Fixational Drift and Nasal–Temporal Pursuit Asymmetries in Strabismic Amblyopes

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This study evaluated to what extent inaccurate and asymmetric smooth pursuit in strabismic amblyopic eyes is attributable to abnormally high-velocity eye drifts that these eyes exhibit during monocular fixation. Smooth pursuit gains (peak eye velocity/peak target velocity) were determined in the amblyopic and nonamblyopic eyes of 11 strabismics for nasalward and temporalward motion; the target oscillated across 6° of the horizontal meridian at frequencies ranging from 0.0625 to 1 Hz. In general, pursuit gains were higher for nasalward than temporalward motion, for both amblyopic and nonamblyopic eyes. Correction for each eye's mean velocity of fixational drift eliminated this nasal–temporal pursuit asymmetry for most of the nonamblyopic eyes, but not for the amblyopic eyes. Compared to the nonamblyopic eyes, corrected pursuit gains of the amblyopic eyes averaged about 0.2 lower nasalward and about 0.4 lower temporalward, but substantial variation occurred among individuals. We suggest that the overall reduction of pursuit gain in strabismic amblyopic eyes (after correction is made for fixational drift bias) stems from the use of a nonfoveal (eccentric fixation) locus for tracking; the further reduction of temporalward gain may result from a nasal–temporal asymmetry in processing motion signals. Invest Ophthalmol Vis Sci 31:968–976, 1990

Amblyopia is defined as a loss of visual acuity, not attributable to detectable pathology or uncorrected refractive error, and generally associated with strabismus, anisometropia, or both conditions concurrently. In addition to acuity loss, several other sensory and oculomotor abnormalities are found, particularly in strabismic amblyopic eyes. These abnormalities include imprecision and inaccuracy of spatial directionization,1–3 relative insensitivity to vertical (compared with horizontal) contours,4 asymmetries of motion sensitivity and perception,5,6 unsteady and frequently nonfoveal fixation,7–9 and inaccurate pursuit and saccadic tracking.10–12 An important and as yet incompletely answered question is the extent to which the different abnormalities that occur in strabismic amblyopic eyes are related.

Although the reduction of acuity usually is confined to one eye, subtle sensory and oculomotor defects, similar to those that characterize the amblyopic eye, have been found to occur in the fellow, nondeviated eyes of strabismic amblyopes. In these nonamblyopic eyes, oculomotor abnormalities appear as a cluster consisting of excessively unsteady fixation with a strong bias for the eyes to drift nasally (interrupted by oppositely directed saccades) in esotropes13,14 a small shift of the time-averaged fixation locus from the central fovea, also generally nasalward in esotropes,15 and an asymmetry in slow eye movement control wherein pursuit tracking and small-field optokinetic nystagmus are notably better for nasalward than for temporalward motion.10,16–18 Bedell and Flom19 presented evidence that these oculomotor abnormalities in the nonamblyopic eyes of strabismic amblyopes were related, and suggested that the nasalward drift bias was primarily responsible for the small eccentricity of fixation and the nasal–temporal asymmetry in pursuit tracking. Tychsen and co-workers6,20 also found substantially poorer pursuit for temporalward than for nasalward target motion in both eyes of subjects with early-onset strabismus, but concluded that the velocity of nasalward drift was insufficient to account for the pursuit asymmetry.

In the amblyopic eyes of strabismics who fixate nonfoveally, the amplitude of fixational eccentricity is attributable only partially to nasalward drifts. In most of these amblyopic eyes, a shift of the reference, or zero point, for motor control to a nonfoveal locus contributes substantially to eccentric fixation.21,22 However, the extent to which drift bias contributes to the abnormal and asymmetric pursuit movements of strabismic amblyopic eyes has not yet been addressed adequately. Most studies that examined the pursuit movements of amblyopic eyes were qualitative and...
did not take drift bias explicitly into account.\textsuperscript{10,11,23,24}

An exception is a study by Schor,\textsuperscript{18} in which gain (eye velocity/target velocity) was determined for pursuit and optokinetic nystagmus separately in the nasal- and temporalward directions. For the two sub-

and displayed, along with target position and an eye

correction was made for the drift bias, the magnitude of the pursuit defects in the amblyopic and non-

amblyopic eyes was not compared after taking drift bias into account.

