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symposium paper

Control of Eye Movement with Peripheral Vision: Implications for Training of Eccentric Viewing

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ABSTRACT

A review of peripheral visual control of eye movements suggests that such control may be easier if the direction of the extrafoveal locus used is orthogonal rather than radial to the direction of target motion. When the extrafoveal locus lies parallel (radial) to the direction of target or eye motion, artificial feedback is usually required to avoid reflexive foveation. These findings have important implications for training eccentric viewing in low vision patients with central scotomata.

Key Words: eye movements, peripheral vision, eccentric viewing, low vision

The oculomotor system is commonly described as a mechanism for foveation.[1] Visual information is acquired during the fixation of points of interest; saccades serve to bring the image of peripheral objects onto the fovea, and smooth pursuit maintains foveation of slowly moving targets. This mode of operation is preferred because of the inhomogeneity of the retina and the superior acuity at the fovea.

In the low vision patient with central scotomata, the fovea can no longer serve this purpose. Such a patient must use another retinal locus to acquire visual information, learning to direct this retinal point as steadily as possible toward the target.[2] The area of best residual acuity may be the first, but not the only, choice for such use. To fully use the ability to view eccentrically, the patient must develop the ability to establish this eccentric viewing in response to targets placed upon other peripheral retinal loci via "peripheral saccades"[3] and learn to track a moving target via "eccentric smooth pursuit."[4]

Patients can eccentrically track a moving target or view a series of stationary targets in either of two ways, which I call the orthogonal and radial paradigms. When tracking a horizontally moving target or reading a horizontal line of text, the patient can use an eccentric retinal locus on the vertical meridian (i.e., above or below the fovea). I call this the orthogonal paradigm because the direction of eccentricity of the retinal locus used is perpendicular to the direction of movement (Fig. 1A). If for the same task a retinal locus on the horizontal meridian (i.e., to the right or left of the fovea) is chosen, the patient is using a radial paradigm. In the radial paradigm, target movements are along the same meridian as the decentration of the retinal locus used (Fig. 1B). The outcome of using either paradigm should be the same: an ability to use an extrafoveal retinal locus for eccentric tracking and viewing of a target. If a patient uses only one paradigm, different retinal loci should be used to track targets moving in different directions.

In the past, the orthogonal[5] or radial[5,6] paradigm has been selected more or less arbitrarily for use in training low vision patients. I will

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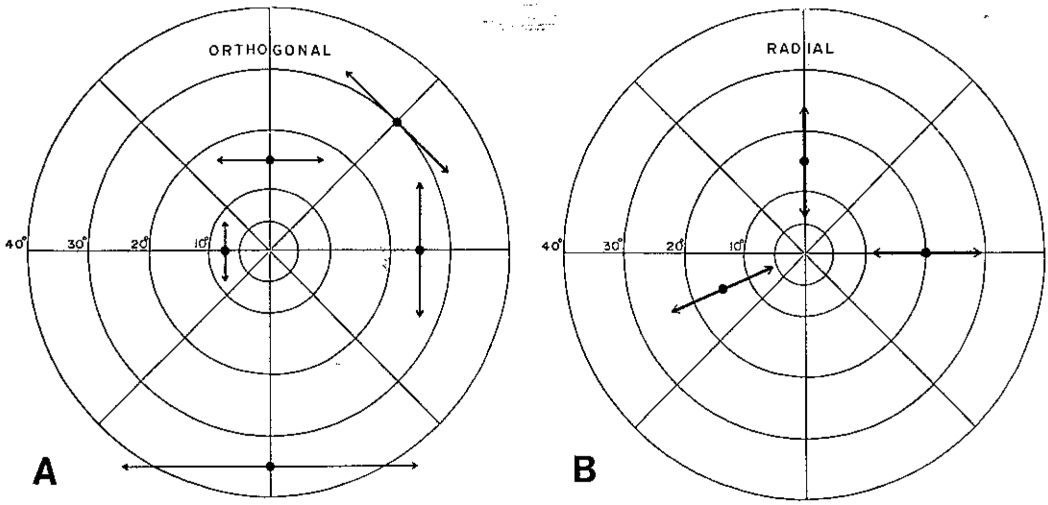

FIG. 1. A, orthogonal paradigm for control of eye movements with peripheral vision. When horizontal movement is required, a retinal locus on the vertical meridian (above or below the fovea) is used. B, radial paradigm for control of eye movements with peripheral vision. When horizontal movement is required, a retinal locus on the horizontal meridian (right or left of the fovea) is used.

review herein studies of fixation, saccades, and smooth-pursuit eye movements with peripheral vision. The findings suggest that the orthogonal paradigm is easier to learn and perform. The radial paradigm usually requires artificial feedback for the subjects to perform accurately and thus represents a more difficult approach to the training of patients with a central scotoma.

