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Fixational eye movements in amblyopia and strabismus

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ABSTRACT — Horizontal eye position was monitored using a photoelectric method during monocular and binocular fixation in four patients having amblyopia without strabismus, thirteen patients having constant strabismus with amblyopia, and five patients having intermittent strabismus. Four abnormalities of fixation were found: increased drift, saccadic intrusions, manifest nystagmus, and latent nystagmus. Increased drift was related to the presence of amblyopia, while saccadic intrusions and nystagmus were related to the presence of strabismus. Understanding dynamic aspects of oculomotor control can provide insight into clinical assessment of fixation in amblyopia and strabismus.

KEY WORDS: eye movements, fixation, amblyopia, strabismus, ocular drift, saccadic intrusions, nystagmus

Introduction

Fixational eye movements in patients with amblyopia and/or strabismus have been studied over the past two decades to determine which aspects of oculomotor control are abnormal and to determine the specific underlying sensory and motor mechanisms responsible for producing these anomalous movements.[1] While basic and applied research in amblyopia and strabismus is desirable and is currently an area of intense investigation, patients can only accrue benefits from these research endeavors if clinicians become familiar with this information to the point that direct in-office application is attempted.

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The purpose of this paper is to provide an overview of our new findings regarding dynamic aspects of fixational eye movements in amblyopia and strabismus, to discuss briefly possible mechanisms underlying these anomalous oculomotor patterns, and to demonstrate how knowledge of these findings can provide insight into clinical assessment of fixation in amblyopia and strabismus. Specific details of this research have been described elsewhere.[1,10]

Methods

A photoelectric method was used to record horizontal eye position.[11,12] Bandwidth of the recording system was 75 Hertz (Hz) (−3dB). Resolution was approximately 12 min arc. A chinrest and headrest, usually in conjunction with a bite bar covered with dental impression material, were used to stabilize the head. A PDP - 8/I minicomputer was used to generate a small (∼3.5) bright test spot on a display screen placed either 57 or 91 cm. in front of the patient along the midline. Target luminance was always maintained at least 1 log unit above screen luminance. Eye movements were recorded during 15-60 seconds of either monocular or binocular fixation.

Patients were obtained from the clinics at the School of Optometry. All had a thorough eye examination and were free of ocular or neurological disease. Ages ranged from 12 - 42 years with a mean age of 27 years. Patients had either amblyopia without strabismus (n=4), intermittent strabismus (n=5), or constant strabismus with amblyopia (n=13). Spectacle or contact lens prescription was worn during all testing.

Results and discussion

Four abnormalities of fixation were found: increased drift, saccadic intrusions, manifest nystagmus, and latent nystagmus. These phenomena will be defined and a quantitative description of each provided.

Increased drift[1,4,5,9]

Drift refers to slow movement of the eye during attempted steady fixation. Drift was considered abnormal if the amplitude exceeded 12 min arc and/or the velocity exceeded 20 min arc/sec; these criteria were developed in our oculomotor laboratory following testing of several hundred individuals, including experienced normal subjects, naive normal subjects, and clinic patients. Increased drift (percent total fixation time, excluding patients with nystagmus) in the amblyopic (or non-dominant) eye was found 75% of the time in amblyopia without strabismus, 50% of the time in constant strabismus with amblyopia, and 20% of the time in intermittent strabismus. Increased drift could be either error-producing or error-correcting in nature. Drift was within normal limits during binocular fixation and monocular fixation with the dominant eye. Increased drift was related to the presence of amblyopia, since it was found in amblyopia without strabismus *but not* in strabismus without amblyopia.

Records showing increased drift amplitude and velocity in two patients are presented in Figs. 1-4. In Fig. 1, the difference between steady fixation with the dominant eye and increased drift with the amblyopic eye is evident. In Fig. 2, increased drift amplitudes and velocities are clearly seen, as well as a paucity of corrective fixational saccades with amplitudes comparable to the drifts. Errors created by abnormal drift were generally corrected by drift movements in the opposite direction rather than by microsaccades. In Fig. 3, comparison between monocular fixation on a dim light in a darkened room by the amblyopic and dominant eye is presented. In the dominant

