it contradicts what is already known about retinal images: that they are not directly accessible to perception.

The perspective illusions offer dramatic examples of the nature of retinal-image perception; a figure which appears to be more distant in a perspective drawing will be seen as larger than a closer figure if the two have identical retinal images. In fact, all of the classical static geometric illusions (Müller–Lyer, Poggendorff, Hering, Wundt, etc.) depend upon the non-equivalence of the geometry of the retinal image and the actual perception. This interpretation is neither new nor unique to the visual system: when feeling an object such as an apple one is aware of the apple's shape, hardness, etc., and is oblivious to the deformations of the hand which mediate the perceptions. Analogously, visual stimuli are seen in the world, and their corresponding retinal stimulations are usually unavailable to perception. Another example of this projection into the world, which is more related to problems of information processing during eye movements, is the perception of a tracked target as moving and the rest of the visual world as stationary, when of course the retinal movements are exactly reversed; the target is moving very little on the retina, and the background is sweeping by at the pursuit rate. Yet we do not become disoriented during pursuit. The movement relationships are reversed between the retinal stimulation stage and the perception stage without interfering significantly with visual-motor coordination or pattern recognition.

Rock and Halper (1969) have shown experimentally that "painting" of a stimulus on the retina is not an adequate stimulus for perception of shape. They compared perception of the shape traced by a moving light in darkness under two conditions. In one condition the subject fixated one light while another light traced a path to be described. In the other condition the *S* tracked one light and was asked to describe the path traced on the retina by the other, which remained fixed in space. The retinal stimulation was identical in the two conditions; nonetheless, *S*s were successful in describing the path of the light only in the first condition, where the light was perceived as moving in space. Our study adds to this result by showing that figural distortions as well as failures of perception can result from frame-of-reference manipulations.

If direct perception of the motion described on the retina is not a viable explanation of the pursuit illusions described here, another explanation must be found. It is useful to distinguish two frames of reference. The background frame of reference (BFR) refers to the large background array, the periphery of the "ambient array" of Gibson (1966), which defines the position of the world and does not move with respect to itself. The object frame of reference (OFR) is a frame attached to the tracked object. Ordinarily this frame moves with the fixation point during pursuit movements. The fact that the pursuit illusion occurs in spite of the availability of information in the ambient array adequate for veridical perception shows that this information is not used, and reference is made to the OFR instead. Information is available in the ambient array in the sawtooth-stimulus experiment to tell the *S* that the stimulus path is slanted, for at each instant the scanning dot is further from the visible left edge of the screen (BFR) than at the previous instant. Thus an alternative interpretation of the illusion is that deviations of an object from the path of pursuit are interpreted with respect to the OFR. When the sawtooth is being tracked, the motion of the stimulus spot is seen as vertical because it is moving laterally at the same rate as the OFR, and only a vertical component of motion remains in this frame of reference. Other examples of this effect include the perception of a point on a bicycle wheel as rotating rather than as describing a cycloid; the motion is interpreted with respect to the moving bicycle (OFR) rather than with respect to the BFR. Steady fixation then becomes a trivial case in which OFR and BFR coincide, so that the path described by the sawtooth stimulus is seen as tilted. This interpretation, while not as readily apparent as the retinal "painting" hypothesis, has just as much explanatory and predictive power, and has the virtue of consistency with other known characteristics of visual perception.

Psychology Board,
University of California,
Santa Cruz, CA 95064, *U.S.A.*

BRUCE BRIDGEMAN
MELANIE MAYER
LOYD GLENN[2]

[2] Present address: Department of Psychiatry, Stanford University.

REFERENCES

Coren S., Bradley D., Hoenig P. and Girgus J. (1975) The effect of smooth tracking and saccadic eye movements on the perception of size: the shrinking circle illusion. *Vision Res.* **15**, 49–55.

Festinger L. and Easton A. M. (1974) Inferences about the efferent system based on a perceptual illusion produced by eye movements. *Psychol. Rev.* **81**, 44–58.

Gibson J. J. (1966) *The Senses Considered as Perceptual Systems.* Houghton-Mifflin, Boston.

Heywood S. (1974) Pursuing stationary dots: smooth eye movements and apparent movement. *Perception* **2** (2), 181–195.

Johansson G. (1950) *Configurations in Event Perception.* Almquist & Wicksell, Uppsala, Sweden.

Lamontagne C. (1974) A new experimental paradigm for the investigation of the secondary system of human visual motion perception. *Perception* **2** (2), 167–180.

Noton D. and Stark L. (1971) Scanpaths in saccadic eye movements while viewing and recognizing patterns. *Vision Res.* **11**, 929–942.

Robinson D. A. (1965) The mechanics of human smooth pursuit eye movement. *J. Physiol., Lond.* **159**, 326–338.

Rock I. and Halper F. (1969) Form perception without a retinal image. *Am. J. Psychol.* **82**, 425–440.

Stark L., Vossius G. and Young L. (1962) Predictive control of eye tracking movements. *I.R.E. Trans. hum. Factors Electron.* **HFE-3**, 52–57.

Stoper A. (1967) Vision during pursuit movement: the role of oculomotor information. Ph.D. Dissertation. Brandeis Univ., May 1967.