Reading Strategies in Infantile Nystagmus Syndrome

Mervyn G. Thomas, Irene Gottlob, Rebecca J. McLean, Gail Maconachie, Anil Kumar, and Frank A. Proudlock

PURPOSE. The adaptive strategies adopted by individuals with infantile nystagmus syndrome (INS) during reading are not clearly understood. Eye movement recordings were used to identify ocular motor strategies used by patients with INS during reading.

METHODS. Eye movements were recorded at 500 Hz in 25 volunteers with INS and 7 controls when reading paragraphs of text centered at horizontal gaze angles of $-20^\circ$, $-10^\circ$, $0^\circ$, $10^\circ$, and $20^\circ$. At each location, reading speeds were measured, along with logMAR visual acuity and nystagmus during gaze-holding. Adaptive strategies were identified from slow and quick-phase patterns in the nystagmus waveform.

RESULTS. Median reading speeds were 204.3 words per minute in individuals with INS and 273.6 words per minute in controls. Adaptive strategies included (1) suppression of corrective quick phases allowing involuntary slow phases to achieve the desired goal, (2) voluntarily changing the character of the involuntary slow phases using quick phases, and (3) correction of involuntary slow phases using quick phases. Several individuals with INS read more rapidly than healthy control volunteers.

CONCLUSIONS. These findings demonstrate that volunteers with INS learn to manipulate their nystagmus using a range of strategies to acquire visual information from the text. These strategies include taking advantage of the stereotypical and periodic nature of involuntary eye movements to allow the involuntary eye movements to achieve the desired goal. The versatility of these adaptations yields reading speeds in those with nystagmus that are often much higher than might be expected, given the degree of foveal and ocular motor deficits. (Invest Ophthalmol Vis Sci. 2011;52:8156–8165) DOI:10.1167/iovs.10-6645

Infantile nystagmus syndrome (INS) is characterized by involuntary rapid oscillations of the eyes that are typically conjugate and horizontal in direction.1 Although individuals with INS perceive a stable visual world2–4 the impact of these incessant involuntary eye oscillations on reading ability is poorly understood.

A few previous studies have investigated reading in INS, mostly in a small number of patients.3–9 Several of these studies describe the eye movement reading patterns in INS as consisting of nystagmus waveforms superimposed on a normal staircase pattern.5–9 In a recent study by Woo and Bedell,8 reading speeds were compared during rapid serial visual presentation of words and during continuous text presentation of short sentences, but strategies used by the participants were not reported. The two methods of presentation fostered similar reading speeds because the underlying nystagmus waveform negated any advantage associated with rapid serial visual presentation of text compared with continuous text presentation. They were also able to show that INS patients use both foveating and nonfoveating periods to read, although with greater levels of accuracy during foveating periods. However, the strategies used to acquire visual information in INS when reading paragraphs of text have never been systematically investigated.

When viewing a single static or slowly moving target, individuals with INS typically attempt to align the fovea with visual targets during periods of slow eye velocity called foveating periods.10,11 However, to accurately ascertain visual information from text requires the successful coordination of foveation periods to a high degree of spatial and temporal accuracy. Individuals with INS may benefit from the fact that although the eyes move involuntarily, they often follow a stereotypical and periodic profile that could be learned and predicted by patients. Also, involuntary drifts and oscillations could be corrected or modulated using voluntary eye movements. In normal individuals, reading consists of fixations, forward saccades (to move from one fixation to the next), and return sweep saccades that occur at the end of the line, to move the eyes to the next line. Occasionally, these movements are interrupted by regressions, which are saccades in the opposite direction to the orientation of the text that are executed to reread text. They account for approximately 10% to 15% of the eye movements during reading.12

Individuals with INS usually have a null region, a range of eye angles where the nystagmus is less intense.13 As a result, the waveform of the nystagmus changes with gaze angle, usually because the eyes drift toward the null region. Consequently, jerk waveforms become more apparent away from the null region, with foveating saccades being used to reset the drift of the eyes toward the null region.