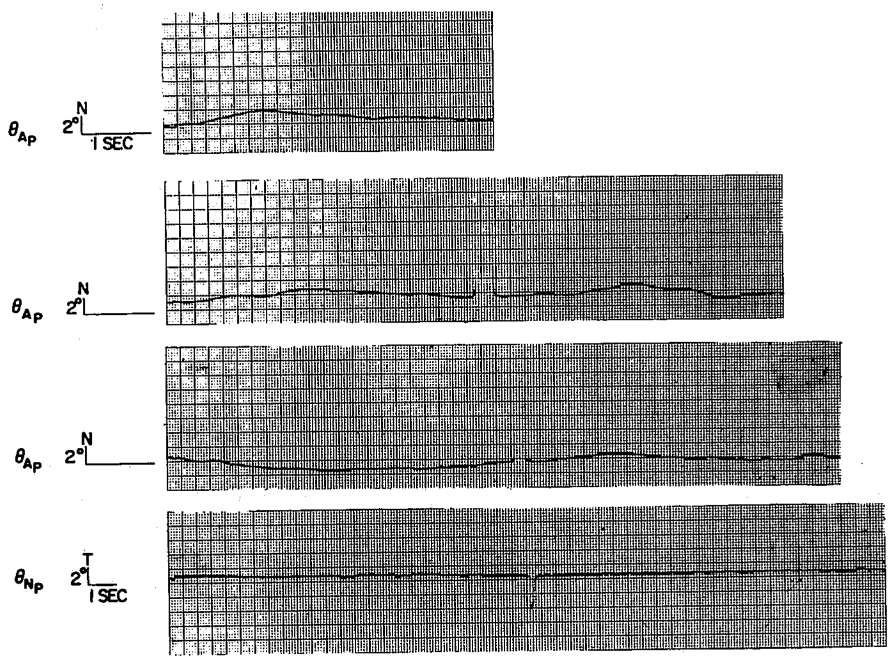

Figure 1: Eye position as a function of time in the dominant eye (bottom trace, 20/20) and amblyopic eye (top traces, 20/40). Monocular fixation. Prominent drift of the amblyopic eye is in marked contrast to steadiness of dominant eye. Symbols: θT = target position, θA = amblyopic eye position, $\dot{\theta}A$ = amblyopic eye velocity, θN = dominant (or normal) eye position, θB = binocular eye position, and subscripts T = templeward eye movement and N = nasalward eye movement.

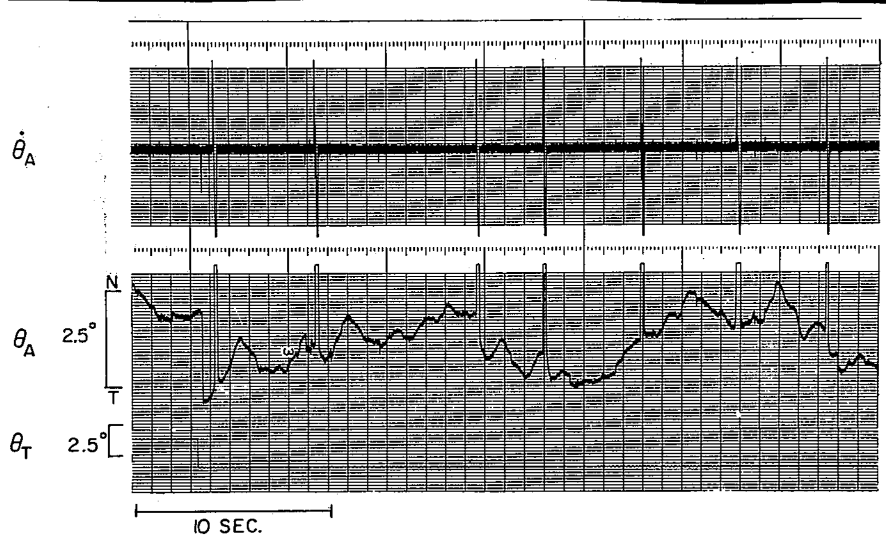

Figure 2: Eye velocity (top trace) and eye position (bottom trace) as a function of time in a patient having amblyopia (20/40) without strabismus. Midline fixation with the amblyopic eye. High gain record. Note increased drift amplitude (and velocity) without comparably-sized corrective fixational saccades. Deflections driving pens to edges of records due to blinks.

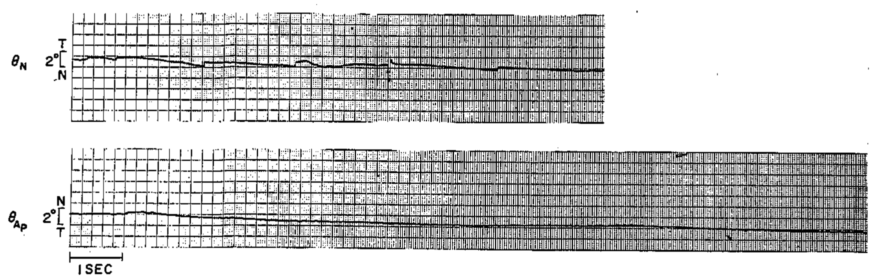

Figure 3: Eye position of dominant eye (top trace) and amblyopic eye (bottom trace) as a function of time in a patient having amblyopia (20/40) without strabismus (same patient as in Figs. 1-2). Monocular fixation. Each eye tested separately. Room darkened and dim fixation target. Note rightward drift bias in each eye. *Nasalward* drift in dominant eye corrected by templeward saccades, while slow *templeward* drift in amblyopic eye remained uncorrected as the position error gradually increased.

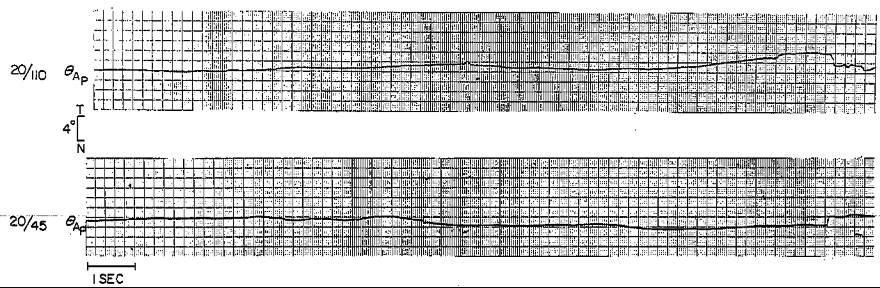

Figure 4: Eye position as a function of time. Monocular fixation with the amblyopic eye at two visual acuity levels (during orthoptics treatment) in a patient having amblyopia without strabismus. Records show slow drift of amblyopic eye without occurrence of comparably-sized corrective fixational saccades: templeward drift in top trace and nasalward drift in bottom trace. Visual acuity was 20/110 with eccentric fixation of 2 prism diopters temporal when top record taken, and was 20/45 with eccentric fixation of 0.5 prism diopters temporal when bottom record taken. Despite differences of acuity and mean fixation region, drift characteristics (with the exception of direction) are similar in both records.