The purpose of the current study was to compare quantitatively slow eye movement control (specifically, pursuit) in the amblyopic and nonamblyopic eyes of strabismics when the velocity of fixational drift was taken into account. The motivation for doing so was to determine the extent to which drift bias contributes to the asymmetrical pursuit that is exhibited by each eye of strabismic amblyopes, and when correction is made for the drift bias, the magnitude of the pursuit defects in the amblyopic and non-

amblyopic eyes.

Materials and Methods

The subjects were 11 young-adult strabismic am-

blyopes, who voluntarily consented to take part in the study after being informed of the purpose and proce-

dures. Corrected visual acuities ranged from 20/70 to 20/600 in the amblyopic eyes and were 20/20 or bet-

ter in the nonamblyopic eyes (Table 1). Pursuit and fixational eye movements were measured in the hori-

zontal meridian using paired photodetectors (Gulf-

Western, Waltham, MA) sensitive to reflected infra-

red light from the nasal and temporallimbi and mounted onto the subject’s spectacles or onto a blank eyeglass frame. Eye position signals were amplified

and

headed

confirmed

piano-1.75 X 130

20/15

20/115

20/15

20/630

20/15

20/100

20/80

6 eso

3 eso

44 eso

4 eso

15 eso

15 eso

2.2 m away from the subject. During experiments,

the nontested eye was occluded with an opaque

patch.

Table 1. Subjects’ characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Eye</th>
<th>Refractive correction</th>
<th>Acuity</th>
<th>Heterotropia*</th>
<th>Horizontal fixation eccentricity(\textdegree)</th>
<th>Drift velocity(\textdegree)/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>OS</td>
<td>-1.50 -3.00 (\times) 170</td>
<td>20/20</td>
<td>12 eso, 3 hypr</td>
<td>0.15 N</td>
<td>0.43 N</td>
</tr>
<tr>
<td>MH</td>
<td>OD</td>
<td>+0.75 -3.00 (\times) 005</td>
<td>20/120</td>
<td>20 eso, 3 hypr</td>
<td>2.03 T</td>
<td>1.01 N</td>
</tr>
<tr>
<td>DC</td>
<td>OS</td>
<td>-0.25 sph</td>
<td>20/240</td>
<td>23 eso, 10 hypo</td>
<td>6.21 N</td>
<td>2.14 N</td>
</tr>
<tr>
<td>JF</td>
<td>OS</td>
<td>+1.75 sph</td>
<td>20/180</td>
<td>20 eso</td>
<td>1.75 T</td>
<td>0.46 N</td>
</tr>
<tr>
<td>JK</td>
<td>OD</td>
<td>-1.00 sph</td>
<td>20/15</td>
<td>8 eso</td>
<td>0.37 N</td>
<td>1.22 N</td>
</tr>
<tr>
<td>DR</td>
<td>OD</td>
<td>-2.25 sph</td>
<td>20/20</td>
<td>3 eso</td>
<td>1.80 N</td>
<td>0.37 N</td>
</tr>
<tr>
<td>RW</td>
<td>OD</td>
<td>+2.00 -0.50 (\times) 060</td>
<td>20/70</td>
<td>44 eso, 8 hypr</td>
<td>1.76 N</td>
<td>0.56 N</td>
</tr>
<tr>
<td>BB</td>
<td>OD</td>
<td>+0.75 -0.50 (\times) 115</td>
<td>20/12</td>
<td>6 eso, 2 hypr</td>
<td>0.34 N</td>
<td>0.93 N</td>
</tr>
<tr>
<td>TM</td>
<td>OS</td>
<td>-3.50 sph</td>
<td>20/115</td>
<td>44 eso, 8 hypr</td>
<td>1.76 N</td>
<td>0.56 N</td>
</tr>
<tr>
<td>HM</td>
<td>OD</td>
<td>+0.25 -0.50 (\times) 180</td>
<td>20/12</td>
<td>6 eso, 2 hypr</td>
<td>0.34 N</td>
<td>0.93 N</td>
</tr>
<tr>
<td>SM</td>
<td>OD</td>
<td>+4.50 sph</td>
<td>20/220</td>
<td>15 eso, 1 hypr</td>
<td>1.00 N</td>
<td>0.34 N</td>
</tr>
<tr>
<td></td>
<td>OD</td>
<td>plano -1.00 (\times) 065</td>
<td>20/15</td>
<td>25 eso, 4 hypr</td>
<td>0.94 N</td>
<td>0.73 N</td>
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<tr>
<td></td>
<td>OD</td>
<td>plano -1.75 (\times) 130</td>
<td>20/80</td>
<td>8 eso</td>
<td>0.32 N</td>
<td>0.92 N</td>
</tr>
</tbody>
</table>

* Measured in prism diopters. eso, esotropia; exo, exotropia; hypr, hyper-
tropia; hypo, hypotropia.

