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Foveation period stability and oscillopsia suppression in congenital nystagmus

An hypothesis ◇

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ABSTRACT. Congenital nystagmus (CN) waveforms contain foveation periods that occur just before the eyes accelerate away from the target and occur when the eye is in position to place the target image, most of the time, on the fovea. Using phase-plane analysis, the authors studied the waveform changes in an individual with hereditary CN who experienced intermittent oscillopsia (OSOP) following an episode of loss of consciousness six years previously. His nystagmus showed two waveforms that alternated approximately every 2 sec. One waveform (with leftward fast phases) provided repeatable, well-developed foveation periods lasting typically 114 msec, during which the image of an object of regard was within 0.5° of the center of the fovea and image drift was $\leq 4°$/sec; these values defined a 'foveation window'. During this waveform, the subject did not report OSOP. During the second waveform (with rightward fast phases), eye velocity (and hence image velocity) was typically $>20°$/sec as the image of the object of regard swept across the fovea (*i.e.*, there were no well-developed foveation periods); during this waveform, the subject reported OSOP. Artificial (electronic) retinal image stabilization (RIS) failed to abolish OSOP during the second waveform.

Efference copy of the CN waveform has been postulated as the mechanism by which individuals with CN suppress OSOP. This mechanism is tenable only if the source of the subject's acquired oscillation occurred at a point beyond where the efference-copy signal is fed back. RIS by itself is insufficient to suppress OSOP since RIS causes OSOP in most CN subjects (who do not ordinarily have OSOP) and resulted in no change in this subject. The authors conclude that the necessary condition for stable (*i.e.*, no OSOP) vision in our subject was the ocular motor stability provided by repeatable, well-developed CN foveation periods (*i.e.*, an efference copy of it) and without it, OSOP is not suppressed even during RIS.

The authors speculate on the application of these findings to the suppression of OSOP in individuals with acquired nystagmus.

Key words: congenital nystagmus; oscillopsia; perceptual stability

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INTRODUCTION

Previously, we identified two possible mechanisms for the suppression of oscillopsia (OSOP) in subjects with congenital nystagmus (CN): (1)

utilization of an efference copy (internal neural signal) of the CN waveform to negate the visual effects of the oscillation[1,2] or (2) the ability to extract visual information during 'foveation periods', when images are most stable on the fovea (see below) and to ignore the smeared visual information during the high-drift velocities that comprise the CN slow phases.

The notion of foveation periods originated from studies of CN waveforms that demonstrated periods of transient eye stability, occurring at approximately the same eye position during each CN cycle just prior to the slow acceleration of the eye away from the intended gaze angle[3]. Retinal cinematography in individuals with CN demonstrated that these periods of transient eye stability indeed corresponded to when the target image was close to the fovea. This verified that, in CN, the eyes oscillated away from and back to the target. Analysis of many subjects with CN showed that, except for a few transient, bidirectional waveforms, all common CN waveforms contained foveation periods that were the subject's *best attempt* at ocular stability during each cycle[4]. More recent studies using the magnetic search coil method, that allows accurate correlation between the measured eye position and retinal image position, revealed that (during the foveation periods) an individual with CN could maintain target position (SD = 0.21°) and low retinal slip velocities (SD = 1.97°/sec)[5]. Thus, target foveation can occur on a cycle-to-cycle basis when the fixation subsystem of an individual with CN accurately maintains the target image on the fovea during the foveation periods. The exact visual conditions or waveform criteria necessary for suppressing the OSOP resulting from the retinal image motion (RIM) induced by CN are unknown. If we can determine the necessary and sufficient conditions for stable vision (OSOP suppression) in CN, we may be able to apply them to cases of acquired nystagmus where OSOP is a debilitating problem.

Recently, criteria for clear and stable vision have been developed, based on studies relating the position and velocity of retinal images of test objects. These studies have established that clear vision is possible if retinal images lie within 0.5° of the fovea and their drift speed is less than 4°/sec (see Discussion). Individuals whose CN waveforms have *well-developed* foveation periods can repeatedly produce periods of eye stability that fall within this 'foveation window'. In our present study, we related the measured characteristics of foveation periods in CN to these criteria for clear and stable vision.

We studied the eye movements of an individual with CN who had intermittent OSOP. Recordings were made under conditions of both normal fixation and retinal image stabilization (RIS) to aid in identifying the specific waveform changes that accompanied periods of both OSOP and stable vision (OSOP suppression).

CASE HISTORY

A 48-year-old man with hereditary CN and congenital strabismus developed OSOP following an episode of loss of consciousness six to seven years prior to our seeing him. He had been attempting to lose weight and was performing sit-ups, when he apparently fainted. When he came to, he noted intermittent horizontal OSOP and vertical diplopia. These symptoms persisted and were troublesome to him. Although treatment with artane was reported to diminish the OSOP the effect was marginal and he preferred not to take this medication. He has a brother and nephew (brother's son) with CN; neither of his two children (one male, one female) have CN. Until the above incident he, like his brother and nephew, had no OSOP.

Our examination revealed a jerk left (JL) nystagmus that spontaneously alternated with a jerk right (JR) nystagmus every 2-3 sec. The right eye was preferred for fixation with the amblyopic left eye in an exotropic position. When forced to fixate

with the left eye, the right adopted an exotropic and hypertropic position. He complained of OSOP when his nystagmus was JR. At the time of our studies, he was taking no medications.