INS can be associated with other visual system disorders, of which the most frequent is albinism. This pigmentation disorder also leads to sensory and structural abnormalities, such as foveal hypoplasia and misrouting of axons at the optic chiasm,14 although it is not clear how these are linked to the nystagmus. INS may also be unassociated with sensory visual system disorders (also termed idiopathic or congenital nystagmus). We have recently compared nystagmus waveforms in individuals with unassociated INS due to FRMD7 mutations15 and albinism.16 The nystagmus in these two groups share many similar features such as comparable amounts of periodic alternating nystagmus,17 a predominantly horizontal waveform, and the presence of a null region. There are some subtle differences, however, including higher proportions of jerk nystagmus and lower nystagmus frequencies in albinism.

From the Ophthalmology Group, Leicester Royal Infirmary, University of Leicester, Leicester, United Kingdom.

Supported by the Ulverscroft Foundation and the National Eye Research Centre.

Submitted for publication September 28, 2010; revised May 11 and July 6, 2011; accepted July 18, 2011.

Disclosure: M.G. Thomas, None; I. Gottlob, None; R.J. McLean, None; G. Maconachie, None; A. Kumar, None; F.A. Proudlock, None

Corresponding author: Frank A. Proudlock, Ophthalmology Group, University of Leicester, Faculty of Medicine and Biological Sciences, Robert Kilpatrick Clinical Sciences Building, Leicester Royal Infirmary, PO Box 65, Leicester, LE2 7LX, UK; fap1@le.ac.uk.

Copyright 2011 The Association for Research in Vision and Ophthalmology, Inc.

8156
We investigated reading strategies in 25 volunteers with INS (10 albinotic and 15 nonalbinotic or unassociated) and 7 healthy controls while they read paragraphs of text. We compared reading at five different gaze angles (−20°, −10°, 0°, 10°, and 20°), to induce a variety of nystagmus waveforms, and at two distances (33 and 120 cm), since nystagmus amplitude is known to decrease with convergence in individuals with good binocularity.18,19 For each reading task we also compared visual acuity (VA) and the nystagmus characteristics during gaze-holding.

**METHODS**

**Study Participants**

The 25 volunteers with INS (10 albinotic: mean age, 39.8 years; range, 21–58; and 15 nonalbinotic: mean age, 58.6 years; range, 21–58) were recruited from neuroophthalmology clinics in the Leicester Royal Infirmary. All nystagmus volunteers underwent ophthalmic examination of the anterior segment using slit lamp microscopy, dilated funduscopy, and electrodiagnostics (electroretinogram/visual evoked potentials [VEPs]). Diagnosis of albinism was confirmed by the coexistence of three signs: (1) the presence of asymmetric hemispheric VEP responses on monocular stimulation, (2) macular hypoplasia confirmed by either fundus examination or optical coherence tomography, and (3) iris transillumination (Summers classification: grades 1 to 4). Diagnosis of unassociated (nonalbinotic) INS was based on onset of nystagmus in the first 6 months of life, absence of oscillopsia, normal ERG, no iris transillumination, no afferent defects, such as foveal hypoplasia, and no asymmetry of VEP. The Lang test and Frisy test were used to assess binocular vision. The seven control volunteers (mean age, 38.7 years; range, 52–23) recruited had no ocular or neurologic disease and had corrected vision better than 0.0 logMAR.

Each subject was ≥18 years of age and reported English as the primary spoken language. Reading acuity (logMAR score, i.e., equivalent to logMAR score) was measured with Radner reading charts.21 All volunteers achieved a logMAR score of 0.6 or better (i.e., 0.1 logMAR lines better than the text presented). All had their verbal IQ scores calculated with the National Adult Reading Test (NART).22 Mean (±SD) NART scores were 114.5 (±4.4) in INS volunteers and 114.1 (±4.6) in controls. The clinical characteristics of the patients are shown in Supplementary Table S1 (http://www.iovs.org/lookup/ suppl/doi:10.1167/iovs.10-6645/-/DCSupplemental).

Three individuals had periodic alternating nystagmus, as determined from changes in quick-phase beating direction during prolonged recordings (≥5 minutes) when participants attempted to maintain fixation at primary position. Since reading speeds and VA measurements at a fixed gaze angle vary with time in these individuals, data were not included in any other analysis except the comparison between left- and right-beating nystagmus.