† Measured by visualization of Maxwell’s spot. N, nasal; T, temporal.

‡ Mean velocity (deg/sec) of horizontal eye drift during fixation.

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gles from the central 1.5–2° of the target’s excursion, when its velocity was maximal and nearly constant. Portions of the record containing saccades, identified from the eye velocity trace, were excluded from scoring. Pursuit records were unscorable at 1 Hz target motion for the amblyopic eye of subject BB and could be scored only for nasalward motion of the target for the amblyopic eye of subject DC. Eye drift velocity was the average of the eye velocities (conserving sign) during intersaccadic intervals for approximately 10 sec of attempted steady fixation. Scoring was primarily by one of the authors (YLY), but good agreement (interscorer reliability = 0.92) was obtained when several pursuit and fixation records were scored independently by a paid assistant. Normal pursuit data, not presented here, showed no substantial difference for nasalward vs temporalward motion of the target, and showed gains that range from just under 1.0 at 0.0625 Hz to about 0.9 at 1 Hz.\textsuperscript{19,25}

The horizontal component of eccentric fixation was obtained by having the subject position an illuminated cursor at the perceived position of the Maxwell spot with respect to a fixation target. The Maxwell spot represents an entoptic visualization of the macular pigmentation, appreciated during alternate viewing in purple and neutral illumination.\textsuperscript{9,15,19} Fixational eccentricity was measured for each eye separately while the nontested eye was patched.

**Results**

Pursuit gain (eye velocity/target velocity) was almost universally higher during nasalward than temporalward pursuit in both the amblyopic and non-amblyopic eyes of our subjects. As illustrated in the averaged data in Figure 1 and in the individual data for three subjects (RW, SM, MH) in Figure 2, the difference between nasalward and temporalward gain was most pronounced at the lowest peak target velocities (oscillation frequencies) and was generally greater in the amblyopic than in the nonamblyopic eyes.
Fig. 2. Pursuit gain is shown as a function of oscillation frequency for the amblyopic eyes (AE) and nonamblyopic eyes (NAE) of three individual observers (O), RW (a), SM (b), and MH (c). Whereas observer RW showed similar degree of pursuit asymmetry in both eyes, observers SM and MH showed much greater asymmetries in the amblyopic than nonamblyopic eyes. Note that at the lowest oscillation frequency, observers SM and MH showed gains that were negative or close to zero for temporalward tracking in the amblyopic eye, and gains that were higher for nasalward tracking in the amblyopic eye than in the nonamblyopic eye. Standard errors (not shown for the sake of clarity) range up to about 0.2 for the lowest oscillation frequency and up to about 0.1 for all other oscillation frequencies.

eyes. Indeed, for targets oscillating at 0.0625 Hz, nasalward gain was greater than 1.0 for 9 of the 11 amblyopic eyes. At this frequency, temporalward gain was less than zero for 5 of the amblyopic eyes, indicating that slow eye movements were nasalward instead of temporalward and that tracking of the target was accomplished by saccades. At higher oscillation frequencies, nasalward pursuit gain decreased substantially in the amblyopic eyes, whereas temporalward gains either decreased much less (three subjects) or increased (eight subjects). The pattern of results exemplified in Figure 1 occurred in 9 of the 11 amblyopic eyes; in the remaining 2 amblyopic eyes, pursuit gain also was higher for nasalward than for temporalward motion, but by about the same amount at all frequencies examined.
All 11 amblyopes exhibited a preponderance of nasalward drifts during monocular fixation, ranging to more than 2° per sec in the amblyopic eye and to more than 1° per sec in the nonamblyopic eye (Table 1). The high gain of nasalward pursuit and the reduced gain of temporalward pursuit exhibited by our subjects’ amblyopic eyes may reflect the contribution of a nasalward drift bias, as suggested previously for the nonamblyopic eyes of strabismics. Consequently, we calculated corrected pursuit gains by subtracting each subject’s mean velocity of fixational drift from nasalward pursuit velocities and by adding the mean fixational drift velocity to temporalward pursuit velocities. The influence of correcting pursuit gains for the velocity of nasalward drifts is shown in Figure 3. On average, corrected pursuit gain for the amblyopic eye is lower for temporalward than for nasalward tracking, but only for frequencies greater than about 0.125 Hz. For the nonamblyopic eyes, residual differences between nasalward and temporalward tracking are smaller than for the amblyopic eyes and occur for frequencies greater than 0.25 Hz.