ECCENTRIC VIEWING

The ability to view eccentrically varies with target luminance, degree of eccentricity, and subject attention. As the target is dimmed, its eccentricity increased, or subject attention lags, fixation becomes less stable with a tendency to shift to foveal fixation.

Under scotopic condition the fovea ceases to be the most sensitive area of the retina. A target that is below threshold for the fovea can still be visible at perifoveal loci.[7] Steinman and Cunitz[8] studied the patterns of eye movements when a subject attempted to fixate very dim lights that previously had been reported[7] to disappear intermittently. The disappearance was found to be the result of maladaptive eye movements. Smooth drifts brought the target image from the more sensitive perifovea to the less sensitive foveal area, and correcting saccades took the image back to the perifoveal location. Both types of movements increased in frequency and amplitude as target luminance decreased. These findings suggest the existence of a reflexive slow eye movement mechanism that guides peripheral targets into the central fovea even when this would cause the target to disappear. However, if the target is bright enough, the subject can maintain eccentric viewing "reasonably well" and avoid these reflexive movements.[8]

Sansbury et al.[9] documented the effect of target eccentricity on the stability of fixation. Subjects were required to maintain fixation at the center of two- or four-disc arrays separated by 10 to 29.5°. Two-dimensional eye movements recorded with the contact lens optical lever technique were analyzed for the effects of target eccentricity and type of array on fixation instability and on the amplitude and rate of saccades and drifts. Fixation instability was evaluated via the SD of eye position measured over 20 s. Instability of fixation increased with eccentricity, whereas type of target array (horizontal pair, vertical pair, or the four discs) had minimal effect. Saccade rate was unaffected by eccentricity, but the amplitude of both saccades and intersaccadic drifts increased as eccentricity increased.

Rattle[10] reported similar experiments covering a range of smaller target eccentricities. His subjects were fixating the center of a circular disc or the centers of two small dots separated either vertically or horizontally. Targets spanned angles of 19 to 240 min arc. Rattle found surprisingly good stability of fixation at the center of the targets. The SD of eye position increased by less than a factor of 2 between the extreme target sizes. The effect of vertical and horizontal display varied with subjects. However, all subjects exhibited better fixation stability in a direction perpendicular to the line joining the dots in the horizontal display than in a direction parallel to this line.

Although fixation using eccentric retinal loci is possible both with and without attention to the peripheral target, acquisition of information can be enhanced with voluntary shifts of attention to the peripheral target.[11,12] Visual, auditory, and proprioceptive external feedback can facilitate the training in this difficult task. Zeevi et al.[13] measured eye movements in an eccentric viewing experiment where subjects' attention was directed to the peripheral target. Eccentric viewing was established using Secondary Visual Feedback (2VFB) by having subjects superimpose a cursor driven by a measured eye-position signal, visible to the subject, on the target display (Fig. 2). When a dc shift was added to the eye-position signal, the cursor became locked to some peripheral retinal location. That is, the feedback target behaved as would a continuously visible afterimage impressed on the peripheral retina. The subject then superimposed the 2VFB signal on the target by observing and eliminating the distance between the two signals. This task requires peripheral attention. This type of eccentric viewing was achievable within 10 to 40 s of the first trial even by naive subjects. Eccentricities up to 8° were tested. Patterns of eye movements were qualitatively similar to central fixation micronystagmus. The stability of the fixation decreased with increased eccentricity (as previously noted by Sansbury et al.[9]), similar to the reduction in visual acuity with eccentricity.