METHODS

Horizontal and vertical eye motion of both eyes was recorded using the scleral search coil method with six-foot field coils (CNC Engineering, Seattle, WA). The coil system bandwidth was 0-150 Hz, linear range of greater than ± 20° and sensitivity of 0.1° in both planes. The subject's stabilized head remained within the 30 cm cube of the magnetic field where the translation artifact was less than 0.03°/cm. Data were filtered (bandwidth 0-90 Hz) and digitized at 200 Hz with 16-bit resolution. Scleral-coil (Skalar, Delft, The Netherlands) gain was calibrated using a protractor device capable of rotations in each plane. During analysis, the mean foveation position of each eye was set to 0° to align the target position when that eye was viewing. This is routinely done for most other types of eye-movement recording methods and although it does not guarantee that the 0° eye position coincides with a target image on the center of the fovea, it does place 0° at the subject's chosen point of fixaton; except for rare cases of extrafoveal fixation or foveal aplasia, we can assume that 0° is equivalent to the foveal center, especially when the subject has good vision. In addition, data could be stored on magnetic tape and displayed on a rectilinear strip chart recorder (Beckman Type R612 Dynograph, bandwidth 0-100 Hz). Horizontal eye movement recordings were also made using infrared reflection. Eye velocities were obtained by analog differentiation of the position channels. The strip chart recording system and tape capabilities were the same as described above and the total system bandwidth (position and velocity) was 0-100 Hz.

Retinal image stabilization (RIS) of a 20° square Amsler grid was accomplished in the horizontal plane using the horizontal signal from the scleral search coil to drive a mirror galvanometer that reflected the target onto the back of a translucent screen. While the subject fixated the center of the grid, a bias voltage was added to the search coil signal until there was no horizontal drift of the display; this ensured that the image was foveally stabilized. This method is independent of whether the subject has nystagmus (congenital or acquired) or oscillopsia. In all cases, the subject senses the slow drift produced by a parafoveal image and can inform the experimenter when the drift has ceased. The experimenter can also see the target drifting, even when it is oscillating with the subject's nystagmus. Ambient illumination was dim. Further details may be found elsewhere[1,2].

Data analysis, statistical computation of means and standard deviations (SD) and graphical presentation were accomplished on an IBM PS/2 Model 80 using the ASYST software for scientific computing and SigmaPlot for plotting results. Further details on ASYST may be found elsewhere[6]. To calculate the SD of the CN waveform's foveation periods in a given interval of fixation, the point of minimum eye velocity (minimum slope) corresponding to the beginning of each slow phase was identified on the position record (foveation periods calculated in this way may not have actually resulted in accurate target foveation). These points (most easily identified on eye position records) were entered into an array using interactive graphics and the SD of foveation-period position was then calculated. To calculate the SD of foveation-period velocity, the velocities of the *same* points (previously identified on the position record) were read into an array using interactive graphics. The foveation-

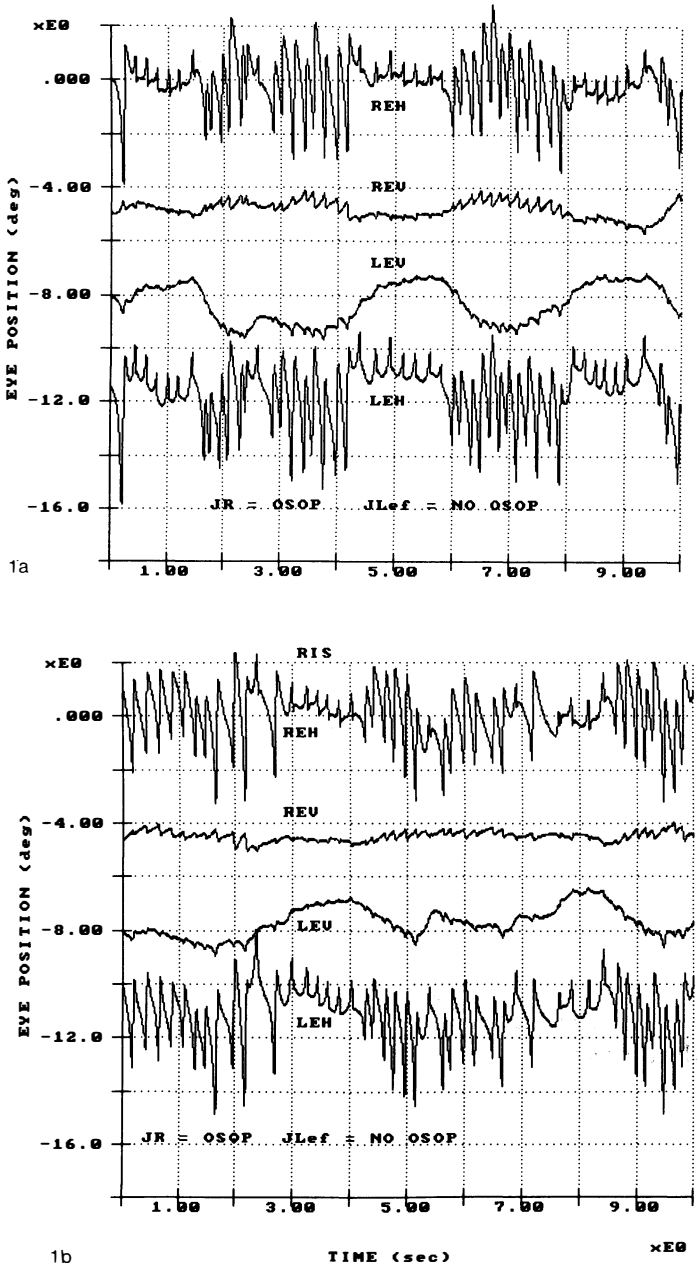

Fig. 1 Ten-second fixation records of the positions of both eyes in the horizontal and vertical directions during (a) normal fixation and (b) retinal image stabilization. In this and the following figures: REH and REV are right eye horizontal and vertical respectively; LEH and LEV are left eye horizontal and vertical respectively; JL_{ef} is jerk left with extended foveation; JR is jerk right; OSOP is oscillopsia; and RIS is retinal image stabilization. The vertical tracings have been shifted for clarity. Positive is rightward and upward.