eye, nasal drift is corrected by templeward saccades. However, in the amblyopia eye, slow templeward drift continued for several seconds without saccadic correction of the accumulated position error. In Fig. 4, slow templeward and nasalward drift is present in the same patient at two acuity levels. The paucity of microsaccades (resolvable by our recording system) is evident.

Characteristics of increased drift amplitude were as follows. Maximum peak-to-peak drift amplitude was 3.5 degrees, while average maximum drift amplitude was 0.7 degrees.[a] Increased drift amplitudes were usually greatest in amblyopia without strabismus. Drift amplitudes were generally higher in constant strabismus amblyopia with exotropia than with esotropia, given the same degree of amblyopia. In constant strabismus amblyopia with esotropia, drift amplitude correlated highly with degree of amblyopia. Drift amplitudes were slightly increased in intermittent strabismus, but this was generally found in those patients also having a mild degree of amblyopia and slight eccentric fixation. Increased drift amplitude could be due in part to at least three factors: ineffectiveness of the microsaccadic system (perhaps due to increased saccadic latencies[2,3]) thereby allowing large drift amplitudes to evolve in the amblyopic eye, delay in the smooth pursuit velocity-correcting system thus allowing large drift amplitudes to occur, and/or normal drift characteristics for fixation with a non-foveal region as most patients had eccentric fixation.

Characteristics of increased drift velocity were as follows. Maximum drift velocity was 3.0 deg./sec., while average maximum drift velocity was 1.7 deg./sec.[a] Increased drift velocities were generally greatest in amblyopia without strabismus. Drift velocities were typically higher in constant strabismus amblyopia with exotropia than with esotropia, given the same degree of amblyopia. In contrast to drift amplitude results, drift velocity did not correlate with visual acuity in the amblyopic eye of patients having constant strabismus amblyopia with esotropia. Drift velocities were increased in some patients with intermittent strabismus, but this usually occurred in those patients also having mild amblyopia and eccentric fixation. Increased drift velocities could be due in part to at least two factors, delay or reduced velocity error detection in the smooth pursuit velocity-correcting system, and/or normal drift characteristics of fixation with a non-foveal region as most patients had eccentric fixation.

Saccadic intrusions[1,5,8]

Saccadic intrusions refer to a pair of horizontal saccades executed in opposite directions separated by 150-500 msec; the second saccade of an intrusion generally brings the eye back towards the baseline, resulting in little *net* change in eye position. Intrusion amplitude averaged 0.7 degrees with a range of 0.25-5.0 degrees. Intrusion frequency averaged 1 per second with a range of 0.3-2 per second. They were sometimes found during binocular fixation and monocular fixation with the dominant eye in patients with strabismus. Since saccadic intrusions were rarely found in amblyopia without strabismus, but typically found in strabismus without amblyopia, the intrusions appear to be related to the presence of strabismus and not amblyopia. Intrusion amplitude did not correlate with visual acuity in the amblyopic or non-dominant eye. They persisted when the patient was instructed to fixate the center of the display screen with the small midline target extinguished. However, saccadic intrusions could be suppressed in the presence of the small target,

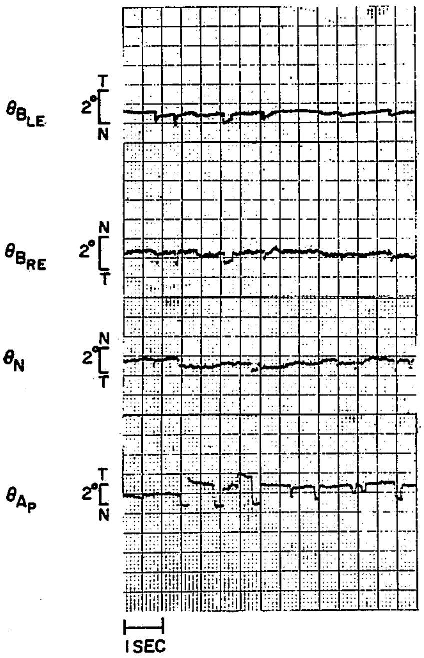

Figure 5: Eye position as a function of time in a patient having constant strabismus with amblyopia (20/122). From top to bottom, left and right eye during binocular fixation, dominant eye during monocular fixation, and amblyopic eye during monocular fixation, respectively. Note increased frequency and amplitude of saccadic intrusions during fixation with the amblyopic eye. Secondary saccade of an intrusion generally returned eye to baseline position, thus correcting position error.