Average corrected gains are lower in the amblyopic than nonamblyopic eyes for both directions of tracking.

The average data shown in Figure 3 include considerable variation among individuals. The extent of this variation is indicated in Figure 4, where corrected pursuit gains are plotted for the three subjects whose data are shown in Figure 2. For each subject, corrected pursuit gain is lower for temporalward than for nasalward tracking at frequencies greater than 0.25 Hz; this result was found for 8 of the 11 amblyopic eyes. Of the entire sample, three subjects (represented by RW in Fig. 4) showed only small reductions in the corrected pursuit gains of the amblyopic eye. Another five subjects showed a substantially greater reduction for temporalward than for nasalward gain in the amblyopic eye, as represented in Figure 4 by SM. The remaining three subjects, like MH, showed notably reduced gains in the amblyopic eye for both nasalward and temporalward directions of tracking. Of the 11 nonamblyopic eyes, 8 conformed more closely to the pattern shown by SM, for whom corrected pursuit
Fig. 4. Pursuit gain is plotted as a function of oscillation frequency after correction for the nasal fixational drift bias of the amblyopic eyes and non-amblyopic eyes of three observers (O), RW (a), SM (b), and MH (c). All three observers showed smaller asymmetries in nasalward versus temporalward tracking compared to Figure 2. For observer RW, temporalward and nasalward gains were reduced only slightly in the amblyopic eye compared to the non-amblyopic eye. For observer SM, temporalward gain of the amblyopic eye was reduced substantially, and for observer MH, it was reduced drastically.

gains were nearly equal for nasalward and temporalward tracking, than to MH or RW, for whom gains were higher in the nasalward direction. The variability in corrected pursuit gains among the different subjects' amblyopic eyes cannot readily be attributed to differences in visual acuity. Correlations between visual acuity and corrected pursuit gains were low for nasalward and temporalward directions of tracking at all oscillation frequencies (median $r = -0.23$, range $= -0.43$ to $+0.40$). Except at the two lowest frequencies of temporalward tracking, corrected pursuit gains correlated inversely with the mean velocity of eye drift (Table 2; also see Ref. 6), and to a slightly lesser extent, with the horizontal magnitude of eccentric fixation (Table 3). Similar patterns of correlation were found for the amblyopic and nonamblyopic eyes. It is noteworthy that drift velocity was highly correlated ($r = 0.90$) with the (un-
Table 2. Correlations of corrected pursuit gain to mean eye drift velocity  

<table>
<thead>
<tr>
<th>Eyes</th>
<th>Oscillation frequency (Hz)</th>
<th>0.0625</th>
<th>0.125</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
</tr>
<tr>
<td>Amblyopic</td>
<td></td>
<td>-0.33</td>
<td>0.15</td>
<td>-0.52</td>
<td>0.25</td>
<td>-0.40</td>
</tr>
<tr>
<td>Nonamblyopic</td>
<td></td>
<td>-0.50</td>
<td>0.31</td>
<td>-0.53</td>
<td>0.00</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

N, nasal; T, temporal.

signed) horizontal magnitude of eccentric fixation in the subjects' amblyopic eyes (n = 10, no data for BB), but only moderately (r = 0.53) with the time-averaged fixation error of the nonamblyopic eyes.

Discussion

We confirm previous studies showing that pursuit tracking is abnormal in strabismic amblyopic eyes, particularly for temporalward target motion.10,11,17,18,23,24 Pursuit responses are asymmetric also in the nonamblyopic eyes of strabismics, but as reported previously,19 this asymmetry was accounted for in most of these eyes (8 of 11 in the current study) by nasalward fixational drifts that decrease the gain of temporalward pursuit and increase the gain of nasalward pursuit. This result contrasts with the conclusion reached by Tychsen et al20 that the velocity of nasalward fixational drifts is insufficient to account for nasal–temporal pursuit asymmetries in strabismic subjects.

At least two factors may contribute to the discrepancy between the study by Tychsen et al20 and our study is that the former group averaged the data for both eyes of their seven strabismic subjects, four of whom had mild amblyopia. In the strabismic amblyopic eyes in our study, correction for the generally higher velocities of nasalward drifts eliminated the asymmetry of nasalward and temporalward pursuit gain only for the lowest frequencies of target motion (0.0625 and 0.125 Hz, equivalent to 1.18 and 2.35° per sec). As might be anticipated from our results, error bars for the data in the study by Tychsen et al indicate substantial eye-to-eye variability for the strabismic subjects, particularly for temporalward pursuit.