Each participant gave informed written consent to participate in this study. The study was performed in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

**Experimental Protocol**

The experimental protocol consisted of (1) a gaze-dependent reading task where paragraphs of text were read at horizontal gaze angles centered at −20°, −10°, 0°, 10°, and 20° (repeated twice at each gaze angle), (2) a gaze-dependent VA task performed at the same gaze angles, and (3) a gaze-holding task consisting of following a 1° target moving from −30° to 30° horizontally in 3° steps every 7 seconds. For tasks 1 and 2, the gaze positions were achieved by altering the head position, whereas the target moved in task 3. All tasks were performed at distance (1.2 m) and near (0.35 m). Standardized logMAR charts were used to assess VA at each gaze position. All subjects were optimally refracted.

A total of 20 reading texts were generated from the Oxford First Encyclopedia (Oxford University Press; Oxford, UK), four paragraphs for each position (two at near and two at distance). The text was taken from a children’s encyclopedia to ensure that no difficulties with comprehension of the text were encountered. The mean passage length was 60.4 words (SD ±3.1), equivalent to 13.7 (±1.0) lines and 264.9 (±15.1) characters with spaces, with 4.5 (±0.29) words per line. The paragraph subtended a horizontal visual angle of 14°, and each lowercase letter a visual angle of 0.4° (equivalent to 0.7 logMAR). Black text (Courier New font, fixed width and monospaced) was displayed on a white background, using a widescreen LCD monitor (Michelson contrast 98%; AL2202W; Acer, Taipai, Taiwan) for distance (enabling calibration) and high-quality printed cards for near. The order of text presentation and gaze position was randomized after a sample text was presented, to acquaint the subject with the paradigm. The volunteers read each paragraph silently, after which a simple question was asked to test comprehension. Only one subject (nonalbinotic) answered incorrectly and was subsequently excluded. The subjects made a vertical saccade to and from a visual target at 20° in the upper visual field to mark the start and end of the reading.

**Data Acquisition and Analysis**

Eye movements were recorded with a pupil tracker (500 Hz, EyeLink II; SR Research Ltd., Canada, Mississauga, ONT, Canada) during the fixational and reading tasks. Each eye was calibrated separately offline by selecting foveations when fixating horizontal and vertical points at ±20° gaze angle and 0° (9-point calibration). The visual target for the calibration and gaze-holding task was projected onto a rear projection screen (1.8 × 1.2 m) using an LCD projector (EMP-1715; Epson, Markham, ONT, Canada) for distance tasks and using a wide LCD monitor (AL2202W; Acer) for the near tasks.

The recordings were analyzed with scripts custom written in neurophysiological software (Spike2; Cambridge Electronic Design, Cambridge, UK). This consisted of automatically identifying sections of data (between blinks) when volunteers were attempting to maintain each gaze angle during the gaze-holding task. The amplitude and frequency of the nystagmus were defined in each section of data from peak-to-peak excursions of the fundamental oscillation determined with an adaptively smoothed copy of the eye position data. The sections of data were also exported into commercial software (MatLab, ver. R2010a; MathWorks, Natick, MA) for analysis using the “OMTools” functions developed by Jacobs and Dell’Osso (see www.omlab.org) for calculating the extended nystagmus acuity function (NAFX).

In addition, an analysis of the foveation patterns was performed for each text reading and the equivalent range of gaze angles during the gaze-holding task, using the algorithms in the OMTools set, with the exception that the position limits could be extended up to ±15° to include the range of gaze angles covered when reading the paragraphs of text. For the analysis, foveation duration, number of foveations per second, and the standard deviation of the eye position during foveations were estimated using fixed velocity thresholds for each individual. The velocity thresholds were set (between 4 and 10 deg/s) as the minimum threshold required yielding foveations on every cycle at the gaze angle where the nystagmus was most intense. Because this meant that the thresholds were relatively high for other gaze angles, a maximum foveation duration was set as 1/5 (for nystagmus with amplitudes >1°, i.e., nystagmus exceeding the foveal extent) and a maximum of 500 ms overall.