period time interval was calculated by subtracting the point when the eye speed fell to 4°/sec from the point when it rose to that value; these intervals were identified on the velocity record using interactive graphics and the mean values were then calculated. To calculate the total time per second (or per cycle) that the target was truly foveated, the eye-position and eye-velocity arrays were analyzed (using array mathematics) for all points when both the ±0.5° and ±4°/sec limits of the predefined foveation window were satisfied. If the eye-position records showed that all foveation periods of interest during an interval of fixation were well-developed (*i.e.*, they fell within the ±0.5° limits), the easier method using array mathematics was employed to calculate the position and velocity SD's.

The use of phase planes was first introduced in the study of CN foveation dynamics[5] and later applied in studying smooth pursuit and the VOR in CN[7]. Their utility lies in the simultaneous presentation of both eye (or retinal image) position and velocity. During fixation, this enables immediate identification of those periods when the target image is both stable and on the fovea. During smooth pursuit or VOR analysis, phase planes of retinal image motion identify those periods of gaze stability indicative of perfect pursuit or VOR.

RESULTS

Our recordings revealed CN with a jerk left with extended foveation (JL_{ef}) waveform when OSOP was absent; the frequency was 4-6 Hz. By marking the record every time the subject reported either perceived target motion ('moving') or stability ('stopped'), we determined that the transition from perceptual stability to OSOP corresponded to the transition from the JL_{ef} to a JR waveform and the OSOP persisted throughout those periods when his nystagmus was JR. When both eyes were open, the right eye was used to fixate; covering the left eye produced no changes in the CN or the OSOP. When left-eye fixation was forced, by covering the right eye, the CN waveforms were of lower amplitude with longer foveation periods. As Fig. 1a (recorded during right-eye fixation) shows, in addition to the abrupt change in the CN waveform to JR, the waveform's foveation periods were shifted in position (biased) up to 2° to the right of the target resulting in a failure of target foveation. Also during those JR periods, his left eye adopted a hypotropic position. The transition from perceived target motion to stability corresponded to the transition from JR to JL_{ef}. Each waveform and the corresponding perceptual state persisted for approximately 2 sec.

Fig. 2 shows the first 1 sec of the 10 sec contained in Fig. 1a (position in 2a, velocity in 2b and phase plane in 2c) to illustrate the transition from JR to JL_{ef}. Corresponding points on each part of one JL_{ef} cycle in Fig. 2 indicate the entry (speed ≤4°/sec) into the foveation period from the previous fast phase (4), the most stable interval (speed ≤1°/sec) of foveation (0-1), the exit (speed ≥4°/sec) from the foveation period (2) and the termination of the slow phase (3) followed by the fast phase (4). Examination of Fig. 2c reveals that the slow phase of the JR waveform did *not* enter the foveation window whereas *all three* JL_{ef} slow phases did. The foveation window has been superimposed on each of the figures showing phase planes for ease of interpretation.

Fig. 1b is a 10-sec record of right-eye viewing during the condition of electronic RIS; the waveforms continued to alternate and the perception of OSOP corresponded to the JR waveform. In Fig. 3 we examined the JR to JL_{ef} transition during RIS. Again, corresponding points in the pos-

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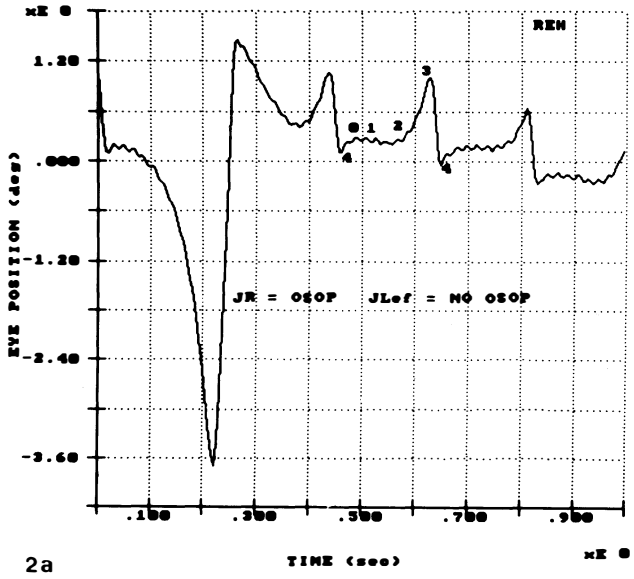
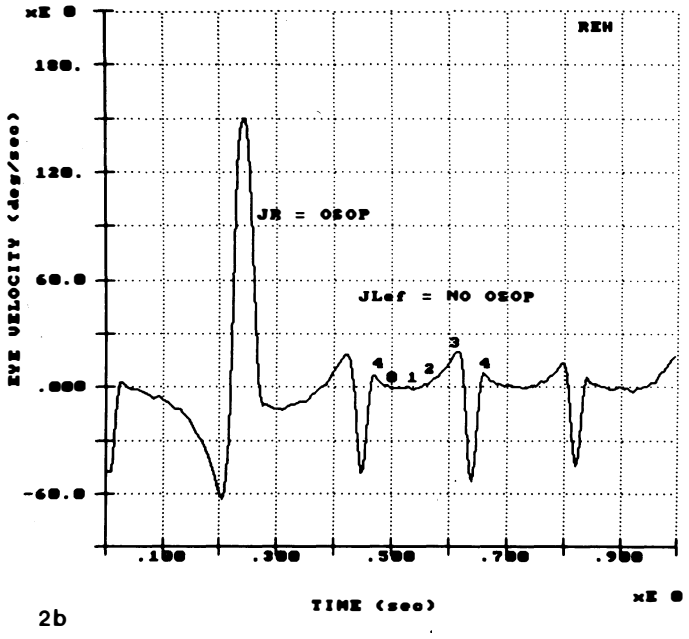