Although the average uncorrected pursuit gains for temporalward motion in our subjects' amblyopic eyes show a broad peak around 0.5 Hz, in agreement with data reported by Schor,18 this peak is discernable in the individual data of only 4 of the 11 amblyopes. The most likely reason for this difference between Schor's study and ours is individual differences in the

Table 3. Correlations of corrected pursuit gain to amplitude (unsigned) of eccentric fixation  

<table>
<thead>
<tr>
<th>Eyes</th>
<th>Oscillation frequency (Hz)</th>
<th>0.0625</th>
<th>0.125</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
<td>N T</td>
</tr>
<tr>
<td>Amblyopic</td>
<td></td>
<td>-0.30</td>
<td>0.00</td>
<td>-0.38</td>
<td>0.26</td>
<td>-0.44</td>
</tr>
<tr>
<td>Nonamblyopic</td>
<td></td>
<td>-0.74</td>
<td>0.32</td>
<td>-0.78</td>
<td>0.34</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

N, nasal; T, temporal.
subjects, which we find to be substantial. Significantly, though, when pursuit gains are corrected for the velocity of fixation drifts, temporalward as well as nasalward pursuit gains show a monotonic decrease with frequency in most of the amblyopic eyes (Fig. 4).

On average, corrected pursuit gain is reduced in the amblyopic eyes (compared to the nonamblyopic eyes) by about 0.2 for nasalward target motion and by about another 0.2 for temporalward target motion. The overall reduction of pursuit gain in the amblyopic eyes is suggested to result from the use of a nonfoveal locus for pursuit. In normal individuals and in patients who acquire visual field defects, pursuit gain is reduced according to the retinal eccentricity at which the pursuit target is imaged. The pattern of negative correlation between the extent of eccentric fixation and corrected pursuit gain, found for the amblyopic eyes of our subjects (Table 3), appears to be consistent with this suggestion. However, these correlations must be interpreted carefully, because: 1) corrected pursuit gains correlate also with drift velocity, which itself covaries with eccentric fixation, and 2) correlation exists between fixation eccentricity and corrected pursuit gain in the nonamblyopic eyes, in which the time-averaged position of fixation is within only 0.5° of the foveal center. The suggestion that pursuit gain is reduced in amblyopic eyes because the target is imaged extrafoveally is consistent with findings of Cuiufreda et al that pursuit gain increased in a strabismic amblyopic patient as fixation eccentricity and visual acuity improved, through orthoptics treatment. Reduced pursuit gain in strabismic amblyopic eyes is not readily ascribed to the reduced acuity, since these two variables were uncorrelated in our study.

Whereas overall reduced gain in the amblyopic eyes may result from the use of an eccentric retinal locus, the further reduction of temporalward pursuit does not. Although normal pursuit is sometimes reported to be weaker for a peripheral target moving away rather than toward the fovea (but see Ref. 28 for a contrary result), amblyope MB in this study as well as amblyopes in prior studies exhibited lower temporalward than nasalward pursuit gain with an eccentric fixation locus in the temporal retina. A second strabismic amblyope in our study with temporal eccentric fixation (JF) exhibited approximately equal gain for temporalward and nasalward pursuit, when correction was made for his nasalward drift bias.

In addition to measuring pronounced nasal–temporal asymmetries for pursuit initiation, Tychsen and Lisberger determined psychophysically for two of their strabismic subjects that targets were perceived to move faster nasally than temporally. Although we have no similar evidence for our strabismic subjects, we concur with their hypothesis that an asymmetric processing of motion signals could contribute to poorer temporalward pursuit gain. In nonamblyopic eyes, the pursuit system’s response to retinal slip information would be expected largely to overcome an asymmetry in the processing of nasalward and temporalward motion under conditions of steady-state, closed-loop tracking, such as in our study. However, if we make the reasonable assumptions that motion signals are more asymmetric and that retinal slip information is less precise in amblyopic eyes (akin to these eyes’ abnormalities of visual directionalization), then substantially asymmetric pursuit may persist even in the closed-loop situation.

Key words: strabismus, amblyopia, pursuit tracking, fixation, nasal–temporal asymmetry

Acknowledgment

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References