The nystagmus waveforms were classified based on waveform morphology using the 12 waveforms described by Dell’Osso and Daroff.23 Quick phases were identified from velocity profiles of eye movement traces after removal of the slow phases by subtracting a median-filtered version of the velocity trace (filter time period, 40 ms, i.e., ±10 samples). An adaptive threshold was set just higher than the high-frequency noise in the recording. This method was able to identify all foveating saccades and all but the smallest braking saccades which were identified from direct observation of the velocity trace.
Statistical Model

Because of the non-normality of the data, Kruskal-Wallis tests were used to compare reading speed between volunteers with INS and control volunteers (also comparing separately the albinotic and nonalbinotic participants). A paired t-test was used to compare reading speeds during right- and left-beating nystagmus and Wilcoxon rank tests, to compare foveation measures between the reading and gaze-holding tasks. Linear regression was used to investigate the relationship between VA and reading speed at the null region (i.e., the gaze angle with the best VA). Linear mixed models were used to investigate the effects of near and distance viewing on ocular motor parameters and reading speed. The absence/presence of stereopsis (i.e., Lang positive or negative) on measured parameters was also compared.

RESULTS

Measurements from a representative control subject and a representative INS patient are shown in Figure 1 during near viewing. Horizontal and vertical eye movement traces are shown during reading (Fig. 1Ai) with a corresponding x-y plot of the same data (Fig. 1Aii). Plots of the reading speeds and VA of the same two subjects recorded across all five positions (Fig. 1Aiii) show that, although reading speeds were similar, VAs were more than 4 logMAR lines better in the control for every position. Examples of real-time video recordings of these two subjects are shown in the Supplementary Videos S1 and S2, respectively (http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.10-6645/-/DCSupplemental). The control volunteers made an average of 4.51 (SD 0.31) fixations per line, indicating that they read most words on each line.

Strategies Used during Line Reading in Nystagmus

Adaptive strategies used by the INS subjects were classified based on nystagmus quick-phase patterns in relation to underlying involuntary slow-phase eye movements. Nystagmus quick phases were (1) suppressed, allowing the involuntary slow-phase eye movement to run (11.3% of strategies used); (2) used to achieve a desired modulation of the underlying slow-phase eye movement (27.4%); or (3) used for corrective realignment of the fovea (61.3%). Three individuals showed periodic alternating nystagmus (PAN), with the quick-phase direction switching every 1 to 2 minutes. Quick Phases Suppressed. When involuntary slow phases of the eyes were to the right at a velocity commensurate with reading, volunteers frequently adopted a strategy of allowing the movement to run, to acquire visual information from a line of text (12.1% of strategies in the albinotic and 10.0% in the nonalbinotic subjects). Consequently, the fundamental frequency of the nystagmus in this group was significantly lower during reading (mean 2.06 Hz, SD 0.63) compared to gaze-holding (mean 4.13 Hz, SD 0.85) at the same gaze angle (P < 0.001, all individuals showed a >33.3% reduction in nystagmus frequency during reading compared with gaze-holding). The involuntary slow phases could be in the form of a drift toward the null region, either with (Fig. 2Ai; 4.3% of strategies) or without (Fig. 2Bi; 1.7% of strategies) the addition of a pendular waveform. Comparisons of the traces during gaze-holding (Figs. 2Aii, 2Bii) highlights the suppression of corrective quick phases. Some individuals (5.2%) allowed their eyes to move with what appeared to be large sinusoidal-like oscillations, with occasional corrective or modulating quick phases (Fig. 2C). Closer examination of these waveforms (highlighted in the dotted rectangle) show that these are pseudopendular waveforms. This effect was associated with rapid reading, as shown in Supplementary Video S3 (http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.10-6645/-/DCSupplemental).

Quick Phases Modulate the Behavior of Involuntary Slow Eye Movements. A common strategy observed with pendular nystagmus waveforms (21.1% of albinotic and 28.6% of nonalbinotic volunteers) was modulation of the oscillations using small quick phases (Fig. 3A). When no quick phases were present, a large sinusoidal-like oscillation persisted (see dashed
that could be used to bring the eyes back toward the beginning of a new line. The quick phases appeared to hasten a reversal in direction of the underlying pendular nystagmus. The volunteer shown in Figure 3 seemed to be able to control the presence or absence, timing, amplitude, and direction of the quick phases, to achieve a desired modulation of the pendular nystagmus. In right gaze, leftward saccades are suppressed, compared with gaze-holding, allowing the overall direction of the nystagmus to be in a rightward direction. In central gaze, the timing of the leftward quick phase was modified during reading compared with gaze-holding, allowing the rightward movement of the slow phase to run farther. A large quick phase was used often to bring the eyes to a new line (as seen in left and central gaze) usually followed by a much longer slow phase which continues in the direction of the quick phase.