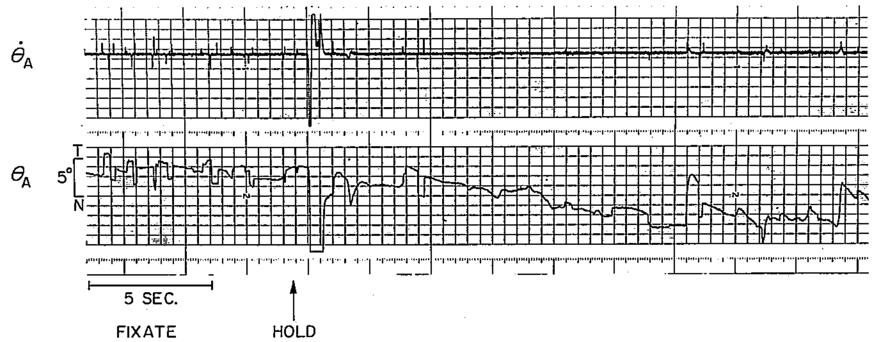

Figure 6: Eye position as a function of time in a patient having constant strabismus with amblyopia (20/122); same patient as in Figure 5. Patient instructed either "to hold the eye steady" (HOLD) or "to fixate the target carefully" (FIXATE). Note marked reduction in saccadic intrusion frequency during "hold" command, as well as pronounced nasalward drift. At other times, drift (with paucity of saccades) only slightly increased during "hold" command, and eye position was maintained within a few degrees of the target.[5]

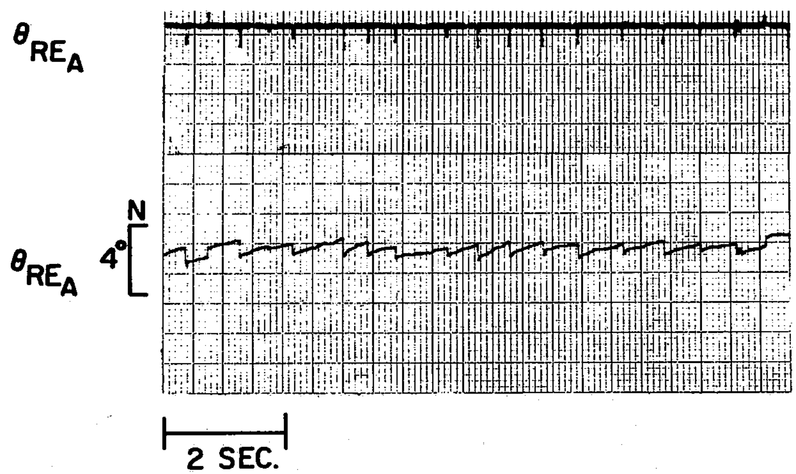

Figure 7: Fixation in a patient with manifest jerk nystagmus. Monocular fixation with amblyopic (20/50) eye.

when the patient was instructed "to hold the eye steady" rather than "fixate" the target.[5,6]

Records showing saccadic intrusions in one of our patients are presented in Figs. 5-6. Saccadic intrusions were present during all fixation conditions, but increased in frequency and amplitude when the amblyopic eye monocularly fixated the target (fig. 5). In Fig. 6, results of the "fixate" and "hold" paradigm are presented. Clearly, saccadic intrusions could be suppressed, but generally with occurrence of increased drift amplitude and velocity. At other times, and in other patients, suppression of saccadic intrusions was possible without occurrence of markedly increased drift.

At least two mechanisms may be involved in generation of saccadic intrusions. They could result from abnormally rapid regional visual adaptation[8,b] (resulting from abnormal visual experience, i.e., suppression and/or mild form deprivation) causing "fading" of the retinal image (the "Lawwill phenomenon"[13]), thus requiring saccades to either prevent fading from occurring or to "revive" a faded retinal image. This interpretation would regard saccadic intrusions as an adaptive phenomenon. Regions over which fading occurred would likely coincide with portions of the eye undergoing suppression during binocular viewing conditions. Saccadic intrusions may also result from strabismus-induced fixation degradation, since they were sometimes observed during binocular fixation and monocular fixation with the dominant eye.[8]

Manifest nystagmus[1,10]

Manifest nystagmus is a disorder of the oculomotor system wherein jerk nystagmus is present during monocular and binocular conditions in patients with strabismus. Mean manifest nystagmus frequency ranged from 1.2-2.2, 0.9-2.3, and 0.7-1.9 Hz during midline fixation with the dominant eye, amblyopic eye, and both eyes, respectively. Mean nystagmus amplitude ranged from 0.24-1.4, 0.32-5.6, and 0.25-2.1 degrees during midline fixation with the dominant eye, amblyopic eye, and both eyes, respectively. Mean slow-phase nystagmus velocity ranged from 0.9-3.5, 1.0-8.0, and 1.0-3.5 deg./sec. during midline fixation with the dominant eye, amblyopic eye, and both eyes, respectively. Mean nystagmus amplitude increased