Auditory feedback was used similarly to facilitate central fixation in amblyopic patients with naturally occurring eccentric fixation.[14,15] In these studies the training was for central foveal fixation, rather than for eccentric viewing as in the other studies discussed here. In eccentric fixation the patient reports looking directly at the object, whereas in eccentric viewing he reports that he is "looking past" the object he is supposed to fixate.[16]

PERIPHERAL SACCADES

A peripheral saccade is defined as a saccadic eye movement whose goal is to place the image of the target on a retinal location other than the fovea.[3] Such movements enable the patient to use effectively his ability to maintain eccentric viewing.

Peripheral saccades in the orthogonal paradigm were demonstrated by Michalski et al.[17] who studied cats with pretrigeminal brainstem transection. In such cats, only vertical eye movements are present. The targets appeared 10° above or below the horizontal meridian and moved at 10 deg/s along the vertical meridian or parallel to it up to 40° in the periphery. Ocular following movements with both saccadic and pursuit components were evoked in all the positions tested. These movements prove that the

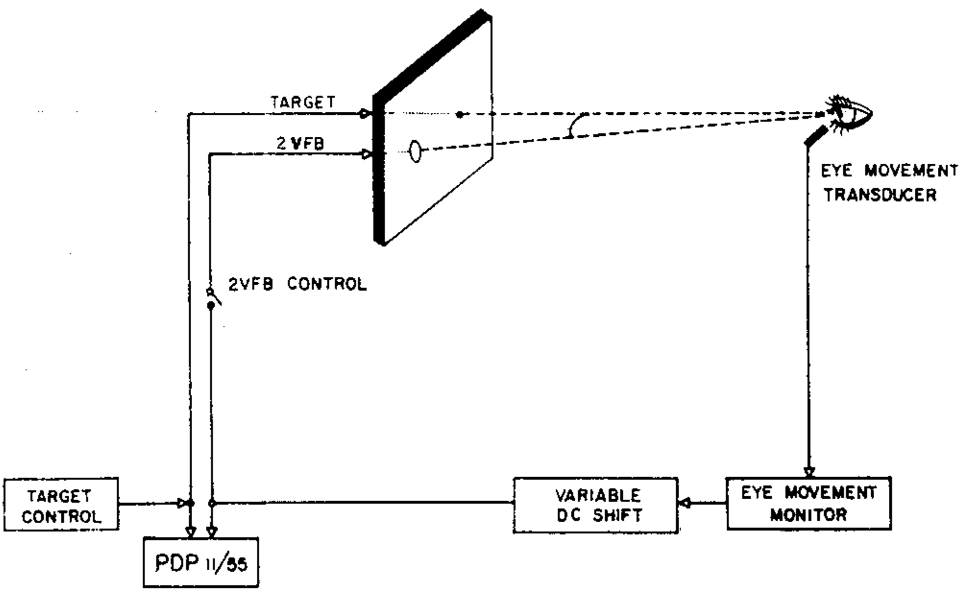

FIG. 2. Secondary Visual Feedback (2VFB) is used to achieve eccentric viewing[12] and radial peripheral saccades.[3] Measured eye position is displayed together with the target. With addition of a dc signal, the 2VFB is locked to a peripheral retinal locus. When the subject superimposes the 2VFB signal on the target, eccentric viewing is achieved.

cat's retinal periphery has the ability to drive the oculomotor system in tracking a peripheral target. Furthermore, saccadic latency, amplitude, and mean velocity did not differ significantly between central and peripheral stimulation.

Hallett[18] hypothesized that the saccadic mechanism is specialized for foveating targets, but maintains some limited capacity to point the fovea in any other direction at will. He studied radial peripheral saccades by presenting subjects with a luminous point target that stepped into one of eight horizontal positions, and instructing them to respond with one of the following eye movements: a saccade away from the target of equal magnitude to the target step ("antisaccade"), a saccade overshooting the target by about 4° ("hypersaccade"), or a saccade only half as large as the stimulus step ("hyposaccade"). Each of these tasks could be performed without extensive training, but performance differed from normal saccadic responses in that peripheral saccades had a longer latency and were less accurate than a normal saccade. Secondary saccades of short latency were corrective but were not based on retinal feedback; they were preprogrammed. The antisaccade task was further investigated for the effect on performance of training using on-line, multimodal feedback. The main effect of training was found to be a reduction in the number of erroneous reflexive foveation responses. However, training did not reduce the saccadic latency or the fixation error of both subjects, despite large numbers of trials, performance feedback, and "rewards." Similar lack of improvement in the reaction time (i.e., the latency of the antisaccade) was also noted by Zeevi and Peli,[3] but these authors found that practice significantly reduced the latency of the other type of peripheral saccades studied with the 2VFB.