REM
EYE POSITION (deg)
JR = OSOP
JLef = NO OSOP
TIME (sec)

2a


REM
EYE VELOCITY (deg/sec)
JR = OSOP
JLef = NO OSOP
TIME (sec)

2b

Fig. 2a, b

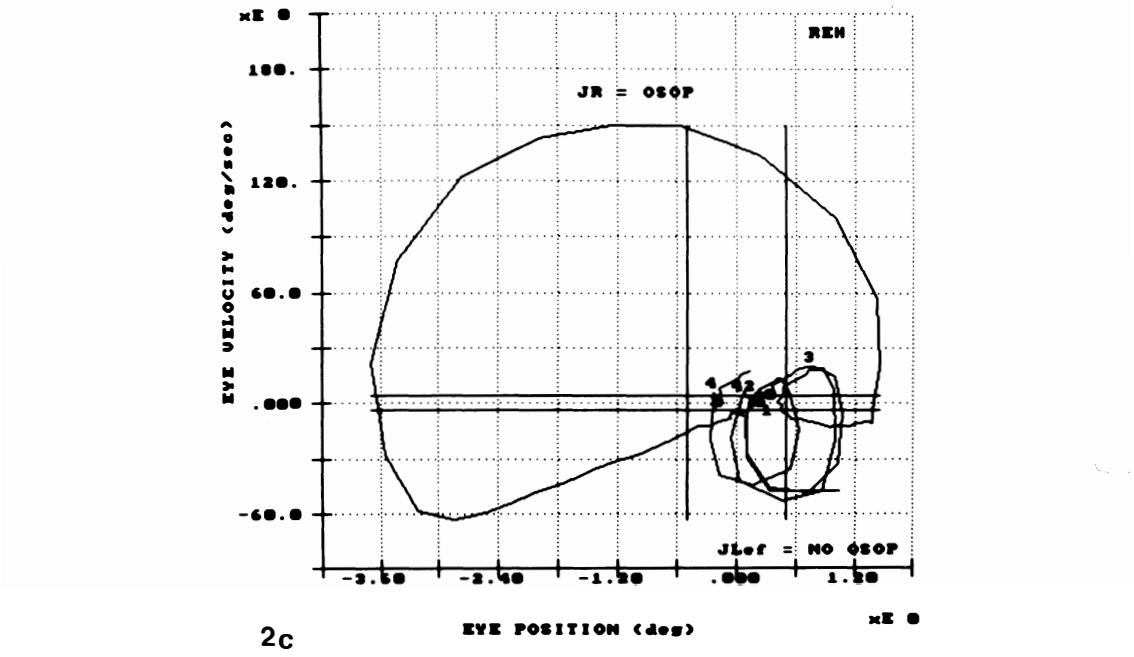


Fig. 2 Horizontal position (a) and velocity (b) of the right eye during fixation showing the transition from JR to JL_{ef}. Phase plane of this transition (c) with the foveation window superimposed. Corresponding instants in time are numbered on each plot.