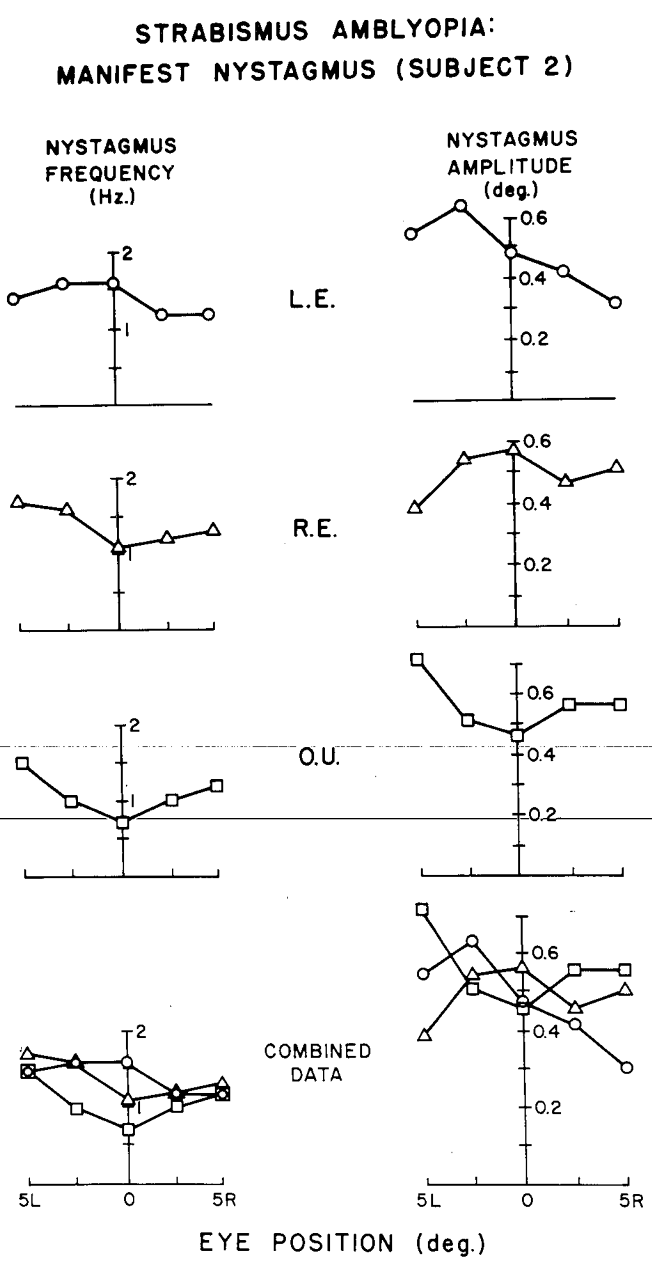

Figure 8: Mean manifest nystagmus frequency and amplitude as a function of gaze angle and fixating eye in a patient with constant alternating strabismus (exotropia) and amblyopia (20/50 right eye); dominant eye visual acuity was 20/25. The patient also had 5 prism diopters of left hypertropia and 2 prism diopters of incyclotropia. Only consistent trend was decreased amplitude in rightward gaze with the left eye.

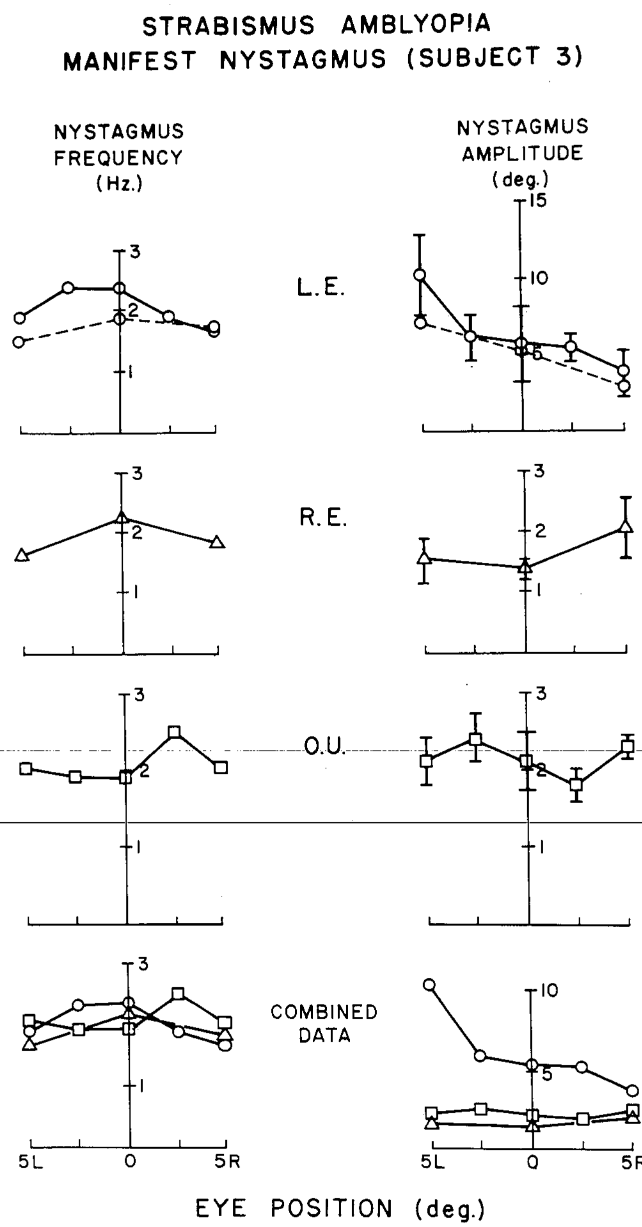

Figure 9: Manifest nystagmus frequency and amplitude as a function of gaze angle and fixating eye in a patient with constant strabismus and amblyopia (20/80); dominant eye visual acuity was 20/40. Mean ± 1 standard deviation is plotted. Dashed lines represent nystagmus frequency and amplitude measured at a later time in the same session, demonstrating close agreement between two sets of data. Note large increase in mean nystagmus amplitude during fixation with amblyopic eye, in contrast to dominant eye fixation or binocular fixation (see lower right graph).