Using the 2VFB, subjects established eccentric viewing of a stationary target at 4° of eccentricity via an antisaccade. The target was then abruptly shifted to a new position 8° to the right or left, and the subjects were instructed to reestablish eccentric viewing at the new position. These radial peripheral saccades were executed easily even by an untrained subject. The eye movements leading to eccentric viewing in this task have an oscillatory pattern. The first response is always a foveation of the target at its new location, followed by a sequence of saccades converging on the target with the "eccentric fovea." (One of our subjects was capable of performing the same task with smooth movements when he chose, and reported better control in this mode.) Although the first "foveal" saccade was expected to have normal saccadic latency, on the first trial its latency was found to be about twice as long. Short periods of practice (fewer than 15 sessions of 40 s each) reduced this latency consistently until it approached the normal foveal saccadic latency. This study demonstrated the power of the compulsive foveation reflex and how it could interfere with peripheral saccades made in a radial paradigm. This interference may be significantly less with the use of the orthogonal paradigm. This conclusion is supported by clinical findings[5,6] as well as by the eccentric smooth-pursuit experiments below, but further studies of orthogonal peripheral saccades are needed.

In their clinical study, Holcomb and Goodrich[6] used the orthogonal paradigm for one subject out of necessity; this subject had central scotomata and bilateral superior field loss. At the onset of training, he already knew to aim his eyes above the desired target. This subject performed better than the other subjects initially, and improved even more with training. The other subjects were trained with a radial paradigm of 2VFB using an afterimage to tag the retinal area that had the best remaining acuity. Training improved fixation and saccades for all subjects as was shown by a tachistoscopic peripheral letter-recognition test. The technique was considered successful, even though subjects experienced some difficulty in learning to appreciate the afterimage. A similar difficulty has been reported by other groups using afterimages as secondary feedback to facilitate control of eye movements.[19] These problems can be overcome by application of the electronic 2VFB[2] or by auditory feedback.[14]

Backman and Inde[5] stated that it is impossible to perform eye movement in the orthogonal paradigm but did not offer supporting evidence. They advocated an orthogonal reading paradigm in which the reading material is shifted laterally in front of the eyes. Rather than moving, the eyes remain fixed at one point above the line.

ECCENTRIC SMOOTH PURSUIT

The ability to pursue a target smoothly with the retinal periphery has been studied using both the orthogonal and radial paradigms. Winterson and Steinman[4] used the orthogonal paradigm. A point target was displaced vertically 6° above the fovea. It oscillated horizontally through an amplitude of 2.18° at a frequency of 0.13 to 5.0 Hz. Subjects were required to track the target with peripheral vision and to avoid foveal fixation. Eye movements monitored with the contact lens technique showed that orthogonal eccentric smooth pursuit is accomplished easily without practice. Furthermore, predictive tracking[20] occurred in this perifoveal area. As expected, the gain of the response was higher in foveal than in peripheral tracking. Large variations of target luminance did not affect oculomotor performance except that eccentric pursuits showed greater lag with scotopic than with photopic targets.

Steinbach[21] demonstrated similar results at a larger eccentricity. He used a diamond-shaped target, part of which lay behind an occluder. The subject tracked the invisible corner of the diamond that was 13° away from the nearest visible edge above the occluder. Horizontal movement could be obtained easily with such peripheral stimulation of a horizontally moving target at a vertical eccentricity. Steinbach further showed that peripheral target information can be processed to calculate a required tracking velocity. In an experiment with subjects who tracked the hub of a wheel in complete darkness, only two small lights mounted on opposite sides of the wheel rim were visible. The peripheral targets were moving in a cycloid motion, but subjects were able to follow the linear motion of the hub inferred from the cycloid motions.