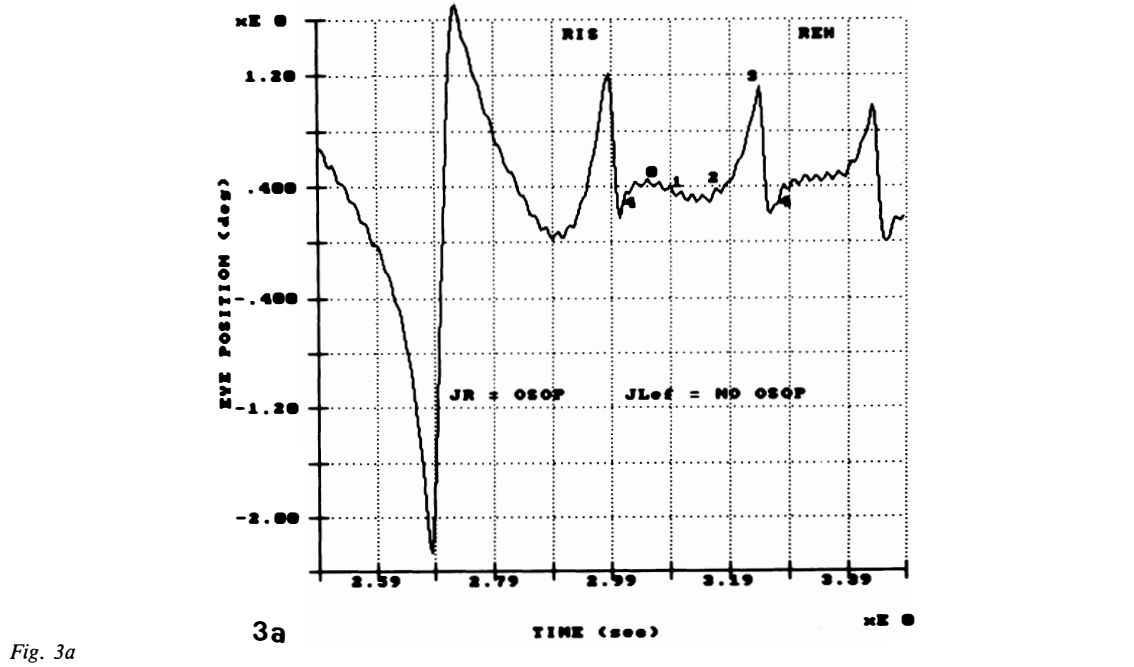


Fig. 3a

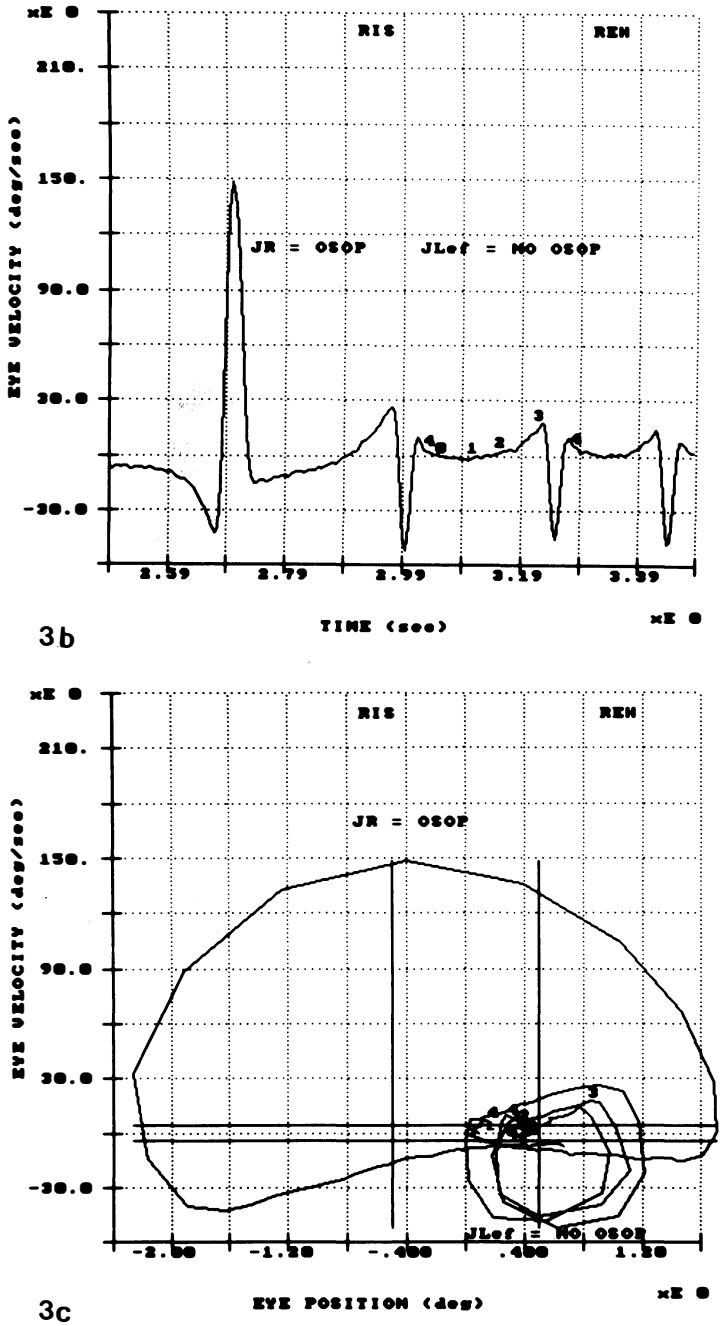


Fig. 3 Horizontal position (a) and velocity (b) of the right eye during retinal image stabilization showing the transition from JR to JL_{ef}. Phase plane of this transition (c) with the foveation window superimposed. Corresponding instants in time are numbered on each plot.