from 0.25 to 1.25 degrees and mean nystagmus slow phase velocity increased from 0.4 to 2.0 deg./sec., when one patient changed from fixation in the light to "fixation" in total darkness (no other patients were tested in the dark); nystagmus frequency remained unchanged at 1.75 Hz. This suggests that in the light a velocity-correcting system (probably smooth pursuit) requiring visual feedback was operating to counteract the true nystagmus as revealed in the dark. Manifest nystagmus was found in four out of eighteen patients with strabismus, and in agreement with Gillies[14] was not found in patients having amblyopia only. Suppression of nystagmus saccades was possible during the "hold" command.[5,15]

A record showing manifest nystagmus in one patient is presented in Fig. 7. Small - amplitude, constant jerk nystagmus is evident. Frequency and amplitude of manifest nystagmus as a function of gaze are presented in Figs. 8-9 for two patients. Nystagmus characteristics did not show any consistent trends as gaze was shifted over this narrow (±5 degrees) range. Mean manifest nystagmus amplitude, fre-

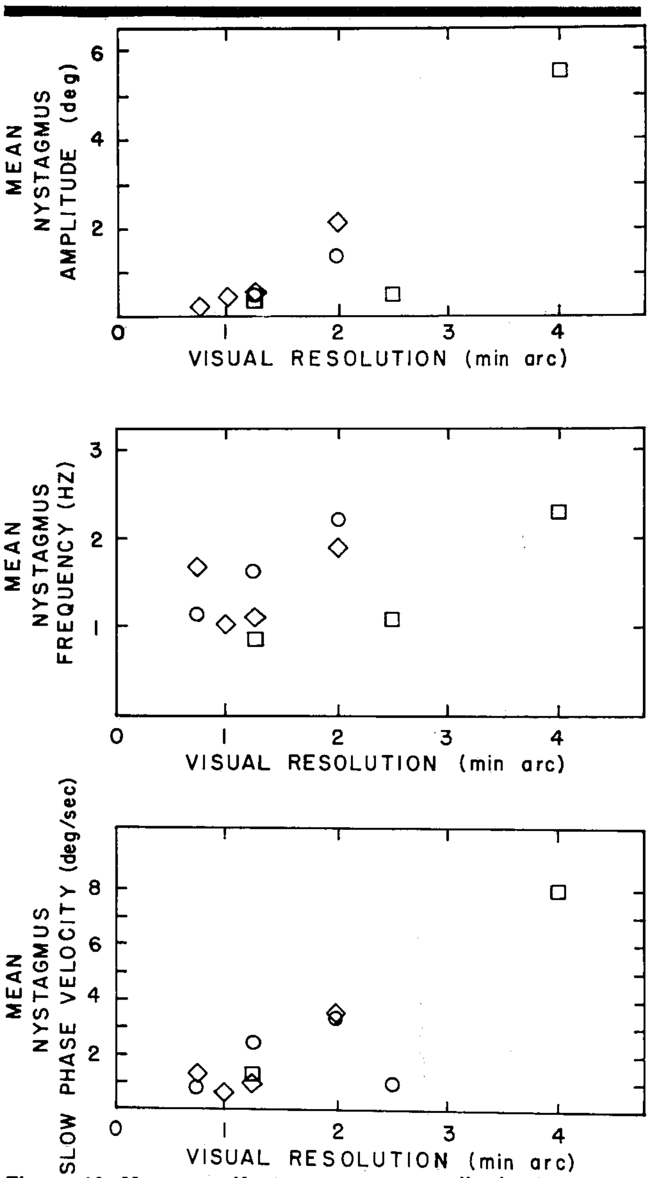

Figure 10: Mean manifest nystagmus amplitude, frequency, and slow-phase velocity for constant velocity segments from top to bottom, respectively, for four patients during monocular and binocular fixation as a function of visual resolution in the viewing eye. Note trend of increasing nystagmus amplitude and slow-phase velocity as visual resolution decreases; nystagmus frequency shows a similar but smaller effect. Symbols: (0) = dominant eye fixating, (□) = amblyopic (or non-dominant) eye fixating, and (Δ) = binocular fixation.