Although orthogonal eccentric smooth pursuit can be achieved quite easily, and without training or any external modification except for voluntary effort by the subject to avoid foveal fixation of the target, radial eccentric smooth pursuit is difficult to achieve even after extensive training with external feedback. Steinman et al.[22] asked their subjects to follow a target moving horizontally through 6° at one of five velocities. The subjects were then asked to try to pursue at either ¼, ½, ¾, or twice the target velocity. Subjects could perform the task at velocities slower than target velocity but not at twice the velocity. When tracking the target at a fraction of its velocity, the subjects used only peripheral retinal signals to drive the smooth-pursuit system. Eccentric pursuit of a target in a radial paradigm has not been otherwise demonstrated to my knowledge, perhaps because the tendency to foveate is strong and difficult to suppress. This tendency results in a foveation saccade that interferes with such an attempt. Zeevi and I thought that the secondary visual feedback that facilitated training of eccentric viewing[13] and peripheral saccades[3] might help subjects perform radial eccentric smooth pursuit. Despite repeated training in the task (up to 10 sessions), none of our subjects could perform it for more than a fraction of a second. Eccentrically stabilized retinal images can be used to generate smooth movements in a radial paradigm in the open-loop mode. Kommerell and Taumer[19] showed that eccentric stabilized images generate eye movements in the direction of the target eccentricity. This response is composed of saccades and smooth movements occurring during the intersaccade intervals. For eccentricities greater than 3°, a series of saccades was the common response. At eccentricities less than 2°, a pure pursuit was almost always generated, velocity increasing with increasing eccentricity. Attention had a significant effect on the speed of pursuit and the number of saccades elicited.

Zeevi et al.[13] showed that subjects can use a decentered stabilized image to generate a smooth movement even if its direction is opposite to the direction of eccentricity and the eccentricity is up to 8°. The subjects performed this by attempting to superimpose the stabilized image on a stationary target. We also showed that the 2VFB can be used to move the eyes smoothly following an abrupt change of target position in both directions.[3] However, this response can be achieved only by subjects with exceptional oculomotor control. Even the best subject in the study was unable to avoid reflex foveation in this mode.

Thus, it has been shown that the radial paradigm of eccentric smooth movement is possible only with the use of artificial external feedback. Even with such feedback it is not clear whether the movements can be used to track a smoothly moving target. However, the orthogonal paradigm of eccentric smooth pursuit is easy to accomplish and requires little or no practice.

DISCUSSION

Senile macular degeneration is the leading cause of new blindness in the United States.[23] Typically, only central vision is lost, and peripheral vision remains intact. With the increasing number of older people, the prevalence of such vision loss is expected to increase. More patients will be able to benefit from training of eccentric viewing.

The current methods[2,6] for training eccentric viewing in a radial paradigm, using afterimages as secondary visual feedback, have been beneficial. However, they require extensive training, which is time consuming and typically very expensive.[24] These drawbacks are even more significant when the age of the potential patient population is considered. Better techniques that require shorter and more interesting training periods are needed. The results of the studies reviewed here suggest that the orthogonal mode of training may offer such an improvement. It was shown that some eccentric viewing tasks can be performed in the orthogonal mode, even without external feedback.[4] The use of feedback might help to shorten the training period and to make tasks more interesting for the patient.

Recent work by Romayananda et al.[25] offers further support for the use of an orthogonal paradigm. They used prism scanning to improve visual acuity in low vision patients with central scotomata. The base of the prism prescribed was in the superior half in 95% of the cases. Therefore, they suggested that a base-up prism shifts the image vertically as a starting point. Although this explanation has been subsequently rejected,[26,27] the result suggests patient preference for the orthogonal mode.

Two questions of importance to the training of low vision patients have not yet been fully addressed: the nature of orthogonal peripheral saccades in humans, and the quality of transfer from training with 2VFB to practical use of the eyes. Clinical reports[6,25] suggest that orthogonal saccades can be performed and are superior to the radial mode of operation, but further detailed study of these eye movements is required. Transfer from the training situation to practical use can only be inferred from the clinical reports.[6,25] Eye-movement measurement of trained patients during performance of reading and tracking tasks is needed to demonstrate such transfer.

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