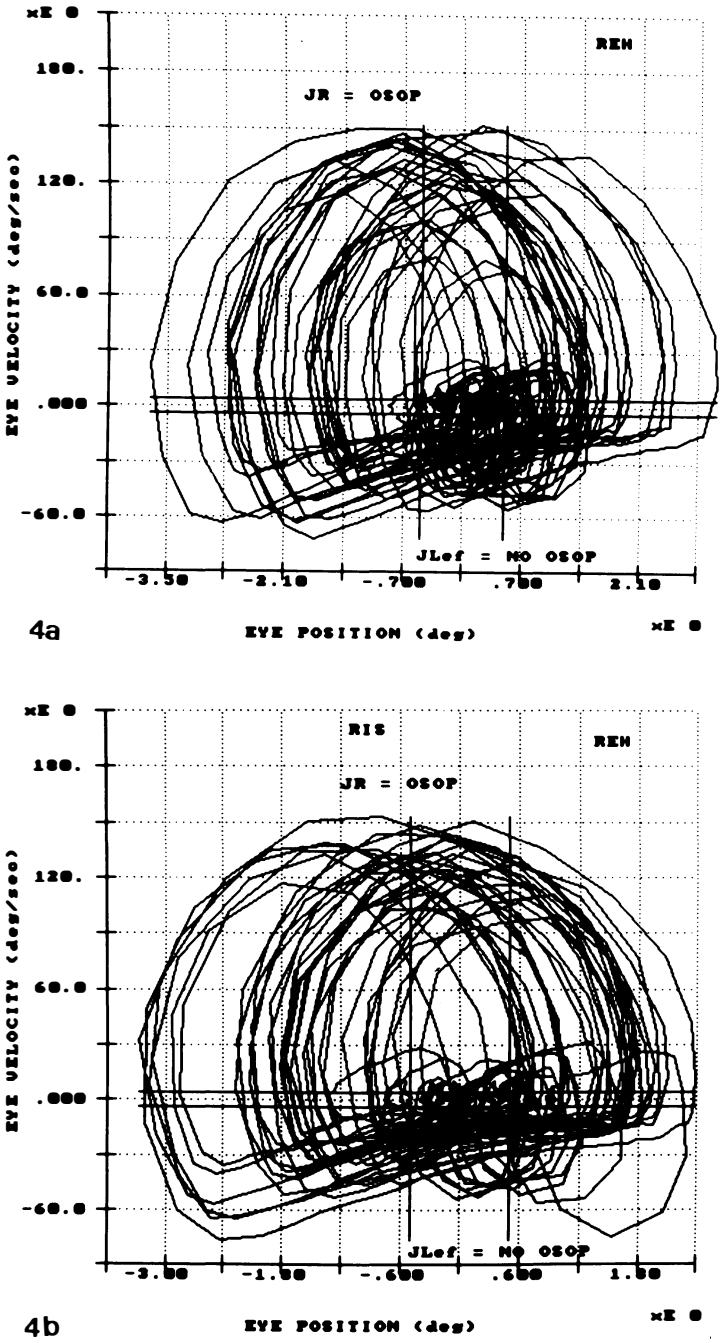
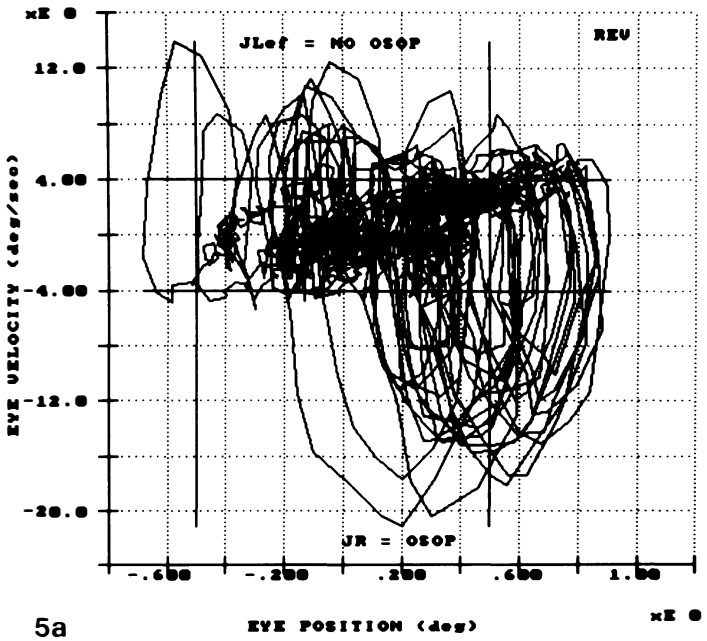


Fig. 4 Phase portrait of the horizontal motion of the right eye during fixation (a) and retinal image stabilization (b). The foveation window is superimposed on the data.



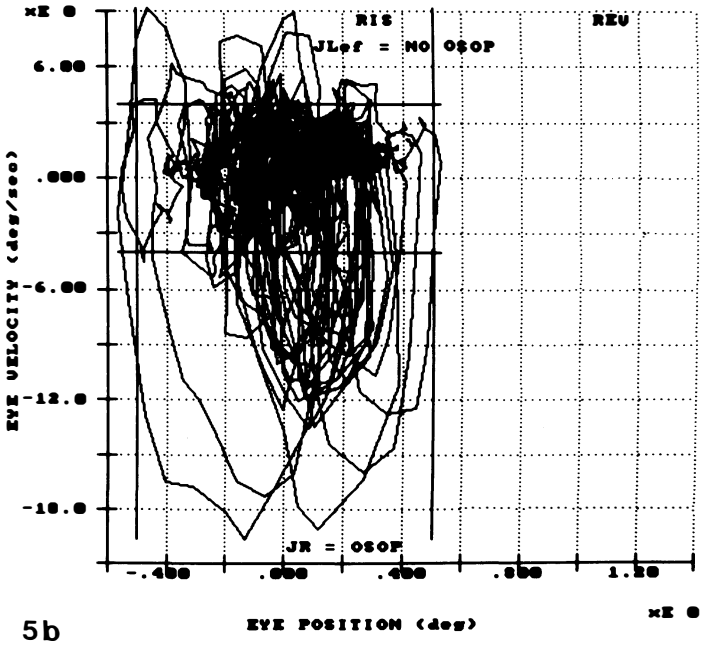


Fig. 5 Phase portrait of the vertical motion of the right eye during fixation (a) and retinal image stabilization (b). The foveation window is superimposed on the data.

ition (3a), velocity (3b) and phase plane (3c) were labeled for one JL_{ef} cycle. As was the case for unstabilized fixation, the JR slow phase did not enter the foveation window and all of the JL_{ef} slow phases did; under RIS, the foveation window is defined by the same eye motion that corresponds to retinal image motion during fixation. RIS did not alter either the waveforms or the reports of OSOP during the JR waveform.