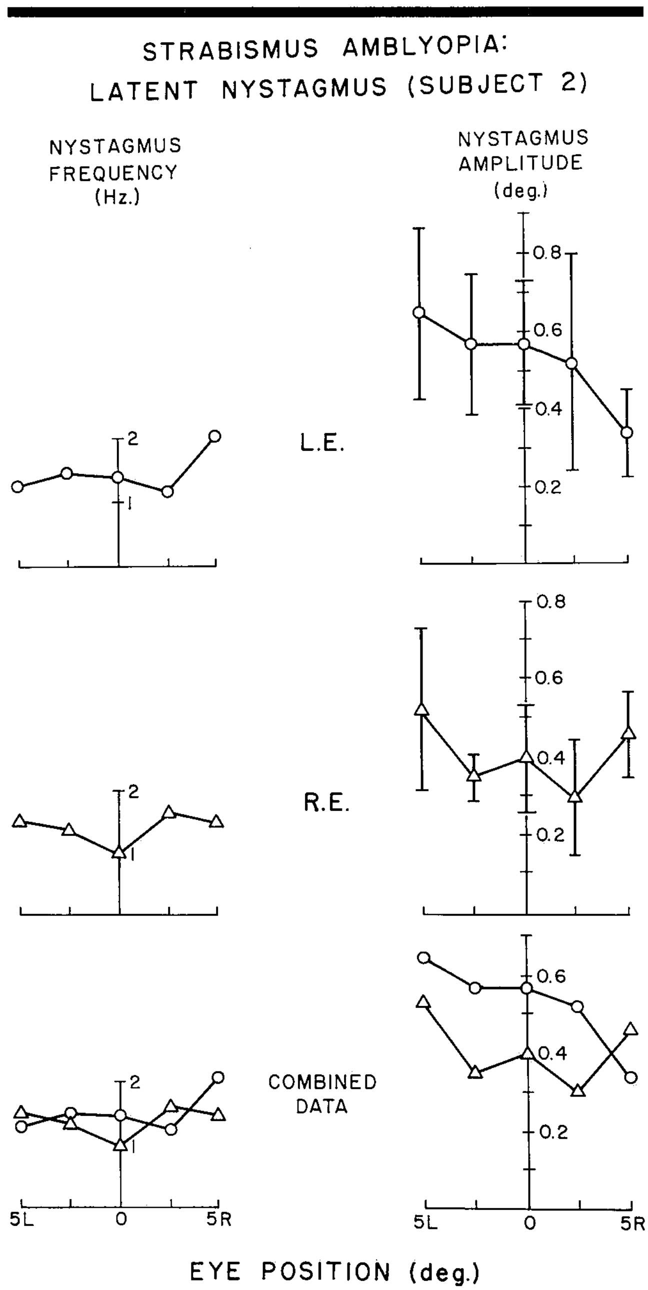

Figure 11: Latent nystagmus frequency and amplitude as a function of gaze angle and fixating eye in a patient with constant strabismus and amblyopia (20/30); dominant eye visual acuity was 20/20. Mean ± 1 standard deviation is plotted.

quency, and slow-phase velocity for our four patients are plotted in Fig. 10. There was a trend for nystagmus amplitude and slow phase velocity to increase as visual acuity decreased; this trend was less prominent for nystagmus frequency.

Latent nystagmus [1,10]

Latent nystagmus is a disorder of the oculomotor system wherein nystagmus is generally not present during binocular viewing, but upon occlusion of an eye, a conjugate jerk nystagmus with the fast (saccadic) phase towards the viewing eye ensues. Latent nystagmus during monocular fixation with the dominant eye had a mean frequency of 1.7 Hz, a mean amplitude of 1.0 degree, and a mean slow phase velocity of 2.0 deg./sec.; similar values were found when the non-dominant eye fixated. In one patient, small amplitude (~0.25 degrees), high-frequency (~5-7 Hz) pendular nystagmus, as well as saccadic intrusions, were sometimes present during binocular fixation. Latent nystagmus was found in two out of eighteen patients with strabismus; it was not found in any patients having amblyopia only.

Latent nystagmus frequency and amplitude as a function of gaze are presented for one patient in Fig. 11. Evident is the low frequency and small amplitude (but with much variability) of the jerk nystagmus under these monocular fixation conditions.

Clinical implications

Our experimental findings have direct clinical implications in the care of patients with amblyopia and/or strabismus in terms of aiding in differential diagnosis, aiding in the funduscopic examination, understanding the influence abnormal eye movement patterns may have on visual acuity, and in helping to understand clinical assessment of fixation.

The importance of *precise*, objective eye movement recordings to aid in clinical diagnosis is borne out in the case histories of two of our patients. We diagnosed them as having manifest nystagmus of low amplitude, frequency, and slow-phase velocity. One patient had never been told she had nystagmus, although she had been examined on numerous occasions over the years. The other patient was referred to our neuro-optometry oculomotor clinic, not with a diagnosis of manifest nystagmus but rather of "bilateral unstead fixation."

Use of the "hold" command during funduscopy may prove helpful in examination of patients exhibiting either jerk nystagmus or saccadic intrusions.[15] Rather than being instructed "to fixate," the patient would be told "to hold the eye steady" as the posterior pole evaluation began. If the patient was capable of reducing saccadic intrusion or jerk nystagmus frequency and/or amplitude, decreased "jerkiness" of the eye would result. This procedure, used in conjunction with the patient fixating in his "null" position, i.e., the gaze position of minimal nystagmus, would allow for a more careful funduscopic inspection by the examiner.