Quick Phases Correct Involuntary Slow Eye Movements. Corrective quick phases (i.e., foveating saccades), in the form of left (21.7%) and right (24.8%) jerk nystagmus and also bidirectional jerk nystagmus (14.8%) were commonly encountered at eccentric gazes (Fig. 4A). Left-beating nystagmus was associated with rightward slow movements that were faster than the reading speed (mean velocity of rightward slow phases was 25.1 deg/s [SD 17.4] compared with a mean reading velocity of 8.7 deg/s [SD 2.9]) and right-beating nystagmus with leftward drifting involuntary eye movements (the direction opposite the reading direction). Left-beating nystagmus was more frequent in left gaze and right-beating nystagmus in right gaze, as is typical of INS (Fig. 5, the five bars on the right). Faster reading speeds were associated with right-beating nystagmus (n = 10, paired t-test; P = 0.0007, difference = 52 wpm, including three individuals with PAN, light gray symbols).
Quick Phases Modulate Slow Involuntary Movements

**A Reading**

- **Left gaze**
- **Central gaze**
- **Right gaze**

**B Gaze holding**

- **Leftward quick phases**
- **Central quick phases**
- **Rightward quick phases**

**FIGURE 3.** Examples of original eye movements of one individual with INS (S1 viewing at 120 cm) who modulated his pendular nystagmus using quick phases to read, comparing left (−20°), central (0°) and right gaze (+20°) during (A) reading and (B) gaze-holding. Dashed rectangles: examples of epochs where no quick phases were introduced showing the large underlying pendular oscillation that results. **Downward arrow:** leftward quick phases; **upward arrow:** rightward quick phases.

whereas VA and nystagmus intensity (amplitude × frequency) were not significantly different (VA, \( P = 0.3 \); nystagmus intensity, \( P = 0.57 \)). In some individuals, corrective quick phases were in both directions near the null region (i.e., bidirectional jerk nystagmus, Fig. 4B) sometimes alternating between two gaze positions.

A breakdown of the percentages of each type of strategy at each gaze angle is shown in Figure 5. Note the presence of left-beating quick phases in left gaze and right-beating quick phases in right gaze in both slow-phase modulating and slow-phase correcting strategies. This effect counteracts an underlying slow-phase drift toward the null region through either foveating saccades, to redirect fixation, or braking saccades, to interrupt the phase of the nystagmus oscillation (as observed in Fig. 3).

**Strategies Used to Move to the Next Line in Nystagmus**

Fast and slow phases were used to bring the eyes to the beginning of new lines (Fig. 6), although the relative proportions changed with gaze because of the direction of the underlying drift.

**Comparison of Foveation Patterns during Reading and Gaze-Holding**

Foveation duration, the number of foveations per second and the standard deviation of eye position during foveations were compared during the reading and gaze-holding tasks (Fig. 7). Longer foveation durations were apparent during the gaze-holding task, with the difference being more apparent during near viewing (Fig. 7A). There were no significant differences in the number of foveations per second between the two tasks (Fig. 7B); however, the position of the foveations was far more extensive (\( P < 0.0001 \)) during the reading task than during gaze-holding, as indicated by the standard deviation of eye positions during foveations (Fig. 7C).

**Impact of Nystagmus on Reading Speed**

There was high intragroup variability in reading speeds in the nystagmus groups compared with the control group (Fig. 8), although a subset of nystagmus volunteers in both the albinotic and nonalbinotic groups could read as fast, if not faster, than subjects in the control group. Consequently, there were no significant differences in reading speed between the three groups for distance reading (\( P = 0.058 \)), although the INS groups and controls were significantly different for near reading (\( P = 0.011 \); post hoc comparisons: albinotic versus control, \( P = 0.015 \); nonalbinotic versus control, \( P = 0.011 \); albinotic versus nonalbinotic, \( P > 0.05 \)). In contrast, all statistical comparisons between groups for VA were highly significant for distance (\( P < 0.0001 \); post hoc comparisons: albinotic versus control, \( P < 0.0001 \); nonalbinotic versus control, \( P = 0.0001 \); albinotic versus nonalbinotic, \( P = 0.025 \)) and near (\( P < 0.0001 \); post hoc comparisons: albinotic versus control, \( P < 0.0001 \); nonalbinotic versus control, \( P = 0.0002 \); albinotic versus nonalbinotic, \( P = 0.005 \)). Reading speed was significantly correlated to VA at the null region (i.e., the gaze angle with the best VA) in the nonalbinotic volunteers (\( P = 0.041, r^2 = 0.325 \) for distance; \( P = 0.021, r^2 = 0.395 \) for near) but not the albinotic volunteers (\( P = 0.26, r^2 = 0.18 \) for distance and \( P = 0.77, r^2 = 0.014 \) for near).
Effect of Viewing Distance