Phase-plane portraits of both 10-sec records of fixation (Fig. 4a) and RIS (Fig. 4b) show that the above transition phase planes were neither unique nor specially chosen to illustrate the above points. Despite the constant alternation between the two waveforms every two seconds, *none* of the JR slow phases entered the foveation window in either record and virtually *all* JL_{ef} slow phases were in the window in both records.

Fig. 5 shows the 10-sec vertical phase planes for fixation (5a) and RIS (5b). Here, the slow phases of *both* the JL_{ef} and JR waveforms were well within the foveation window in both records; there was no vertical OSOP under either condition.

To quantify the motor stability of the foveation periods of the JL_{ef} waveform, we calculated, over the entire 10-sec period, the SD's of both the mean foveation-period position (FPOS) and velocity and the mean duration of the foveation period. During fixation with the right eye, the mean foveation-period position had an SD = 0.24°, the mean foveation-period velocity had an SD = 1.87°/sec and the mean duration of the foveation period was 113.9 msec/cycle (555.1 msec/sec) of the JL_{ef} waveform. During RIS, when no retinal slip information is available, the corresponding values were, 0.25°, 2.00°/sec and 127.9 msec/cycle (646.0 msec/sec) respectively; these latter figures were calculated by averaging the values for two 10-sec periods of RIS. In contrast, the calculations for the JR waveform showed much more variability. During fixation, the mean foveation-period position was 1.37° to the right with an SD FPOS of 0.69°. During RIS, the mean foveation-period position was 1.31° to the right with an SD FPOS of 0.62°; these latter figures were also calculated by averaging the values for two 10-sec periods of RIS. As Figs. 4a and 4b show, the eye velocities corresponding to zero eye position ranged from 15-45°/sec.

DISCUSSION

Studies of the effects of retinal image motion (RIM) on visual acuity provided data from which we derived the limits of the foveation window. Good acuity is possible throughout the foveal floor of 1.5° (the central bouquet of 20′ gives the best acuity)[8] and there is a 50′ isoacuity area around the center of the fovea[9]. Westheimer and McKee[10] found excellent acuity at RIM up to 100′/sec and Murphy[11], using target motion during both stationary fixation and smooth pursuit, found little change in contrast sensitivity at RIM up to 2°/sec. No difference was found between target-induced and subject-induced RIM. Barnes and Smith[12], using moving targets with limited exposure time, found more correct responses at higher target velocities if the target's exposure time was reduced from 40 msec to 10 msec. At exposure times up to 80 msec, there still was a 90% correct response at velocities of 3°/sec. They, along with Guedry[13] who used vestibular responses to generate RIM, concluded that acuity was two to three times higher if RIM was produced by eye, rather than target, motion.

Steinman and Collewijn[14] studied RIM under more natural conditions. They found appreciable failures of VOR compensation (RIM of 4°/sec) in each eye and concluded that we perceive a clear, fused and stable world despite substan-

tial RIM. Further study of vision during natural RIM (head motion) has shown that it is better than could be expected from experiments done with artificially stabilized heads[15]. Studies of the precision of gaze have led to the following conclusions: (1) gaze precision deteriorates by a factor of 2-4 when restraints are removed; (2) active head motion causes a further deterioration by a factor of 5; and (3) such imprecision and the resulting RIM does not degrade vision[16]. Thus, high levels of RIM can be associated with perceptual stability. Taken together, these results suggest that the ocular motor system acts to preserve the RIM that is 'normal' for an individual and only when it fails to achieve this, is OSOP perceived. Subjects with CN have been found to have sensitive differential velocity discrimination[17] despite an elevated motion detection threshold[18].

What is the role of the saccadic fast phases of CN in the suppression of OSOP? We know that prior to saccades the threshold for detection of faint flashes of light is depressed by about half a log unit[19]. However, such a small change in threshold can hardly be responsible for OSOP suppression of real-world targets in bright illumination. Li and Matin[20] concluded that the basis for saccadic suppression was in the transient saccade-related resetting of extraretinal eye position information. Such information is not accurate (less than 1°) and could not be used for 'trans-saccadic' fusion that has been postulated to allow visual stability from saccade to saccade (or, in CN, fast phase to fast phase)[21]. Foveation periods occur after the foveating saccades and before the high-velocity slow phases of CN waveforms. The high velocities associated with saccades are known to suppress the perception of a blurred visual image; this has been attributed to visual masking[22]. Perhaps suppression in CN occurs *both* during the saccades that precede and the high-velocity slow phases that follow the foveation periods and this helps in the suppression of OSOP.

The importance of the waveform-specific foveation periods in determining visual acuity was suggested by earlier studies of CN[4,23] and has been confirmed by more recent work[24-26]. In addition to the above figures on normal gaze precision, a study of foveation dynamics and acuity in CN[5] was used to derive the position and velocity limits that defined the foveation window that constrains well-developed foveation periods. A subsequent study of foveation period precision in CN supports these values[27]. When the target image on the retina repeatedly and simultaneously satisfies both these criteria, OSOP should be suppressed. Since this subject's CN was mainly horizontal with minuscule vertical and torsional components, this discussion will be limited to the horizontal plane. When the nystagmus is bi- or triplanar, the foveation periods must simultaneously fall in the respective foveation windows for OSOP to be suppressed.