It is well-known that visual acuity is quite variable in amblyopic eyes.[16,17] However, the contribution abnormal eye movement patterns make to this increased variability has received little attention.[1,8,9,16,17] What effect would increased drift have on visual acuity in amblyopic eyes? It has been clearly demonstrated that retinal-image motion across the horizontal meridian of the fovea in normals must exceed 2.5 degrees per second before visual resolution is degraded.[18,c] If this result is applied to amblyopic eyes, visual acuity should be little if at all affected by the increased drift velocities (generally < 2.5 degrees/second). However, increased drift amplitudes moving the retinal-image onto more eccentric positions would reduce acuity (as demonstrated by recent measures of the visual acuity gradient in the horizontal meridian of amblyopic eyes[19]), while increased drift amplitudes in any direction would contribute to increased variability in the acuity measure. That saccadic intrusions do not adversely affect visual acuity was supported by the finding that they occurred in patients with intermittent strabismus having normal visual acuity in each eye (20/20). Furthermore, Ciuffreda, Kenyon, and Stark (unpublished results) have recorded saccadic intrusions during fixation in patients with normal visual acuity free from strabismus, amblyopia, or neurological disease. This lack of interference by saccadic intrusions on visual acuity appears reasonable, since the intersaccadic interval for an intrusion was rarely shorter than 400 msec, thereby allowing adequate visual processing time during these periods. Furthermore, since intrusions averaged less than one degree in amplitude, the change in visual resolution for those retinal areas used during the intrusion relative to the preferred fixation locus would not seriously impair overall resolution. In fact, it appeared to go unnoticed in our strabismic patients during everyday viewing conditions. Moreover, since saccadic intrusion frequency ranged from 0.3-2.0/sec, the interval during which a target and preferred fixation locus would be coincident also provided an adequate processing period.

Knowledge of drift characteristics can help in understanding and in clinical assessment of fixation in amblyopic eyes. With aid of a calibrated grid projected onto the fundus, the clinician estimates the magnitude (time-average position of the fovea) and range (maximum peak-to-peak drift amplitude with microsaccadic amplitude super-imposed) of eccentric fixation. The clinician also estimates "steadiness" of fixation (based on some unknown combination of average and maximum drift amplitude and velocity with microsaccadic amplitude superimposed). The absolute value of mean and maximum drift velocity is impossible to ascertain using standard clinical techniques and presence of abnormal drift in terms of percent total fixation time is difficult to quantify accurately. However, in light of recent findings which clearly show that average maximum drift amplitude and velocity tend to normalize during orthoptics treatment,[4] and thus can provide important information regarding success of therapy and normalization of oculomotor function, precise objective eye movement recordings now become an important part of the fixation examination armamentarium. Objective eye movement analysis as well as careful (low illumination[20]) visuscopic analysis are *essential* for a complete, quantitative description of fixation in amblyopic eyes.[4,21] **AOA**

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FOOTNOTES

a. Drift amplitude was determined in two ways: maximum peak to peak drift amplitude regardless of time required for completion of the movement was found, and maximum peak to peak drift amplitude during consecutive one second fixation intervals was obtained and averaged. Drift velocity was also determined in two ways: maximum drift velocity regardless of time required for completion of movement was obtained, and maximum drift velocity during a 200 msec period for consecutive one second intervals was obtained and averaged.

b. Some of our patients with deep amblyopia reported rapid fading (sometimes with distortion) of the small fixation spot, small and large acuity targets, and even portions of the laboratory room during monocular fixation with the amblyopic eye; fading *was not* reported during monocular fixation with the dominant eye. One patient volunteered that *he made saccades* to "revive" the faded or blanked out portions of the target retinal-image during monocular fixation with the amblyopic eye (K. J. Ciuffreda, in preparation). Hess et al (Hess RF, Campbell FW, and Greenhalgh T) "On the nature of the neural abnormality in human amblyopia; neural aberrations and neural sensitivity loss," Pflugers Arch. 377(3):201-207, 1978) recently reported fading of sinusoidal gratings in some amblyopes during testing of contrast sensitivity.

c. Further evidence that relatively large amounts of retinal-image motion can be tolerated without significant decrease in visual performance has recently been presented by Murphy (B. J. Murphy, Pattern thresholds for moving and stationary gratings during smooth eye movement, Vis. Res., 18:521-530, 1978). He clearly demonstrated that retinal-image motion, regardless of whether it is created by a moving object and a stationary eye or vice versa, of less than 1.0 deg/sec had little effect on contrast sensitivity measures in normals.

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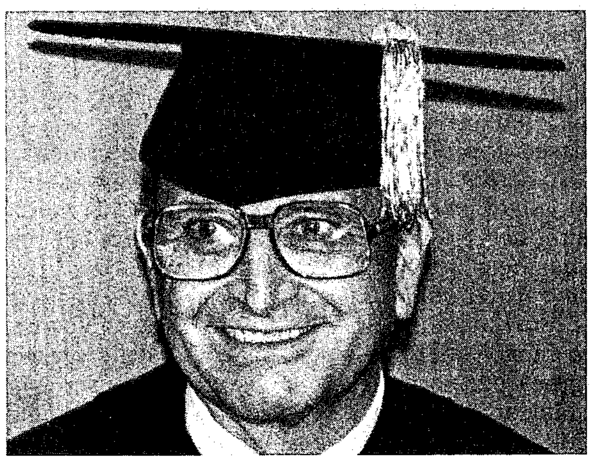
Dr. Charles McQuarrie Receives Honorary Doctor of Laws Degree



Dr. Charles McQuarrie, Lancaster, CA optometrist and past president of the American Optometric Association, is pictured at the October Pacific University convocation when he received the honorary degree of doctor of laws. Dr. McQuarrie took his undergraduate and doctor of optometry degrees at Pacific. The convocation was held on the occasion of the ground-breaking for the chemistry unit of the new science building at Pacific.