Reading speed was not significantly different during near and distance viewing in the patients with albinotic ($P = 0.16$) or nonalbinotic ($P = 0.38$) INS at null position (mean reading speeds: albinotic, 242 wpm at distance and 231 wpm at near; nonalbinotic, 229 wpm at distance and 226 wpm at near). NAFX also showed an improvement in nonalbinotic volunteers ($0.26 \log\text{MAR} \text{ at distance}, 0.19 \log\text{MAR} \text{ at near}; P = 0.001$) during near viewing. However, there was no significant difference in intensity ($P = 0.38$; mean intensity $17.6\text{ /s} \text{ at distance}, 17.7\text{ /s} \text{ at near}$) or NAFX ($P = 0.78$; mean intensity $0.37 \log\text{MAR} \text{ at distance}, 0.37 \log\text{MAR} \text{ at near}$) for near and distance viewing in albinotic patients. VA was not significantly different during near and distance viewing in the albinotic ($P = 0.19$) or the nonalbinotic ($P = 0.77$) volunteers. The absence or presence of stereopsis did not significantly affect any parameter, except NAFX, which was lower (i.e., better predicted VA) in the participants with stereopsis during near viewing ($P = 0.030$).

DISCUSSION

This investigation describes for the first time the versatility of the ocular motor reading strategies used by patients with INS. Our INS subjects used a battery of adaptive strategies, including (1) suppression of any corrective movements of the underlying involuntary drift or oscillation, (2) modulation of invol-
untary slow-phase movements by manipulating quick-phase characteristics, and (3) correction of involuntary slow phases using quick phases. Using these strategies, the INS volunteers were able to position foveations over a wider range of gaze angles than when attempting to hold gaze at a fixed position.

An interesting finding of this study is that volunteers could adapt their nystagmus to achieve the desired gaze patterns rather than observe the nystagmus superimposed on a normal reading pattern. This adaptation was apparent when subjects allowed involuntary slow-phase drifts and oscillations to run across the lines of text (Fig. 3) rather than employing a stair-case or foveation strategy. During voluntary eye movement tasks such as fixations, large saccadic gaze shifts, vestibulocular reflex, and smooth pursuit tasks, eye movement patterns in INS resemble normal patterns with superimposition of the nystagmus. The use of slow phases to reach a desired target has been described for other tasks, such as small saccades to changes in visual stimuli would suggest that they are under a high level of voluntary control. Studies have shown a change in predominant nystagmus waveform within the first few years of life, progressing from square-wave jerks and a triangular waveform, through to an asymmetric pendular waveform, and finally a jerk with extended foveation waveform. This progression reflects the initial calibration of the ocular motor system as the afferent visual system becomes capable of providing high-quality visual information through foveal and cortical development. Individuals probably learn to introduce quick phases to generate foveations—slow periods when the eye is lined up with the target.

The present study suggests that individuals with nystagmus can control the absence or presence, timing, amplitude, and direction of nystagmus quick phases leading to modulation of involuntary slow oscillations. Analysis of foveation data from individuals with INS indicates that nystagmus quick phases were not effective at increasing the duration or frequency of foveations during reading, in comparison to gaze-holding. Indeed, foveation durations were significantly longer during gaze-holding than during reading for some tasks (Fig. 7), possibly because of a greater level of control over nystagmus when trying to hold the eyes at a fixed gaze angle. Analysis of the standard deviation of foveation position indicates that quick phases, however, were effective at positioning foveations over a wider range of gaze angles during the reading task. This reflects the pattern observed in most of the INS volunteers who used quick phases to correct or modulate slow phases with a view to positioning foveation periods sequentially across lines of text. Predictably, the resultant foveation patterns in the INS volunteers followed patterns similar to those of the fixations observed in controls during reading (Figs. 3, 4A).