The foveation-period SD's and foveation times computed by the interactive graphics method are measures of the beat-to-beat repeatability of the CN waveform and include the one foveation period associated with each CN cycle[4] regardless of its relationship to the target. The computations made using array mathematics include only those well-developed foveation periods that fell within the predefined foveation window and are, therefore, more stringent. For subjects who have low SD's, the two methods yield similar results. The computation of foveation-period SD's and foveation times during RIS requires some comment since the target image is always locked on the retina regardless of the CN waveform. Comparison of these values to those exhibited during fixation illustrates the *motor stability* of the CN waveform even under this

artificial condition. Furthermore, the presence of well-developed foveation periods during RIS, as well as in the dark, reveal that they do not require vision or rely on retinal slip information; they result from the maintenance of eye position by the fixation mechanism using *only* motor signals. Another factor possibly related to the loss of OSOP suppression might appear to be the reversal of CN direction. However, CN direction shifts, common in many CN subjects, do *not* normally result in either the loss of stable foveation periods or OSOP. CN reversals are commonly produced by shifts in the null region during pursuit or OKN and may occur with cover of one eye (latent component) or even spontaneously (aperiodic alternating CN). We presume that this subject has always had direction reversals of his CN under many of these conditions and we know from his history that it did not produce OSOP. RIS changed neither the CN waveforms nor the statistics of the foveation periods.

In this subject, the JL_{ef} CN was essentially horizontal, with a long foveation time; there was a minimal vertical component. The suppression of horizontal OSOP was due to this long period (113.9 msec) of repeatable and accurate target foveation. The subject we studied previously had average foveation times of 57.27 msec with similar position and velocity SD's and no OSOP[5]. Many individuals with CN and foveation times of about 30 msec do not have OSOP. While there is surely some minimum foveation time (<30 msec) below which OSOP might appear despite low SD's of the foveation periods, in this case it was the high SD (0.69°) that precluded repeatable foveation periods during the JR waveform and resulted in OSOP. If the SD FPOS was low, we would expect the 1.37° rightward bias of the mean foveation position during the JR waveform to produce only the perception of a leftward shift of the visual scene. Since this subject's foveation periods either conformed to those subjects without OSOP in position, velocity and duration during his JL_{ef} waveform (when he had no OSOP) or did not satisfy any criteria during JR (when he had OSOP) we could not evaluate the relative importance of each individual statistic. We expect that all are important and that failure of any one of them will result in OSOP. The subject's vertical diplopia was due to the hypotropia of the left eye during the JR waveform.

We documented in a study of the foveation dynamics of a subject with idiopathic CN that the SD's of both foveation-period position and velocity tend to increase slightly at lateral gaze angles[5]. That subject showed increases of up to 5 minarc and 13 minarc/sec respectively when we tested fixation out to 40° laterally. The highest increases were not always at the most extreme gaze angles. Such increases are not sufficient to move the foveation-period statistics out of the foveation window but do affect acuity and were used as a basis for a nystagmus foveation function for the evaluation of potential acuity in CN. These increases are minuscule compared to this subject's JR waveform's position and velocity variations where foveation should occur. Inspection of his JL_{ef} waveform at lateral gaze angles showed no noticeable change in foveation and his reported perception of alternating OSOP and stability did not vary with gaze angle. Therefore, we confined our analysis to primary position.

Phase-plane analysis revealed that, during the periods of horizontal OSOP, only the JR waveform was present and it did not enter the foveation window. Thus, the horizontal motor stability normally associated with CN foveation periods was absent during intervals of JR nystagmus. Since the vertical components of both waveforms remained within the foveation window, no vertical OSOP resulted. We conclude that the mechanism used to suppress OSOP in

CN requires well-developed foveation periods (that fall within the foveation window) greater than some undetermined minimum duration (*i.e.*, it is a *necessary* condition for OSOP suppression). We have recently presented preliminary results of a study of a subject with biplanar CN whose OSOP depended on the fixating eye[28]. Those results support and extend the conclusions made in this study.

How do these findings relate to the perception of visual stability in normals? Two theories have been put forth to explain our perception of stability under all combinations of target and eye motion. They rely on the use of 'inflow' or 'outflow' motor information to 'suppress' sensory information during eye motion or 'subtract' eye motion from the sensory information. Since neither theory explains all of the experimental data, MacKay[29] proposed that the information necessary to correctly interpret the RIM produced by such motions is the result of using corollary motor information to set criteria of evaluation of sensory information. The attractiveness of this mechanism lies in its ability to function with less accurate motor feedback information than would be required for an algebraic subtraction mechanism; the latter is almost certainly required for sensorimotor coordination but *not* for the perception of stability.

Efference copy of motor commands was postulated as the mechanism for sensorimotor coordination in a model of the ocular motor system with CN[30] and as a result of a study of induced OSOP in CN subjects[1]. For that mechanism to be responsible for OSOP suppression, the source of the acquired oscillation in this subject would have to have occurred at a point after that of the efference copy. Usually, RIS induces OSOP in individuals with CN and no OSOP[1]. Under certain RIS conditions OSOP can be present, however. In this subject, RIS did not alter the periodic transitions between visual stability and OSOP nor their correlated waveforms.

Inherent in MacKay's[29] theory is the supposition that the motor information necessary to alter one's perceptual framework (due to eye movements or real motion) is available. What if this were not the case? Can such a mechanism function if the eyes are *never* still and on target? The ability of the subject with CN to achieve perceptual stability using the same mechanism available to normals, seems to require some minimum time of repeatable motor stability during which proper position and velocity criteria can be set. If such ocular motor stability were artificially removed in normals or removed secondary to neurological dysfunction, OSOP should result; it does in the latter condition. Conversely, if that were the case, we should be able to restore visual stability by reimposing some minimal motor stability to again allow this mechanism to reestablish perceptual stability. The results of this study suggest that OSOP secondary to acquired nystagmus should be alleviated by the imposition of brief, repeatable periods of motor stability.

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