The variability in reading speed is likely to be related to the wide range of strategies adopted to counteract the underlying drift of the eyes. One volunteer took advantage of their large pendular oscillations to move the eyes across the text imposing a rapid reading speed (Fig. 2C, Supplementary Video S3, http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.10-6645/-/DCSupplemental). We also show that reading speed is slower during left beating compared to right-beating jerk nystagmus (Fig. 4A), presumably because the former relies on the slow phase to move the eyes across the text. In addition, factors that lead to differences in VA, such as foveal hypoplasia, are likely to result in the range of reading speeds observed.

Median reading speeds were considerably slower in our study compared with those in previous reports by Woo and Bedell, for both INS and control groups, possibly because Woo and Bedell used 8- to 13-word sentences compared with the paragraphs of 60.4 words on average used in our study. Given the degree of retinal motion, reading speeds in individuals with INS are remarkably high. Retinal slip velocities of

![Figure 6](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933458/)
greater than 4 deg/s are known to cause considerable motion blur due to high spatial frequency filtering.\textsuperscript{34,35} Despite this retinal motion, individuals with INS report spatial constancy (including all the volunteers in this study), a phenomenon that is probably due to monitoring of the efference copy signal.\textsuperscript{3,36,37} The fast reading speeds in a subgroup of INS patients

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7}
\caption{Analysis of foveation patterns during the reading (○) and gaze-holding (●) tasks for equivalent gaze angles. Median values are displayed (error bars indicate quartiles) at distance and near viewing for (A) foveation duration, (B) number of foveations per second, and (C) standard deviation of eye position data during foveations. *Significant difference between the reading and gaze-holding tasks ($P < 0.05$).}
\end{figure}
could also be due to increased sampling efficiency during favorable epochs.

Damping of nystagmus on near viewing was observed in the nonalbinotic subjects but not in the albinotic ones, possibly because of more frequent strabismus in albinism. This effect was not significant during the reading task, either in terms of mean reading speed or foveation duration, possibly because of poorer control over the nystagmus damping mechanism during a more active task such as reading. These findings agree with those of Hanson et al. who observed nystagmus amplitude decreasing with near-viewing in some individuals, but with no corresponding improvement in VA.

The experimental design involved using a fixed font size of 0.7 logMAR equivalent for volunteers who displayed a range of reading acuities. This approach allowed direct comparison of the strategies adopted by individuals with INS when acquiring visual information from text which has a fixed spatial arrangement (i.e., with the same font size and spacing, vertical line spacing, and horizontal extent of the text). A limitation imposed by using this methodology, however, is that several of the volunteers (mainly those with albinism) were likely to be reading at suboptimal speeds. The influence of crowding-related effects, such as font size and spacing on reading speed and strategy in nystagmus is an area that warrants further investigation.

The experimental design also required volunteers to navigate through a static paragraph of text, a task that is representative of reading tasks frequently encountered in daily life. Another limitation of the paradigm is that it does not allow us to determine with certainty the nature of the quick phases used in the reading strategy, such as distinguishing leftward foveating or braking saccades from regressive saccades used to reread some text.

Analysis of fixation patterns in control volunteers included in this study indicates that they were likely to be reading most words on each line (~4.5 fixations per line compared with 4.5 words per line). Usually not all words are fixated by healthy individuals reading normal font sizes. For example, in normal
reading, three-letter words are skipped ∼67% of the time, whereas words that are seven to eight letters in length or greater are skipped ∼20% of the time. Also, the perceptual reading span is generally invariant within a certain range of font sizes (3-4 letters to the left and 14-15 letters to the right) and leads to similar oculomotor reading patterns. This suggests that the fixed font size used in this study may have been suboptimal for the control and INS volunteers with better vision due to its large size.

This study provides fascinating insights into adaptation to involuntary eye movement disorders caused through pathology. We demonstrate that in the oculomotor system, humans take advantage of involuntary movement to achieved desired goals, presumably through prior learning of the expected behavior of their eyes through skills that may have been acquired over many years during visual development.

Acknowledgments

The authors thank Cris Constantinescu for his helpful feedback on the manuscript.

References

8. Woo S, Bedell HE. Beating the beat: reading can be faster than the frequency of eye movements in persons with congenital nystagmus. *Optom Vis Sci.* 2006;83:559–571.